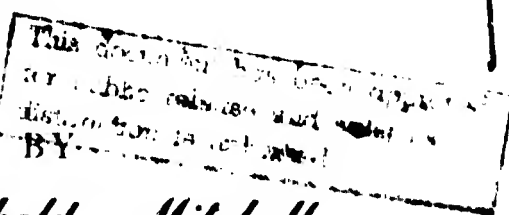
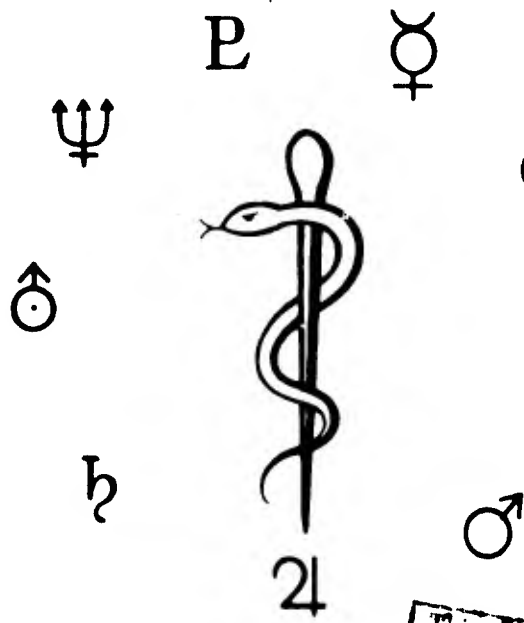


AD 687893

*Fourth International
Symposium on
Bioastronautics
and the
Exploration of Space*



EDITED BY

Roadman • Strughold • Mitchell

AEROSPACE MEDICAL DIVISION (AFSC)
BROOKS AIR FORCE BASE, TEXAS

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THE COVER



The cover illustrates symbolically the relationship between biomedical science and space science. In the center is the symbol of Aesculapius, the patron god of medicine, surrounded by symbols of the planets of the solar system, beginning with Mercury at the upper right and followed clockwise by Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune and Pluto.

AD 682893

The Proceedings of the Fourth
International Symposium on

BIOASTRONAUTICS AND THE EXPLORATION OF SPACE

Sponsored by the Aerospace Medical Division (AFSC),
United States Air Force, Brooks Air Force Base, Texas

Edited by

Major General Charles H. Roadman, MC, USAF

Prof. Hubertus Strughold, MD, Ph.D.

Prof. Roland B. Mitchell, Ph.D.

Editorial Associates

Jack Harmon

Richard C. Schafer

This symposium was held in San Antonio, Texas, June 24-27, 1968, under USAF Contract AF41(609)-67-C-0034.

Published November 1968

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ACKNOWLEDGMENT

It would be impossible to express our gratitude on this page to all of the individuals who contributed to the success of this Symposium and thus to the publication of this book. The Editors would like to use the small space available to express their appreciation to the following individuals for the time and effort so generously given from the beginning to the end of this endeavor.

Mrs. Margaret P. Beck
Records, Correspondence
and Office Administration

Mr. Arthur F. Ryan
Publishing Management

Mr. David L. Black
Major Sydney Lester
Mr. Frank McCall
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Arrangements

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WELCOME ADDRESS

Welcome to the Fourth International Symposium on Bioastronautics and the Exploration of Space

Maj. Gen. Charles H. Roadman*

On behalf of the Aerospace Medical Division, I bid you welcome.

As participants in this Fourth International Symposium on Bioastronautics and the Exploration of Space, you are following in a noble tradition—even though it is one of only 17 short years. It is an exciting tradition—one which has been in the vanguard of man's conquest of the vertical frontier.

The first meeting of this series was held in the fall of 1951 with an attendance of about 400. It was unique because it marked the first time the physician had sat down with the scientist and the engineer to consider the problems and promises of manned flight. It was modest in its scope—the title of the symposium indicates that: Physics and Medicine of the Upper Atmosphere.

Its main area of consideration was the aeropause, the hostile region from about 10 miles up, where the atmosphere could not support manned flight without artificial support, to the end of atmosphere at heights of 120 to 140 miles.

It was a self-conscious time. The then Surgeon General of the Air Force, Maj. Gen. Harry G. Armstrong, defended this far out look.

*Commander, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas.

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He said, "Aviation medical research should be completed prior to the time the aeronautical engineer first sits down at the drawing board, which is usually some 5 to 10 years before the first airplane is first flown."

And then, somewhat apologetically, he added, "In view of this time relationship and a realistic appraisal of the trend in aircraft performance, I feel that the Air Force Medical Service is not premature in its expression of interest in the subject matter of this volume."

We now can smile at this, but we must remember that, although this was less than 17 years ago, it was in the relatively dark age of aerospace research. The Douglas Skyrocket had astounded the world by reaching the speed of 1300 mph. Our most advanced rockets reached out only 240 miles in space.

But our pioneers were undaunted. Dr. Strughold was calling for attention to the problems of weightlessness and radiation. Robert M. Salter, Jr., of RAND, saw the newly discovered transistor as a means of cutting down instrumentation weight in space probes. And Wernher Von Braun expressed his spatial enthusiasm by giving a paper—not on how to get man into space—but how to get him back!

That was the first—the meeting dedicated to progress in aviation, the symposium which was a study of the aerospace.

The second symposium, as was the first, was also the brain-child of Maj. Gen. Otis O. Benson, Jr., but things had now changed. The United States had entered the space age. It was 1958. The Explorer satellite—all 30.8 pounds of it (including the last stage of the rocket)—was sending back its signals. Over 800 people attended the second symposium and the excitement ran high. Dr. James Van Allen announced his finding of the radiation belts which now bear his name. Krafft Ehrlicke urged a "Man on the Moon" program as ideal training for interplanetary operations. Dr. Strughold, the Father of Space Medicine, hailed the new sister field of *astrobiology*. And Wernher Von Braun proposed weather satellites, and communications satellites—the latter as the means of raising, through revenue, enough money to finance the space exploration of deep space. Col. Paul Campbell and others were

already concerned with the problems of escape and rescue during space operations.

This was the meeting which displayed the growing interest of government leaders in the importance of the exploration of space. The dinner speaker put it eloquently. He was Lyndon B. Johnson, then a Senator, who saw in this an added goal for the pioneer whose westward movement was halted by the Pacific. Mr. Johnson said:

"Now we have arrived at the new frontier—the 'vertical frontier' as you call it—the space frontier to the layman. You scientists assembled here are the pioneers of this frontier. You are leading your nation—and all mankind—into it, with a frontier so vast that it will never become settled and static and fixed. The space frontier is, above all, a perpetual frontier."

The Third International Symposium was held in 1964. The picture had changed radically. There were now nearly 500 man-made objects, probes, casings, and debris floating in the space junkyard. The A-11 was unveiled. It could reach 2,000 mph thanks to the use of titanium. The meeting was one of great scientific moment. The U.S. showed pictures which the Ranger VII had sent back from the Moon. The U.S.S.R. revealed that the Voshkhod had gone fourteen orbits with men in shirtsleeves. Billy Welch and Hans Clamann worried about proper cabin atmospheres. And many of the men who are here today—like Drs. Ponnampereuma, Steinhoff, and von Gierke—gave their early results which have set out the new important areas which they will discuss in this symposium.

It has been an exciting 17 years, ladies and gentlemen. But space exploration has always been exciting. Let me share this quotation from Johannes Kepler, who said to a friend in the year 1610:

"There will be certainly no lack of human pioneers when we have mastered the art of flight. Who would have thought that navigation across the vast ocean is less dangerous and quieter than in the narrow, threatening gulfs of the Adriatic, or the Baltic, or the British Straits. Let us create vessels and sails adjusted to the heavy ether, and there will be plenty of people unafraid of the empty wastes. In the meantime, we shall prepare for the brave

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sky travelers, maps of the celestial bodies—I shall do it for the moon, you, Galileo, for Jupiter.”

That is our mission here at this conference. In this international meeting, we are mapping the conquest of space—and we have no lack of pioneers! The frontier is constantly expanding—as long as there is someone like you to push it back!

INTRODUCTION

History and Tribute to Aerospace Medical Pioneers

Col. George E. Schafer*

The birth of the art of Aerospace Medicine followed closely the use of aircraft as a weapon systems in World War I. Unexplained accidents led to the establishment of a facility in the United States for research and development, education, and medical evaluation. This institution, now known as the USAF School of Aerospace Medicine, paralleled in growth and espoused many of the leaders in aerospace medicine. A major growth of the school was seen in World War II when marked increase in educational responsibilities would be imposed. Accompanying this growth in education was a resurgence in research activities. This growth would continue and result in the establishment of new facilities presently occupied by the USAF School of Aerospace Medicine at Brooks Air Force Base, Texas. A few of the leaders in Aerospace Medicine, especially those associated with the Air Force School of Aerospace Medicine are herein cited.

AEROSPACE MEDICAL PIONEERS

Although the conceptual period for aerospace medicine reaches back many decades, the birth of the art can be established as following closely the first involvement of aircraft as weapon systems in World War I. Prior to this time several countries established medical standards for flying. In the United States,

*USAF School of Aerospace Medicine, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas.

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the War Department prepared a special medical examination to evaluate candidates for duty in aviation. This was instituted in 1912.

The British experienced a high accident rate early in World War I, the greatest percentage attributable to unfitness. As a corrective measure, they established a special medical service in the Royal Flying Corps known as *Care of Flyer*. This was to insure merely that the flyer was in good shape to fly prior to flight. After the United States entry into World War I, the medical problems of flyers became apparent. Maj. Theodore C. Lyster, an authority on aviation standards in the Office of the Army Surgeon General, and Dr. William Holland Wilmer used their vision and foresight to form an Aviation Medical Research Board. A direct result of this board was the establishment of a research laboratory at Hazelhurst Field, Long Island, which initiated operations in January of 1918. This laboratory, soon to be named the School of Aviation Medicine, had responsibilities in education, medical standards, and research. These responsibilities have remained intact to this date at the USAF School of Aerospace Medicine. Its many moves and changes in parent commands have merely stressed one responsibility over others as the times and requirements demanded. Maj. Wilmer was the school's first officer in charge and Maj. Louis H. Bauer was the second. It was Dr. Bauer who wrote the first text on aviation medicine, who was the first medical director of the aeronautics branch of the Bureau of Air Commerce, and who was the first to suggest the establishment of the Aero Medical Association.

So now, in its 50th anniversary year, the USAF School of Aerospace Medicine serves as an edifice to the pioneers in aerospace medicine who had foresight and the strength of their convictions. The school has gone through 5 decades of progress along with its sister laboratories and educational institutions in the military services. It fostered and espoused men of vision who led other military departments in the expanding art as it did with the practice of aerospace medicine in the civilian community.

To trace the expansion of aerospace medicine, one must look to all of the civilian and military organizations involved in the various aspects of aerospace medicine practice, research, and education, but as it is the 50th anniversary year of the USAF School of Aerospace

Medicine, I have chosen to limit my remarks and pay tribute to but a few of the outstanding pioneers who built the school and hence contributed immeasurably to the art of aerospace medicine.

The rapid growth of the USAF School of Aerospace Medicine occurred after it was located at Randolph Air Force Base and during World War II. It was during this time period that the school trained over ten times the number of flight surgeons than had previously been trained since its inception. As spectacular as this growth in education was and just as contributory to the growth of the School was that of the revival of research. During this time period, Col. Eugen Gottfried Reinartz (later to be promoted to Brigadier General) was assigned as Commander. His chore was to build the entire school to better encompass the larger responsibilities. Just prior to his arrival, Maj. Harry G. Armstrong was assigned as head of the Research Division of the school. These pioneers shaped the vast expansion not only of the school but also of the art of aerospace medicine. Harry Armstrong would leave the school after laying the groundwork for the expanding research in a brief 8 months' tenure. He became the Surgeon, 8th Air Force, and was headquartered in England. He returned to the school as its Commandant after the war and his foresight brought about a further increase in the expansion of research capabilities, the development of plans for new facilities, and an expansion into an aerospace medical-center concept.

In 1949, Gen. Armstrong went to Washington to be Maj. Gen. Malcolm Grow's deputy. Gen. Grow was the first Air Force Surgeon General, and Maj. Gen. Harry Armstrong would soon replace him.

Gen. Armstrong was succeeded by Brig. Gen. Otis O. Benson. It is interesting to note that Gen. Benson followed Gen. Armstrong at the facility now known as Aerospace Medical Research Laboratories. Both were instrumental in the development and growth of that research institution which today has produced leaders in many fields. It was Gen. Benson who would push through and assist the development of aerospace medicine as a specialty and insure the guidance of the concept for new facilities that 10 years hence would be the home of the USAF School of Aerospace Medicine at Brooks Air Force Base. Gen. Benson accomplished this in two tours at the School, the second of which would see him as a Maj. Gen. in command of the new facilities.

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At the present time, the School of Aerospace Medicine occupies a multimillion dollar complex. Its educational capabilities are responsible for practitioners in aerospace medicine as well as the associated disciplines that make up the USAF Medical Service. Its research and development programs utilize the largest portion of the facilities and cover a wide gamut of activities devoted to man in flight and man in space and men who support these missions. Its medical practice activities include a referral service for flyers and medical selection procedures for astronauts, as extensive and specialized as can be found anywhere.

These facilities, these capabilities, and the people who comprise the USAF School of Aerospace Medicine are a tribute to all of the pioneers—to Lyster, to Wilmer, to Bauer, to Reinartz, to Armstrong, to Benson, and to the specialists who surrounded them, as well as to the many others. This monument will continue to grow. It was people of this type who saw the need for multidisciplinary approach to aerospace medicine. Out of this approach evolved programs such as these symposia, and this, the 4th International Symposium on Bioastronautics and the Exploration of Space, is indeed a tribute to our pioneers of the past and to those who will be the pioneers of the future.

Keynote Address: Space Perspective

Edward C. Welsh*

It is an honor and a pleasure—a real source of satisfaction to me—to have been invited again to give the keynote address to this Symposium. This is the fourth of these events, which increase in stature and reputation each time they are held.

JUSTIFIED OPTIMISM

When I participated in the Third International Symposium here in 1964, I was optimistic about our space program and particularly about the role of man in space. I even went so far as to suggest that the United States must and would move with sufficient speed and competence to attain world leadership in space technology. We were behind then! We are ahead now!

CAUTION

I wish it were not necessary—but unfortunately it is—to follow such a declaration of relative status with a word of caution. We will not remain ahead for long if we grow complacent, if we fail to recognize in full the true benefits of the space program, or if we overcut space spending—as the Congress is apparently trying all too successfully to do. We just cannot afford to waste the taxpayers' money which has been invested in national strength; yet slowing down advances in space technology would do just that. It would be wasteful and, in my judgment, contrary to the best interests of the United States. I can emphasize that point even

*Executive Secretary, National Aeronautics and Space Council.

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further by being more specific: our national security would be weakened by failure to pursue such technological innovations.

If it would not seem to have political overtones, I would interrupt right here to make the factual statement that only one candidate for the Presidency of the United States—the man who is now our Vice President and Chairman of the Space Council—has come out forthrightly for pushing forward the National Space Program. I also would risk stepping on personal toes, but I would not risk any conflict with the facts, if I were to assert that he who opposes continuing advance in space technology and space experience may be honest, may be sincere, but most certainly is wrong.

ROLE OF TECHNOLOGY

Expansion of our population does not come from adroit use of technology—that might win a prize as the most obvious statement of the year—but the capacity to support such a burgeoning population does depend upon technological competence. In other words, pregnancies occur and children are born with a minimum use of technology and certainly without knowledgeable application of systems analysis, but standards of living will rise for the expanding numbers of people only if there will be continuing advancement; continuing progress in science, engineering, and management. No program has ever before given such impetus to technological growth as has the National Space Program.

One need only cast his vision towards a map of the world while referring to statistics of each nation's per capita income—and the story will be clear. We know where poverty is greatest and living standards are lowest. We know where turmoil is most likely and national strength weakest. We know these things because they are not secret—in fact they cannot be concealed—when countries invest little or nothing in technological advances. Our nation of more than 200 million people does not enjoy its high standard of living primarily because of its location or its other natural assets but, rather, because of its employment of technology in making effective use of its human and natural resources. Again, I suggest that you look about the world and note that, where there is progress in human welfare, it correlates closely with progress in technology.

Those who oppose adequate financial support for space technology are deliberately or inadvertently campaigning for lower standards of living for our people, a declining Gross National Product for our nation, and a position in strength secondary to that of the Soviet Union.

SPACE PROGRESS

When I attended the Third Symposium almost four years ago, I expected great things of the space program, and I have not been disappointed. At that time, the six flights of the Mercury Program had been completed, and we were indeed encouraged to see that we were making positive advances in catching up with the Soviet's manned program. Then, after an adequate time of preparation, we entered upon the 10-flight Gemini Program and, in so doing, flew right past our energetic competitor. Today, the two nations together have totalled slightly more than 2500 man-hours of space flight. Approximately 80% of this total was logged by U. S. astronauts. We have had almost twice as many manned flights; we have the record for flight duration; we have 12 hours compared with their 20 minutes of extra-vehicular activity; and our ten rendezvous and nine dockings of manned spacecraft are the only ones which have taken place to date.

While all this was going on, we have continued to expand our knowledge and experience in other aspects of space. We have not neglected the national security features, either manned or unmanned. We have not neglected the scientific studies of the solar system. We have examined in detail the physical characteristics of the Moon: that natural satellite which we plan to visit soon. Yes, this has been the most fruitful technological decade in man's history. One cannot help but be amazed at the speed of progress, at the rate at which technological advances have taken place—even though it is characteristic of space programs to require long lead-time investments and the use of new techniques.

Yet, while still retaining some optimism, I hasten to alert each of you to the fact that our investment in the space program to date has mostly been an investment for the future, the returns from which can be lost in large measure if we lack the vision and the vigor and the desire to keep this country great by maintaining a vigorous space effort.

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U. S. ECONOMY

It may seem to be a far cry from the purposes of this Symposium to enter into a discussion of the state of our economy. But, I still think that it is pertinent to make at least a brief reference to it, since many who want to slow down our technological progress use the excuse that we cannot afford it. I would make two points in that regard: First, the country has never been economically stronger than it is today. Employment is at an all-time high; unemployment is low; and the Gross National Product is at a record peak, as are profits, wages, and salaries. Second, none of those practical indices would be so favorable if we had spent less on research and development in prior years. It is foolish to believe that we cannot afford technological advance; the fact is--we cannot afford to slow it down.

To such a learned audience, it is unnecessary for me to point out that funds spent on the space program are spent right here in this country, rather than out in space, and that the technology born through such effort remains here to further private enterprise in many, many fields. I say it is unnecessary to point that out to you, but I mention it anyway as a suggestion that you may want to pass these facts on to others who are less knowledgeable. It is probably somewhat less obvious, but just as true, that there would be more unemployment and more poverty, almost automatically, if the space program were to be severely curtailed. I suggest to those whose sight is not on the stars and whose feet are not on the ground that they give some additional thought to that very point. We should all know that the United States is stronger and wealthier because of its space program, and we should also know that such strength and such wealth make us much better able to handle the other urgent problems which confront us. Surely, a means of handling such problems cannot help but come from increased income, increased products, increased jobs, and new sources of employment through advances in technology. This is the vital role of our space program.

DEFEATIST ATTITUDE

There are those, of course, who are trapped by the illogical proposition that if the money involved were not spent on space and if the talents of the manpower employed were available for

use elsewhere, those resources would automatically flow into projects of health, housing, air or water pollution, education, and other problems of our complex society. Hence, they suggest that it would be better to invest our resources in those areas instead of in space technology and space exploration. I do not agree. It is not an "either/or" situation. I have great confidence in the capabilities of this country to handle many high priority projects at the same time; I believe that the problems of poverty and its related ills certainly deserve high priority—and I believe that the space program likewise merits high priority. I never have been able to understand those who favor solving problems with the wasteful approach of "let's wait and maybe do it later."

FUTURE SPACE ACTIVITIES

Not long ago, I prepared and submitted to the Congress in response to a Committee request a summary identification of space projects that we should be carrying out and space capabilities that we should be building, for the future. That list included improvements in methods of propulsion, both chemical and nuclear. It pointed out that we should also be melding the major features of aeronautics and astronautics so that space vehicles will have great maneuverable reentry ability and will be recovered, maintained, refueled, and reused.

We not only expect to have men land on the Moon in the next few years, but we also expect to follow this with other trips to explore the lunar surface and possibly to establish one or more bases there. We will also have permanent manned Earth orbiting stations with a variety of functions and missions. Such activities would include looking away from the Earth to take a magnificent step forward in astronomy and looking down toward the Earth to increase our knowledge of Earth's activities, Earth's characteristics, and Earth's environment. We also would expect to have unmanned probes throughout the solar system and to have manned expeditions to visit other planets whenever it becomes promising and practicable.

While all this is going on, we expect great progress in communications, navigation, weather prediction, and perhaps weather control—all through the use of the space dimension, all stressing the practical and doing the seemingly impossible.

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INVESTMENT IN PROGRESS

Recently, during his presentation of the Collier Trophy, Vice President Hubert Humphrey said:

"The people who don't explore today find themselves without the ingredients of progress for tomorrow. This great economy of ours is not the product of accident. The so-called technological gap, even between ourselves and other developed nations, is not just good luck on our part or bad luck on theirs. The investment that this nation has made, both public and private, in men and materials, in the fields of science and technology, and particularly in all of the related fields that surround our space exploration, has contributed immensely to our technological and scientific successes."

He then went on to mention some of the benefits of the space program and emphasized the major returns which flow from space technology into the field of medicine.

In our space program, we learn more about healthy people, preventive medicine, effects of drastic changes in environment on humans, the application of space-developed electronics to hospital care, and the adaptation of space equipment to medical science. Surely, health is not the least of our interests and, certainly, one effect of a slowdown in manned space exploration would be to handicap our efforts toward health improvements.

Some of you know that I make it a practice of speaking not only rather bluntly but also quite briefly. Today, I have done the former, and, if I stop right soon, I can also do the latter. For emphasis, I will add a few concluding points, however.

CONCLUSIONS

First, the benefits of the space program are things of which we can be proud—things to boast about, not incidental items to apologize for. I refer to the stimulus to our economy; the new materials and services; the advances in communications, observation, and navigation; the contributions to medicine; the influence on our educational system; to the major additions to our store of scientific knowledge; the potential contributions to national security.

Second, the economy of this country is built on technological capability—the greatest supplier of which is the aerospace industry

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and the related parts of our Federal Government. But, if we grow blind to the clear light of truth about the benefits of space exploration, the economy will slow down, and the United States will risk becoming a lesser nation.

Every major power and every nation eager to raise its standard of living and world influence strives to participate in space technology and space exploration. It certainly would be ironic if the United States, as the world's leader in international cooperation and the world's leader in standards of living, were to abandon or even to neglect the sources of such strength. I believe it might be labeled the worst mistake in history. The national and international effects would be disastrous. I hasten to state that I do not believe we will make that mistake. To avoid it, however, I suggest that those who are as well-informed as you, the attendees to this symposium, need do an even better job of nation-wide—yes, even world-wide—education than we have been doing to date.

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II

On Fundamental Scientific Advances Resulting from the Space Program

Fred L. Whipple*

It is indeed a pleasure to attend this Fourth International Symposium on Bioastronautics and the Exploration of Space, again held in San Antonio. I remember so vividly the circumstances of the first symposium, 17 years ago, with its too daring title, "The Physics and Medicine of the Aeropause." In the final publication, "Aeropause" became "Upper Atmosphere." I gather that the change was made because "Aeropause" might be mistaken for a medical condition befalling aviators near the age of 50. Gratifying is the number of familiar faces here today of those who attended the first symposium. We sorely miss the late Dr. Randy Lovelace, an outstanding contributor to the subject. I wish that Dr. Joseph Kaplan, Dr. Wernher Von Braun, and Dr. James Van Allen had attended this time, and others such as the Haber brothers, Heinz and Fritz, Dr. Sam White, and Cornelius Ryan who was inspired to edit the *Collier's* magazine series of the future of space. These men and others fill my memories of the first symposium.

It would be fun to recount the history since those "early days" of space science 17 years ago when we all felt like pioneers, intrepidly demanding the opportunity to explore the wilderness of space. However, my approach will be from a different vantage point because a basic human weakness today confronts the space program and is giving ominous signs of reducing its effectiveness. Almost universally, people tend to accept all that has gone before as natural and then to resist any further change. Such a tendency

*Director, Smithsonian Astrophysical Observatory, and Phillips Professor of Astronomy, Harvard College Observatory.

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is now becoming expressed nationally in the form of a growing reaction against science, with a concomitant reaction against financial support for basic scientific research and possibly an even greater negativism toward the very expensive space program. I was delighted to hear Mr. Welsh's wise and lucid warnings against this tendency. I hope that I can add something to his argument by pointing out the enormous scientific advances that have resulted from the space program and then how the program satisfies certain national needs and goals.

In spite of many "firsts" in space by the U.S.S.R., by far the highest quality and the greatest bulk of scientific observations come from the U.S. program. An area of striking advance lies in the study of magnetic fields and high-energy particles in space, the magnetohydrodynamics or plasma physics of the solar system. The complex word *magnetohydrodynamics* identifies the physics of ionized gases or *plasmas* where the energy in the magnetic fields supported by the charged particles is comparable to the energy of their random motions or thermodynamical activity. The subject comprises the magnetosphere of the Earth, the Van Allen belts, the solar wind, solar-terrestrial relationships, the solar corona, and finally, or really originally, the Sun itself as a mighty celestial hydrogen-burning furnace. In 1951, we knew that the Sun sends out high-energy particles, not only from observations of optical, magnetic, and radio effects on the Earth, but also from the clear evidence that solar radiation is inadequate to blow out the gas tails from comets, the trails of molecular ions observed to stream in a direction away from the Sun (Fig. 1). Stoermer's 50-year-old research had shown that charged particles could be trapped in the Earth's magnetic field, but no one suspected that their number would be significant. James A. Van Allen's early success in discovering the highly energetic pools of ions and electrons near Earth stimulated an enormous effort via many satellites, rockets, and several space probes to investigate this complex realm of high-energy particles and magnetic fields. The early goal of studying the low-energy cosmic-ray spectrum was quickly extended. The early picture of the symmetrical Van Allen belts soon grew into a great complex, still only partially understood, including a tail extending out for several tens of Earth radii on the lee side from the Sun (Fig. 2). The neutral sheet behind the Earth, the magnetosheath or the shock front interaction area between the magnetosphere and the solar wind, the complex electrical currents, the plasma effects, the Alfvén waves, the complicated auroral



Figure 1. Comet Ikeya-Seki, 1965f. (Courtesy C. F. Capen and J. Young, Table Mountain Observatory, Wrightwood, California.)

phenomena of photons, electrons and plasma waves, the complex of solar-storm phenomena observed by radio, high-energy particles, magnetic effects and optical means, and a host of other subtle solar-terrestrial effects are now a part of the literature. This literature is expanding by hundreds of pages per month; only the specialist in each small segment of the field can keep track of the enormous progress made in his own area. Few, if any, can follow the entire subject.

The key to the entire subject lies in the outflowing solar wind of a million tons per second at a velocity of some 400 km per second. This wind accounts for the great ion tails of comets and is measured not only by interplanetary probes but also by the aberration of the comet tails: that is, by their tendency to trail behind the comet's motion with respect to the radial direction to the Sun. Space probes have evaluated the temperature, strength and direction of this wind, its magnetic fields, and the variations that are now tied to solar activity in the low corona and below.

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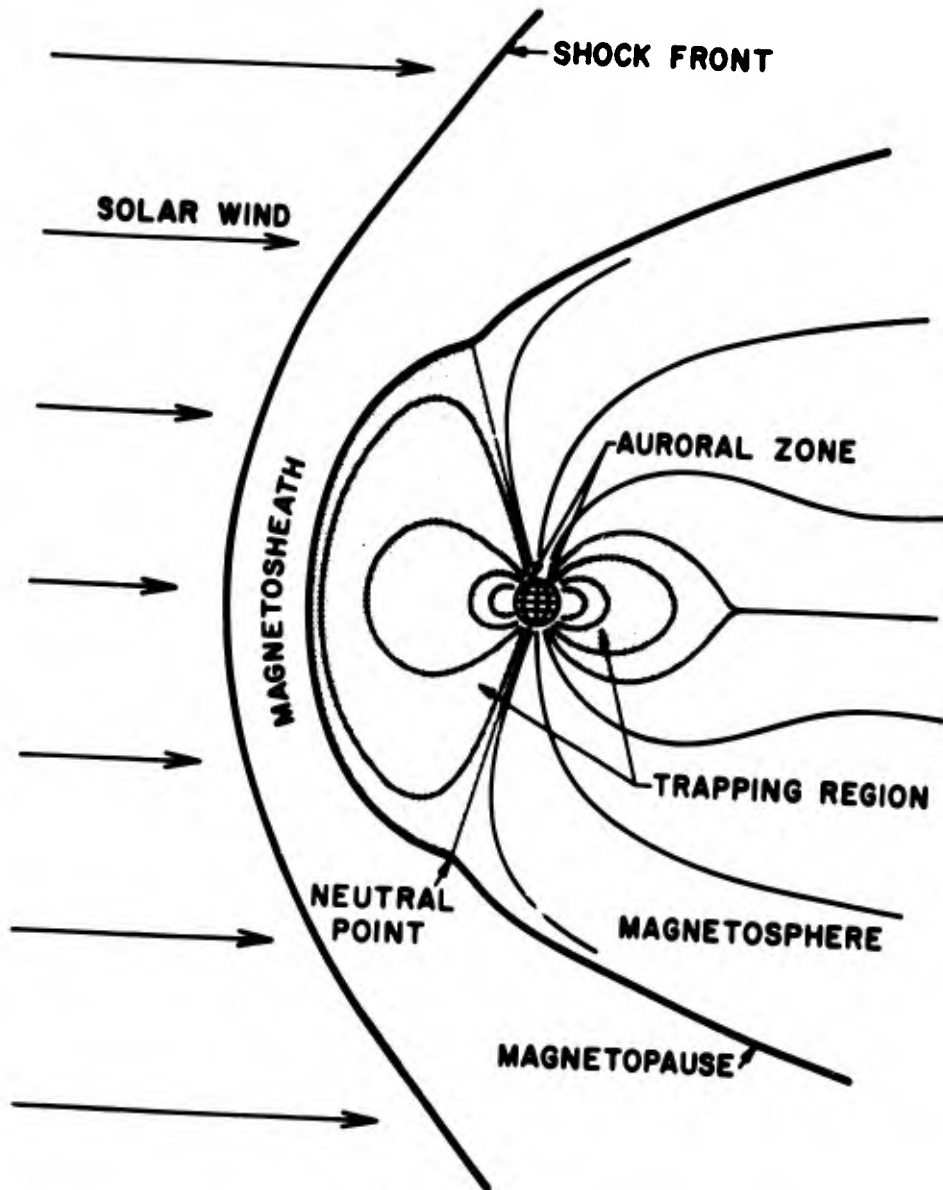


Figure 2. Solar wind and Earth's magneto complex. After Dessler and O'Brien, 1965.

On the theoretical side, Eugene N. Parker's theory of quasi-stable expansion in the solar corona is now completely vindicated. He showed that, if an extended temperature zone exists in the high-temperature corona (over a million degrees absolute as already known to the astronomer), the only possible configuration

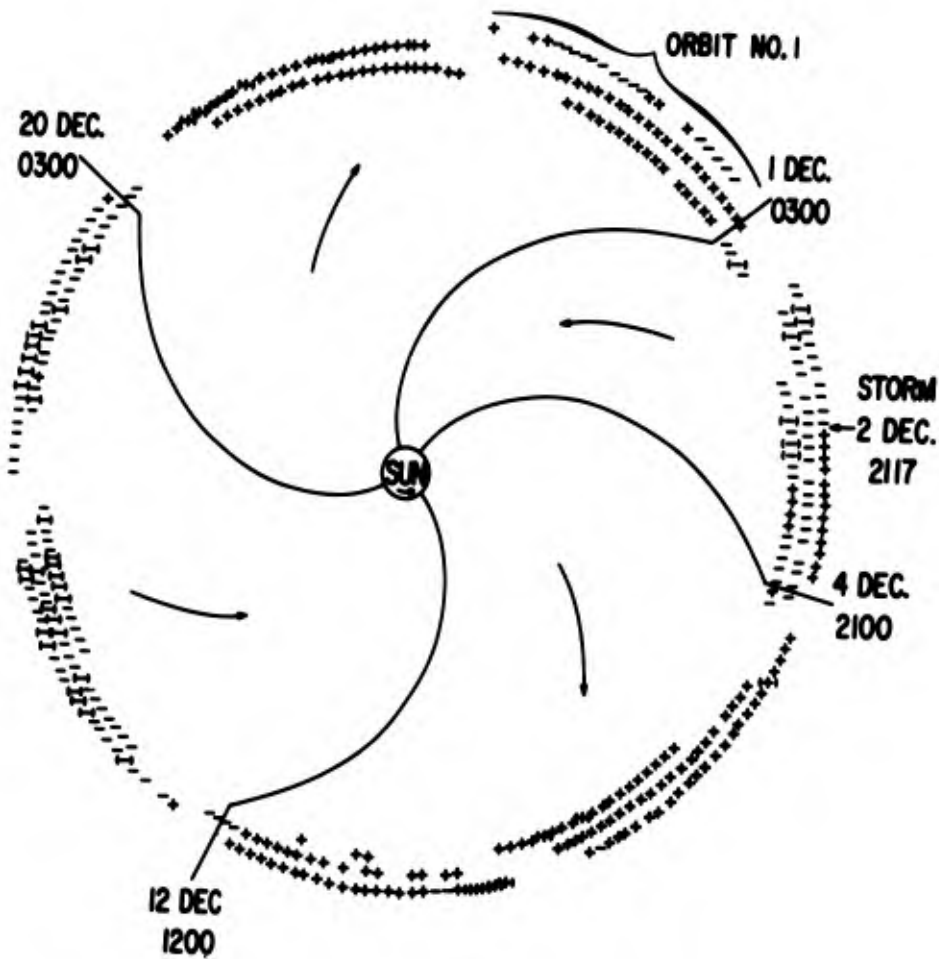


Figure 3. Interplanetary magnetic field orientation. After Wilcox and Ness, 1965.

is a rapidly expanding atmosphere that we observe as the solar wind.

That the magnetic-field lines in the solar wind actually rotate with the Sun, almost like a solid body, is to me an amazing phenomenon. Let us visualize a "garden-hose" wind in which the ions and the electrons of the solar wind move radially from the Sun, whereas the magnetic fields and related phenomena show a spiral structure turning almost rigidly with the Sun (Fig. 3). This observation is of vital importance to all astronomy. Theorists in the late 1940's demanded some such concept to account for the slow rotation rates observed in old stars, whereas new stars turn

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very rapidly. No theory of the evolution of the solar system made sense without a double mechanism—a transfer of angular momentum to slow down the Sun's rotation and the removal of gaseous material from the primordial solar nebula in which the planets, asteroids and comets must have collected. The solar wind, now a "breeze," demonstrates what a solar "gale" must have done eons ago in the solar system. Such radial "gales" are now observed to blow from new stars, such as the T Tauri variable stars, in great stellar "incubators" of the Galaxy. The great Orion Nebula is an example.

The space program has provided direct observations of these phenomena to build a theoretical foundation of critical value to astronomy. The theoretician is no longer "flying blind" in his efforts to understand the interaction of charged particles and magnetic fields throughout space. He has a local solar-system laboratory in which the space program provides direct measurements of processes too complex for armchair prediction. He has a tool to help uncover the nature of flares not only on the Sun but also on the observed dwarf flare stars and on the great magnetic and hotter A-type stars. These new methods will certainly be involved when we finally understand the still mysterious *quasars*. The centers of many galaxies show phenomena on a majestic scale that we see in miniature about our small Sun. Unbelievably huge outbursts involving millions of solar masses over galactic distances are detected both optically and by radar. We still have to explain how the great planet Jupiter, with a much greater and more powerful magnetosphere than the Earth's, sends out powerful radio noise from certain areas and how its satellite, Io, can modulate this radio noise into sharp bursts. Unquestionably, the newly discovered radio stars that send out radio flashes with clock-like repetition rates of one per second or less must do so by means of plasma processes.

In the area of cosmic rays, we know much more about the modulation of the low and even the higher energy cosmic-ray flux by solar effects in the 11-year cycle. The space program helps us to understand the origin of these unbelievably high-energy particles by means of examples of local acceleration processes on and near the Sun.

I wish not to encroach on the domains of other speakers in the program who will present striking and fundamental scientific

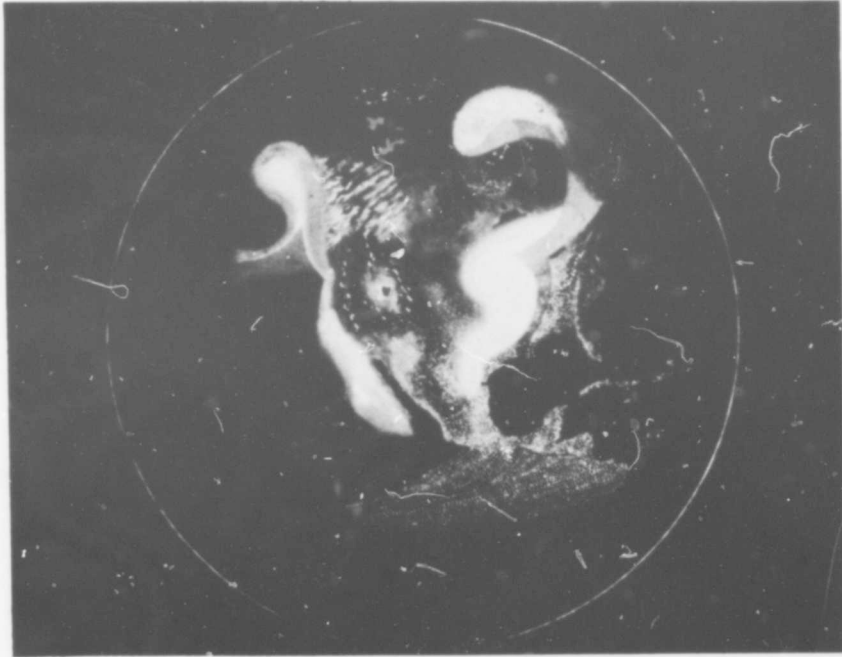


Figure 4. Dr. Harry Wexler's concept of North and Central America as seen from space (circa 1952).

results obtained from the space program about the Moon, about Venus, about the Sun, and about the other planets. You will hear about space chemistry and basic physical experiments that can be done from space. With respect to the Earth, I simply mention that space science is changing meteorology from an art to a science, with far-reaching ramifications both in theory and in practice. In memory of the late Dr. Harry Wexler, of the U.S. Weather Bureau, I note that the painting of the North American area from space as he imagined and commissioned it (Fig. 4) shows a meteorological cloud pattern almost exactly like that in the first ATS satellite picture (Fig. 5).

Not only are weather forecasting and intercontinental communication being revolutionized by satellites but new space tools are being sharpened for study of the Earth's surface, oceans, flora and fauna, geological deposits, and basic Earth structure.

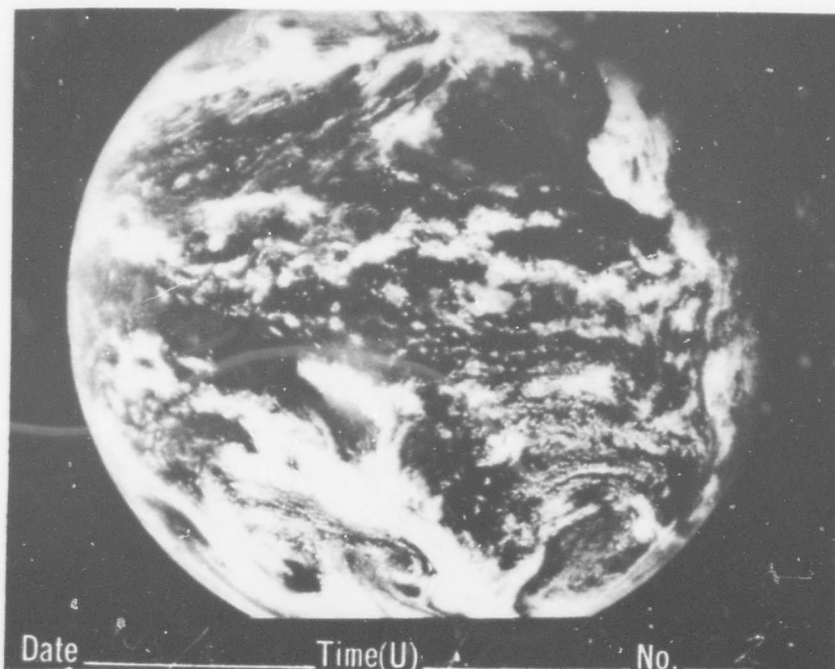


Figure 5. First Earth photograph by U.S. applications Satellite I, December 9, 1966, from an altitude of 23,000 miles. (Courtesy National Aeronautics and Space Administration.)

In the realm of my own activity, satellite geodesy has reduced the uncertainties in worldwide geodetic positions from 100 meters to 10 meters, tying together the geodetic nets of the world with this increased accuracy. Furthermore, it is unravelling the twists and warps in these geodetic nets in a fashion that is a delight to old-time geodesists. The observations give us a huge store of factual information about the gravitational field of Earth as related to its still poorly understood internal constitution and local deviations. The oblateness of Earth represents the second-order zonal harmonic; the "pear-shape," the third-order term. Now more than the 20th-order terms are determined, and we are in the process of determining fifteen orders of the *tesseral* or longitudinal terms. The "1966 Smithsonian Standard Earth" involved the solution of some 80,000 simultaneous equations for 100 unknowns. (See Fig. 6 for the contours of constant gravity with

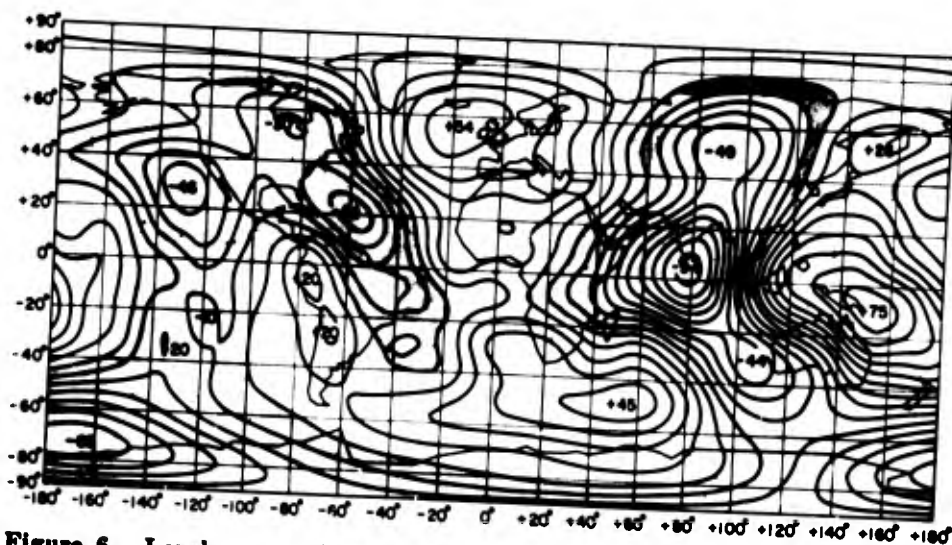


Figure 6. Level curves of geoid height at 10-meter intervals (Lundquist and Veis, 1966).

respect to an ideal oblate spheroid.) The next solution will involve some 250,000 equations in nearly 300 unknowns. We have successfully used the laser in many satellite observations, and there is no question but what it can present us with solutions to these geodetic problems to an accuracy of 1 meter, certainly on a world-wide scale, with the eventual hope of one-fifth of that error. Now that continental drift is recognized as a reality, we can hope within a few years to measure this motion via observations of satellites.

In the three previous symposia at San Antonio, I discussed the data concerning meteoritic particles in space and their hazards to space vehicles. In recent years, the space penetration experiments, particularly those by the Pegasus satellites, have clarified this problem for very small particles in near-Earth space. Also, the Mariner 4 acoustic results between Earth and Mars make it clear that the hazards for space travel in this region are not extraordinarily large as compared to those near Earth. On the other hand, both the collection and the acoustic methods on balloons, rockets and satellites have shown deficiencies that once led to gross overestimates in the quantity of fine dust in space, especially near Earth. It appears now that we are reaching equilibrium with regard to this solution (Fig. 7). Evidence for space erosion on meteorites sets an upper limit to the average space density of interplanetary dust in rough agreement with measures near the

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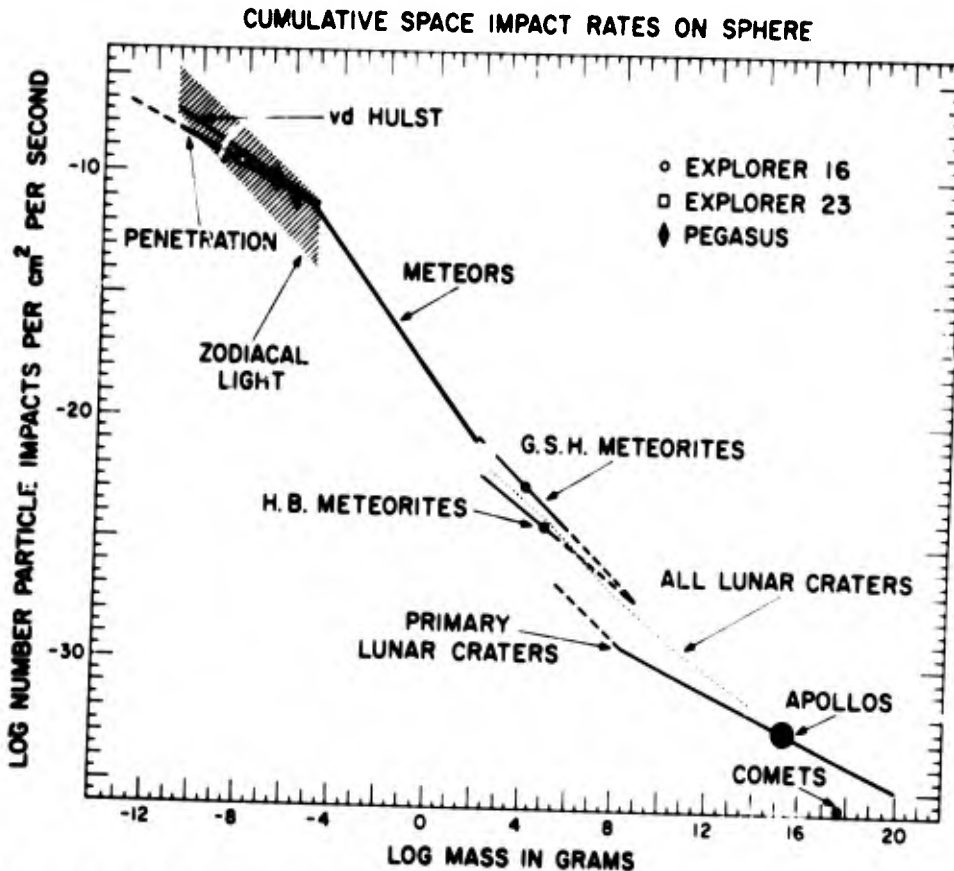


Figure 7. Influx rates for interplanetary solids on sphere in Earth orbit. Compiled by author, 1967.

Earth as made by satellite penetration experiments and direct meteor observations in the atmosphere. Thus, the space program has finally clarified the problem, generally reducing by a large factor our earlier estimates of both the amount of dust in space and its hazard to space vehicles or men in space suits.

Incidentally, the production of a truly clean surface, i.e., clean enough to collect and measure the tiny cosmic input to the high atmosphere, is an extraordinarily difficult problem, but it is being solved. Whereas, biological and medical means for cleaning surfaces were first used in rocket and balloon collectors, it is now likely that new techniques developed for space experiments will contribute to the laboratory preparation methodology.

We now know that almost all the smaller particles in near-Earth space are of cometary origin. The input of some 10 tons/second is probably enough to keep the system and the resultant zodiacal light in quasi-equilibrium. But we have some major problems left concerning the larger pieces whose mass is a ton or more. We face a very real question as to whether the Earth-crossing asteroids, the Apollo type, are defunct cometary nuclei or are truly asteroidal in origin. I hope that the recent observations of Icarus in its near approach to Earth on June 14 may throw some light on this problem.

In studying Earth's atmosphere, we started in the middle 1940's with no more than a crude sketch of the density-temperature distribution with altitude. The rocket and satellite programs now give us precise knowledge about the density, temperature, ionization and composition of the atmosphere above 1000-km altitudes as a function of latitude, solar hour angle, season and solar activity. The upper atmosphere is a highly sensitive barometer of solar activity with respect to solar storms and with respect to long-term variations, rising by a factor of 10 or more in density at maximum activity above the density at solar minimum. The high atmosphere is indeed like an eyeball following the Sun, with a lag of some 30° . The bulge extends over a huge breadth in latitude, the "elongation of the eye" depending again upon solar activity.

Only in X-ray and ultraviolet astronomy of the Sun have we made a major start in utilizing the vast potential of space telescopes to probe the universe in the radiation regions denied us from the ground. Solar ultraviolet light and X-rays show bright over local regions of solar activity, expose the corona over the disk of the Sun, and even reveal iron atoms stripped down to the last single electron of the original twenty-six. X-ray stellar astronomy is just beginning, via rockets and satellites, with the striking discovery of a number of X-ray stars. One class is clearly distinguishable, like the Crab Nebula, the consequence of an old supernova explosion. Others may be due to rapidly revolving binary stars in which material is being transferred from one to the other, perhaps to neutron stars. We are not clear as to the source of the X-rays in the latter case, although in the supernova type it appears almost certain that we are dealing with magnetic bremsstrahlung, that is, synchrotron radiation from energetic electrons spiralling in strong magnetic fields. Can some of the X-ray

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sources and possibly the pulsating stars actually be neutron stars? Can matter be so condensed that a million tons of mass could be contained in the volume of the ball in my ballpoint pen? My experience is that any physical process or situation that is deemed possible from physical experiment and theory will eventually be found as a natural occurrence in our fantastic universe. In fact, just recently, clear evidence for gamma rays from stellar sources has been obtained.

In stellar ultraviolet and infrared astronomy, the space program has unfortunately lagged so that we have only fragmental information concerning stars in these exciting regions of the spectrum. The chromospheric bright lines and coronal radiations that we expect from stars are almost completely hidden from us until space telescopes of appreciable size become a reality. A 120-inch or 3-meter-diameter space telescope of high optical precision could improve our astronomical reach from the ground by more than an order of magnitude beyond the great 200-inch telescope at Palomar or even the giant 6-meter optical telescope under construction in the U.S.S.R. The space telescope should be manned, in the sense that men would first adjust it for operation and from time to time make repairs and provide maintenance. Pointing to an accuracy of 0.01 arcsec precludes a man in actual contact with the instrument body because of inevitable body motions. Nor should frequent film changes or adjustments be necessary. The telescope should operate entirely by remote control, which can be done as well from the ground as from a space station. But man is the key to long-term operation, the only type of operation that appears to be cost efficient. Also he is the key to optimum performance, not only by his ability to make repairs but, most important, by his ability to update the sensing equipment and the observational programs. Today, the advances in sensitivity and effectiveness of radiation detectors are so rapid that automatic space telescopes are already technically obsolete by the time they are launched. A great telescope can operate near the technical frontier only by the aid of man to replace little black boxes with new ones recently updated.

A manned space telescope of 3-meter aperture could quintuple the dimensions of the observable universe, a hundred-fold increase in the volume, if indeed, the universe is that large. It could answer fundamental questions about the early history of the universe,

how the original atoms were made. Hydrogen only? Or hydrogen and helium, plus a few heavier atoms? Did the universe explode from a fantastically compact and hot nucleus? And when? Was 10 billion years ago the beginning? How did galaxies originate? Do quasars lead us back to majestic explosions in the nuclei of galaxies?

I believe that these questions can be answered by a 3-meter manned space telescope, today a technically practical instrument. The unexpected results will certainly be even more exciting than the answers to these few questions I have listed. In addition, there are basic physical experiments that can parallel these direct astronomical explorations. They likewise are in both time and space and will answer important questions. How good an approximation is Einstein's theory of general relativity? What forms do the equations for the universe really take? Do any of the physical constants change with time? Are we being deceived about the past because of such changes? What is the basic nature of gravity? Are there gravity waves and do the very distant parts of the universe control the value of gravity here, as in Mach's principle?

Finally, and to many people the most important question: What of life beyond the Earth? What is the story to be found on Mars? Is there other intelligent life to be contacted in the universe?

The answers to these few selected questions, or much more likely, the unexpected new concepts that will arise as we attempt to answer them, swell the imagination and will give us a better perspective on ourselves as a reasoning part of this vast unthinking universe. Or is there more than physical matter and energy to be found beyond Earth's frontiers?

Now I must return to the foreboding shadow of negativism toward basic science and toward its support in this country. The attitude is equivalent to saying that we have enough basic discovery for now; let us settle down to the practical application of what we have already discovered; tomorrow or many years from now is just as good as today for basic science because the time lag from discovery to application is several to many years.

These arguments carry the ring of sensible practicality, especially in view of the critical and explosive social needs of the

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country. But are they truly realistic and practical in terms of the national welfare? Will turning off the spigot of support for basic science save national resources that can then be used in the vital war against poverty? I think not. Adolph Hitler gave us a remarkable historical example of the folly inherent in such a policy. In 1939, he decided that Germany had enough radar development to win the war. He disbanded the electronic research and development laboratories so that he could send technicians, engineers, and scientists out to the front lines of battle. By 1942, however, the Allied microwave and countermeasure developments had showed up the weaknesses of the early German radar. Hitler then tried, but was unable, to reconstitute the research and development program for useful results during the war. More importantly and generally, his negative attitude toward basic science and scientists undermined German science severely. We in this country have, indeed, reaped benefits from his limited foresight—his concentration on immediate and popularly understood facets of national security and power.

I venture to predict that when the practical process of controlled hydrogen fusion becomes a reality, to give an almost unlimited source of energy for man's good, basic elements of the method will owe much to the understanding of plasma physics that our space program has given us. When the day comes that we can use a gram of water as an energy source equivalent to a ton of coal, we will wonder in our opulence why anyone ever questioned the value of the space program.

If we follow a shortsighted policy of political expediency and hesitate in our support of basic science, we will undermine the spirit of scientific inquiry in our growing universities and therefore in the young minds who are the most creative. We will discount the value of the scientific method at just the time when its more general application in all realms of our complicated activities, not just in science, could be of enormous value—possibly of critical value. To attempt to revitalize the scientific effort at some convenient later date will have lost us an invaluable headstart. Our world superiority in technology rests firmly on our leadership in basic science not only because of scientific discoveries but also because of science's inherent attitude of innovation. Technological innovation spins off both wealth and national security. No indeed—we do the poor and the underprivileged no service

by diverting a tiny portion of our national income to them from science, at the expense of the huge benefits that will soon be theirs from a continuing high level of scientific support. In so doing, we are indeed selling their birthright for a bowl of porridge.

Human culture, measured both by the attitudes and by the goals of people, has reached a turning point because of the space program. We can no more return to an earthbound way of life than to the horse and buggy. Our thinking has become global and international since the space program shrank the world to an 88-minute round trip. And in the science as well as in the technology rests the basis for these new attitudes.

I submit that only by the continuing use of the tools man has developed can we extend our advance beyond the status of *slaves of nature*. Only by persisting in the development of new tools, a process that we understand fully in scientific exploration, can we hope to attain the magnificent destiny that is ours for the taking. To hesitate now, after the wonderful foundation we have so painstakingly built, is both acute cowardice and spiritual myopia.

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III

Some Remarks on the Evolution of the Atmospheres and the Oceans*

Harold C. Urey†

In 1956, I was invited to write an article for the *Handbuch der Physik* on the planetary atmospheres. The subject proved to be a very interesting one from the purely chemical standpoint, but, of course, the physical phenomena of escape of the atmosphere of the Earth and the probable production of volatile materials from the interior of the Earth needed to be considered as well. At that time, the effect of the solar wind on the abundance of the rarer constituents of the atmosphere had not received the prominent attention that it has in recent years. Spitzer, indeed, had given a very scholarly discussion of the subject, but, since then, a very considerable development of the subject has occurred.

It should be emphasized that none of us has been able to make direct observations on the ancient atmosphere of the Earth and planets, and also that in the absence of observational data no one has succeeded in developing a satisfactory theory for the atmosphere. This means, of course, that all discussion of the subject must be regarded as tentative, at least at the present time. What is presented in this paper is a discussion of the evidence, mostly of a chemical kind, and the deductions that can be made therefrom. It should also be emphasized at the outset that, in recent years, there has been some paleontological and biological evidence bearing on the subject.

*This paper is a review and extension of a paper by Miller and Urey (1959) and two papers by Urey (1953, 1959).

†University of California (San Diego), La Jolla, California.

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Berkner and Marshall (1964) and Holland (1964) have discussed the history of the atmosphere and oceans, and have concluded that the atmosphere was essentially oxidizing, which is a point of view very different from that presented here and very different from the previously presented views of myself and others.

THE ORIGIN OF THE EARTH

It will be assumed in this discussion that the Earth accumulated from solid objects of the approximate type of the asteroids, or perhaps even larger objects similar to the Moon. It is contended that the Earth could not have accumulated in its present form with any important amounts of the primordial solar gases present in the neighborhood in which the accumulation has taken place (Page, T., 1949. The reason for this is that, had the earth accumulated with these gases present in their primitive proportions, the Earth and the gases together would have the mass of Jupiter, and it is very doubtful that any possible method for the removal of these gases could occur once a planet of this magnitude was formed. Moreover, small amounts of gases remaining in the nebula would be difficult to remove to the extent required by the very small amounts of the heavier inert gases, particularly krypton and xenon, that are present on the Earth. The escape-layer temperature required to remove xenon as rapidly as helium is estimated to be removed from the Earth at the present time would need to be somewhere in the neighborhood of 30,000 to 50,000°K. It is impossible that a high temperature Sun could do this, and it is improbable that even a much more vigorous solar wind could accomplish such a removal of these gases. It is assumed that the Earth accumulated slowly, probably during some 100 million years, from solid objects and that the component of solar gases had been lost from the neighborhood of the terrestrial planets. The 100 million years is a most uncertain estimate. The age of the Earth is usually assumed to be $4.5-4.7 \times 10^9$ years, i.e., the same as that of the meteorites, but there is no certainty that it did not require 10^9 years for the Earth to accumulate. At present, objects crossing the Earth's orbit have half-lives of some tens of millions of years, but, if the Earth were much smaller, say of the mass of the Moon or even less, the probability of capture would be much less. It is tacitly assumed here that lunar-sized objects were present and that these provided a more effective nucleus for accumulation than would asteroidal-sized objects.

Assuming that the Earth accumulated from solid objects; we have some idea as to the temperatures that may have obtained during the accumulation of the Earth, particularly the terminal stages. Objects arrived at the surface of the Earth with at least the escape velocity, namely 11.4 km/s. For a substance having a molecular weight of 20, this velocity corresponds to about 100,000°K, if all of this energy were localized in the colliding object. But, of course, the energy was not distributed in the colliding object entirely, but partly, and to a large extent, in the surface of the Earth being bombarded. In any case, one must expect local temperatures which are sufficient to volatilize not only water but other substances as well. Even silicates and iron were volatilized from the colliding object and the material of the immediate neighborhood of the collision crater. The local atmosphere that was present on the Earth at that time was partly expelled back into space and, of course, was probably partly re-accumulated by the Earth. However, in a short time, the temperature fell, and the materials condensed on the Earth. The water was absorbed by the silicate rocks or it condensed into pores between grains of material. All was quiet until the next object came in, when the process was repeated. But by the time of the termination of the accumulation process, it is reasonable to suppose that there was some surface water on the Earth.

The atmosphere of the Earth probably contained water, hydrogen, nitrogen, ammonia, methane, and carbon dioxide. It is difficult indeed to estimate how much water was present at that time. Rubey (1951) has proposed that most of the surface water of the Earth has come from the interior, and it is a very reasonable proposal which is generally accepted today. Perhaps it is reasonable to say that some 10% of the present surface water of the Earth was present on the surface at the terminal stage of the formation of the Earth. Immediately, one wonders how much of the present superficial carbon of the Earth was present in some form or other in the surface regions of the Earth as methane, carbonaceous material, carbides, or graphite, and what fraction of the present atmospheric nitrogen of the Earth was present at the beginning. It is probable that some fractions of the present surficial quantities of these elements were present at the beginning, but it is surely impossible to state with any confidence how much of the present elements of this kind were present at that time. The same statement applies to the inert gases. Though they do not form

compounds, they would, nevertheless, be covered in the accumulating granular material which was probably something like the superficial materials of the Moon at the present time. Also, gases are coming to us from the Sun, and these have fallen on the Earth during the entire time that the Earth has stood, but some of them were probably here at the beginning. However, they are chemically inert, and hence did not take part in the chemical developments of the superficial regions of the Earth in any important way. We shall assume that one-tenth of the present surface carbon and nitrogen, as well as water, was present on the surface of the primitive Earth. The escape of carbon and nitrogen from the colliding objects and the Earth was as probable as the escape of water.

THE EARLY SURFACE OF THE EARTH

It is safe to conclude that the early surface of the Earth was a pockmarked terrain similar to what we now see on the surface of Mars or on the Moon, with great collision craters covering the whole landscape. It is probable that some water was condensed from the original atmosphere and that pools of water had formed in the various craters and between them. Today, the surface of the Earth is very different, with enormous ocean basins and continental masses. Geologists over the years have unraveled the history of the continents, and these studies show that continents are growing at the present time and have grown over the past eons. Also, in recent years, studies of the ocean beds have shown that they are undergoing a creep slowly toward the continental masses. Basaltic lava flows occur along the mid-Atlantic region and then move slowly toward the continents. We not only have observed that the continents have grown during the past, but we are observing the mechanism by which they grow.

In view of our present observations of growing continental masses and the creep of the ocean floor, it seems certain that the original surface of the Earth was generally more uniform in elevation than it is at the present time. This means that there were no large ocean basins and no large continents. The Earth was covered with bodies of water-like lakes or perhaps like Mediterranean seas. Possibly, water masses more than 200 km in diameter were very exceptional. However, volcanic activity began; water started to

flow from the interior of the Earth, carrying with it carbon compounds and nitrogen compounds, and the ocean basins began to form. Sedimentary rocks are known from 3.0 eons ago, but whether these were deposited in large shallow oceans or in seas of the dimensions of the Mediterranean Sea is quite unknown. It has been mentioned to me that possibly one-fifth of Africa was covered by sedimentary rocks 3 billion years ago. Of course, the sediments must have come from mountainous masses somewhere else. Even sedimentary rocks a fifth the size of Africa are small when compared with the ocean basins at the present time.

COMPOSITION OF THE PRIMITIVE ATMOSPHERE AND OCEANS

Water vapor has been a constituent of the atmosphere from the beginning of the origin of the Earth. In addition to this, it is very probable that volatile carbonaceous materials were also present and that nitrogen in the form of nitrogen gas or ammonia or carbonaceous nitrogen compounds was present as well. It seems certain that there was no free oxygen. There probably was some free hydrogen. We postulate that this was the case with very considerable confidence because of the highly reduced character of all primitive materials available to us, namely, the meteorites and the Earth. The Earth as a whole represents a very highly reduced material because of the enormous amount of elemental iron in its core. If even a fraction of the metallic iron could be brought to the surface of the Earth and reacted with all the oxygen and oxidized compounds, including the ferric oxide, we would find that the state of oxidation of the Earth would be very similar to that of the meteorites. This, of course, excludes the possibility of free oxygen on the early Earth but permits the presence of hydrogen.

The most important chemical process that took place during early geologic time was due to the escape of hydrogen from the Earth. This was discussed by Spitzer (1952) quite some years ago and by Urey somewhat later (1959). The rate of escape of hydrogen from the Earth appears to be determined at the present time by the rate of diffusion of water to the high atmosphere rather than the rate of escape of hydrogen from the high atmosphere. The rate of escape at the present time is consistent with a pressure of hydrogen at the surface of the Earth of about 0.5 ppm. Whatever may be the cause for this pressure of hydrogen, the

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rate of escape from the high atmosphere is consistent with it. The present rate of escape calculated for the Earth, however, indicates that this flux would result only in the escape of the hydrogen from 20 grams of water per cm^2 in $4\text{-}1\frac{1}{2}$ billion years, quite an inadequate loss to account for the present oxygen atmosphere of the Earth and the production of many oxidized substances on the surface of the Earth.

Table I gives an estimate of the amount of water that must be decomposed to produce the oxidation that is observed on the Earth. If we assume that the rate of escape of hydrogen is proportional to the surface pressure of hydrogen, no matter what it is that produces this pressure, then we find that the surface partial pressure of hydrogen on the Earth should be 1.5×10^{-3} atm in order that the escape rate should be sufficient to produce the oxidation required during some 2.5 billion years. (The figure of 2.5 billion years will be justified later in this paper.)

Table I. Estimate of water dissociated to produce observed oxidation of surface elements*

Element	Amount g/cm ²	Amount in 10 ²⁰ g	Oxidation reaction	Dissociated water required g/cm ²
C as (CO ₂)	3,000	150	C → CO ₂	9,000
N as (N ₂)	882	45	NH ₃ → N ₂	1,700
S as (SO ₄ =)	724	37	S → SO ₄ -	1,600
Fe as (Fe ⁺⁺⁺)	112,000	5,600	Fe ⁺⁺ → Fe ⁺⁺⁺	18,000
Total				30,300
Probable loss of water needed to increase deuterium concentration in oceans by 4%				14,000

*Notes: The data used in this table have been gleaned from a study of Rankama and Sahama's "Geochemistry" Univ. of Chicago Press (1949) and personal estimates from the data there presented. Approximately these data were presented at Stockholm in 1953 (Urey, Plenary Lecture XIII Int. Congress of Pure and Applied Chemistry, IUPAC, 1953, see p. 211). The deuterium datum depends upon measurements of Kokubu, Mayeda and Urey (1961). See also Edwards (1955) Nature 176, 109. If no deuterium has been lost from the earth, the value 14,000 applies, but, with some loss of deuterium, possibly the 14,000 is in reasonable agreement with the 30,000 g/cm². The quantity of carbon reported is only that which has been oxidized to carbon dioxide. Some 1000 or 2000 grams per cm² are present as coal, petroleum, or other reduced carbon.

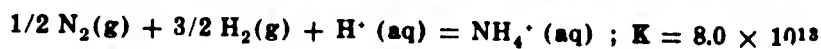
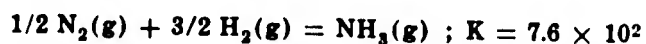
Holland (1964) arrived at very different values, but his method of estimating the amount of oxygen required is not clear to me. If the Earth's surface at the beginning had the oxidation-reduction state of meteoritic matter, which in view of the large amount of iron present in the core seems very likely, then oxidation can only occur by the elimination of some reduced substance. Only two seem to be available: (1) hydrogen which escaped from the Earth, and (2) iron which sank to the core. Some basalts are reported to contain native iron (Rankama and Sahama, 1949). If native iron is formed by disproportionation of bivalent iron to native iron and ferric iron, with the former transported to the core and the latter to the earth's surface, then a means for oxidizing ferrous iron to ferric iron, or graphite to carbon dioxide or monoxide, would be available. It has not been possible to find the necessary data for thermodynamic calculations on this point. However, the stone meteorites have been melted and contain only ferrous iron and elemental iron with no ferric iron of importance, and, thus, the disproportionation of ferrous iron to metallic and ferric iron is not evident. Of course, reduction of ferrous iron to metal by carbon, for example, may occur, with the iron mostly sinking to the deep interior, and only rarely being carried to the Earth's surface, though this mechanism has not been a popular one in the geological literature. Our estimate of the amount of oxidation required is very approximate and is arrived at by very rough methods, but, for the discussion which follows, the value could be changed by a factor of 10 in either direction without greatly changing the conclusions.

It is very improbable that during the first 2.5 billion years which we will be discussing in some detail that the pressure of hydrogen remained constant or that the rate of escape was constant. This pressure depends upon how hydrogen was transported to the high atmosphere, upon the temperature of the escape layer which is very high at the present time but which may have been considerably lower in the past, and, to a great extent, upon what kinds of chemical compounds were present in the atmosphere. As a tentative estimate, we will take 1.5×10^{-8} atm as the pressure of hydrogen and ask some questions in regard to the chemical composition of the early atmosphere.

First, it is most probable that nitrogen was present. We may ask: Would the nitrogen be present as elemental nitrogen or

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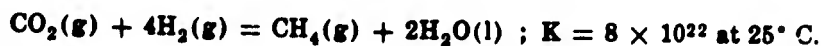
ammonia? Would it, instead, be dissolved in water? These questions were discussed by Miller and Urey (1959) some years ago. The chemical reactions involved are:



with the equilibrium constants at 25°C as indicated. The first equation shows that with the pressure we have assumed and the temperature of 25°C not much of the nitrogen would be present as ammonia. The second reaction shows that most of the nitrogen would be present as ammonium ion, providing the pH of the ocean was the same as it is at the present time, i.e., 8. From the equilibrium conditions and assuming 0.1 as much surface water and nitrogen as the present amounts, we find that the molality of the ammonium ion would be 0.19 and the partial pressure of nitrogen would be 8×10^{-6} atmospheres. If the pressure of hydrogen was 1.5×10^{-4} atmospheres, the equilibrium pressure of nitrogen is 8×10^{-3} atmospheres, and about 10% of the nitrogen would be present as N_2 .

Bada and Miller (1968) have discussed this problem recently and point out that NH_4^+ should be concentrated in clay minerals as is K^+ , and, in this case, the concentration in the primitive oceans could not be greater than 0.01 molal. Hence the pressure of N_2 would be even lower than that given here. It is evident that a very considerable amount of nitrogen could be present in combined form.

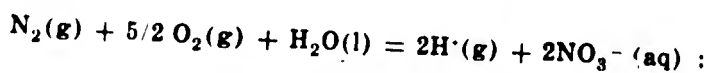
If we have hydrogen present, we may ask: Would the carbon be present as carbon dioxide or as methane? The following equation, together with its equilibrium constant, is pertinent in the following connection:



Substituting a pressure of hydrogen equal to 1.5×10^{-3} shows that the carbon would be predominantly in the form of methane and not in the form of carbon dioxide if equilibrium were established near the Earth's surface. Since the reaction is highly pressure-dependent and reaction between the constituents may depend on catalysts at the Earth's surface or activation by light

in the high atmosphere, it is difficult to arrive at firm conclusions in regard to the oxidation state of carbon. If all the present surface carbon (5000 g/cm²) were in the atmosphere as methane, the surface pressure would have been some 7 atmospheres. It is probable that much of the present surface carbon has come from the earth's interior during 4.5×10^9 years. Similar calculations involving carbon monoxide show that it would not present in the primitive atmosphere.

We may ask if oxygen would be present. The reaction of carbon with oxygen to give carbon dioxide goes strongly in the direction necessary to form the carbon dioxide, and, if hydrogen were present in excess, all oxygen in excess of that required in the rocks would be present as water. Even at the present time, if carbon were sufficiently exposed to the atmosphere, reaction to carbon dioxide would occur, but the carbon is buried to a high degree, and the oxygen cannot react with it. In the next place, we may ask if the oxygen would react with free nitrogen. The formation of nitric acid was considered by Lewis and Randall (1923) many years ago, and it was concluded that if a suitable catalyst were available all the present oxygen of the earth would react to give nitrate salts in the oceans, assuming, again, and quite reasonably so, that the hydrogen ion concentration was the same as it is now in the ocean:



$$K = 1.5 \times 10^{-3} \text{ at } 25^\circ\text{C.}$$

The calculated equilibrium pressure of oxygen with the present pressure of N₂ is 10⁻⁸ atmosphere. Thus, whether the oxygen of a present atmosphere makes contact with carbon or not, it should react with nitrogen gas and, in the course of time, would react to give nitrate ion. Oxygen in the present atmosphere at any moderate pressure must be maintained by the activities of green plants. This point has been overlooked by many authors.

In a reducing atmosphere containing any small pressure of hydrogen such as 1.5×10^{-3} atmosphere, oxygen could not be present. Of course, all attempts to exclude any particular element or compound from the atmosphere should be qualified because, in an atmosphere such as that present on the Earth, very small amounts of substances are present in spite of the fact that they

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are thermodynamically unstable. For example, hydrogen, methane, oxides of nitrogen, etc., are all unstable in the present atmosphere but do exist in the range of parts per million, and we could assume that the primitive atmosphere also contained small amounts of compounds that were not in equilibrium, perhaps again to parts per million, for example O_2 , CO , CO_2 , etc.

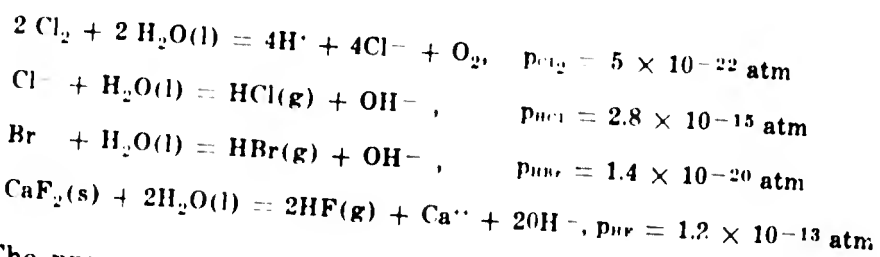
Carbon dioxide will react with the calcium and magnesium silicates of the Earth's surface to produce calcium and magnesium carbonates and silicon dioxide. This is the end result of processes taking place on the surface of the Earth now and of processes which took place in the past. The mechanism is complex because the reaction takes place in the ocean and is often promoted by living organisms at the present time, but the end results are those given in the following equations:



The equilibrium constant for the first reaction shows that the pressure of carbon dioxide required to produce equilibrium is 10^{-8} atm. Calcium, of course, is usually present in more complex silicates, rarely as $CaSiO_3$, and probably the pressure indicated here for the conversion of the more abundant calcium minerals is too low. The precipitation of magnesium carbonate would require a CO_2 pressure greater than 10^{-5} atm. At present, the pressure of carbon dioxide in the atmosphere is 3.3×10^{-4} atm. Hence, it is unmistakably out of equilibrium with the silicate rocks on the surface of the Earth. We can only remark that this probably is true because carbon dioxide cannot come rapidly to equilibrium with the massive silicate rocks of the Earth because of poor contacts for chemical reactions and because, over long periods of time, volcanic activity has been steadily supplying additional carbon oxides to the atmosphere or carbon in such a form that it is oxidized to carbon dioxide in the atmosphere. Therefore, the entire existence of plants and living organisms depends upon an unstable situation. To get vigorous plant growth, a concentration of carbon in the atmosphere approximately equal to that which now exists should be present, or a somewhat greatly decreased growth of plants and supply of food for other organisms dependent upon the compounds produced by plants will result. And, as demonstrated above, the oxygen content of the present atmosphere

is unstable. Hence, the existence of all higher animals and most microscopic ones depends upon an unstable situation with respect to both carbon dioxide and oxygen.*

Goldschmidt in his classical work on geochemistry classified a number of elements as volatile which I believe should not be so classified or should have at least a qualified classification. Of course, any substance is volatilized at a sufficiently high temperature. Thus, Rankama and Sahama (1950) in their very informative treatise list SO_2 , SO_3 , S_2 , and Cl_2 as volatiles, and bromine is often so listed. Some of these substances appear in volcanic gases, but they do not remain in gaseous form under present terrestrial conditions or under any that existed generally in the past. For example, Cl_2 is highly unstable in the presence of any reducing substance, such as H_2 , ferrous iron, or carbonaceous matter, and reacts with water to give the soluble Cl^- ion. Chlorine probably occurs in these gases as HCl . Many other elements will be volatilized at the temperatures of volcanoes, e.g., mercury, cadmium, arsenic, iodine, fluorine, hydrogen sulfide, and others. The true volatiles are those that may remain in the atmosphere at reasonable pressures; the nonvolatiles are those that remain in the rocks; the solubles are those that concentrate in the oceans. Thus, chlorides, bromides, and iodides are predominantly solubles, sulfates are partially so, and fluorides and sulfides are nonvolatiles. A few examples can be illustrated by considering the following equations:

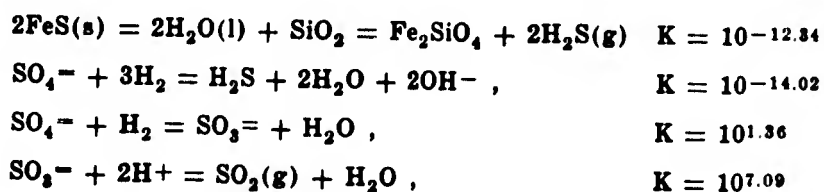


The pressures of the gaseous substances are calculated assuming equilibrium with seawater, pH 8. It is evident that Cl_2 , HCl , HF , and HBr are not volatile in any important sense under present Earth conditions, that Cl^- and Br^- are soluble, and that F^- is fairly insoluble (1.4 ppm) and nonvolatile.

*It is also true that terrestrial surface temperatures in the neighborhood of 0° to 40° C depend upon a nice balance between solar irradiation or other energy sources such as heating by tidal action and atmospheric composition. The high temperature of the Venus surface is an example of this point.

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The history of sulfur compounds can be followed reliably by the use of thermodynamic data. Sulfur occurs in the meteorites, mostly as troilite, i.e., FeS. It is present in carbonaceous chondrites as sulfate also, but material of the composition of these meteorites could not have contributed to the accumulation of the Earth in an important way because of their high water content. Hence, we assume that the primitive sulfur was present as iron sulfide. The inorganic reactions of sulfur during the time of the reducing atmosphere can be discussed using the following reactions:



We shall assume that the pH of the ocean was the same as it is at present, i.e., 8. The first reaction means that $p_{\text{H}_2\text{S}}$ may be $10^{-10.05}$ atm or less than this assuming equilibrium troilite and wuestite. If other reactions remove H_2S , its pressure may be less than this. The second reaction requires that the SO_4^{2-} molality in the ocean may be

$$a_{\text{SO}_4^{2-}} \leq \frac{10^{-4.15}}{p_{\text{H}_2}^3} = 2.1 \times 10^4, \text{ if } p_{\text{H}_2} = 1.5 \times 10^{-3} \text{ atm.}$$

and the third that

$$a_{\text{SO}_3^{2-}} \leq \frac{10^{-2.79}}{p_{\text{H}_2}^2} = 7.2 \times 10^3, \text{ if } p_{\text{H}_2} = 1.5 \times 10^{-3} \text{ atm.}$$

and finally the fourth equation requires that

$$p_{\text{SO}_2} \leq \frac{10^{-11.70}}{p_{\text{H}_2}^2} = 8.9 \times 10^{-5}, \text{ if } p_{\text{H}_2} = 1.5 \times 10^{-3} \text{ atm.}$$

Since the activity of SO_3^{2-} and the pressure of SO_2 are proportional to the activity of SO_4^{2-} and since the molality of SO_4^{2-} in the oceans today is only 0.028 as compared to the very large activity of 2.1×10^4 indicated above, the concentrations of SO_3^{2-} and pressure of SO_2 would be very low in the primitive oceans and

atmosphere; therefore, sulfur in the oceans always existed mostly in the oxidized state of $\text{SO}_4^{=}$ in the terrestrial surface water and as CaSO_4 in the sediments.

Of course equilibrium is never attained, and sulfides exist in the igneous rocks as well as sediments. Living organisms, with their ability to utilize the free energy of sunlight, maintain a disequilibrium condition so that sulfides and sulfur exist in the sediments. (Sulfur is highly unstable both in the reducing and oxidizing atmosphere and would react to yield H_2S or SO_2 , both of which would disappear through the reactions listed above.) An example of a natural sample illustrating this point is the Orgueil Meteorite which certainly has been subjected to water and which contains both sulfate and elementary sulfur. Thermodynamic calculations indicate that this could be an equilibrium condition if the hydrogen pressure was 10^{-6} atmosphere and the sulfate concentration was that of the present oceans. The Orgueil Meteorite presents a curious mixture of highly oxidized and highly reduced substances.

So far, we have been discussing the simple compounds: water, hydrogen, nitrogen, ammonia, methane, carbon dioxide, oxygen, compounds of sulfur, etc. But carbon forms an exceedingly complicated group of compounds, as we are well aware. These compounds are of very particular interest because they are the ones that compose the biological material on the surface of the Earth.

In fact, most of the carbonaceous material that we now find on the surface of the Earth has probably been through the bodies of living organisms many times. Many of these compounds are thermodynamically unstable in the surroundings in which they are now found. In fact, all of them will react with oxygen spontaneously to produce carbon dioxide, water, and nitrogen gas. The process is steadily going on, and slowly. Nevertheless, it does proceed. These chemical compounds are being produced again by the action of radiation on green plants which produce biological compounds of great variety.

Recently, studies have been made on quasi-equilibria involving carbon compounds, hydrogen, oxygen, nitrogen,* etc., by Dayhoff,

*These authors have assumed that graphite would not be formed, and this does not appear to be probable over long periods of time.

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et al. (1964), and experimental work has been done very recently by Studier, et al. (1968) and Hayatsu, et al. (1968) on the reaction products of nonequilibrium mixtures of simple substances. These papers assume that the postulated conditions of catalysts, temperatures, pressures, and proportions of elements apply to the solar nebula, but that they are more applicable to the surface conditions of the primitive Earth from which most of the hydrogen component has been lost. These studies indicate that an enormous array of these carbon compounds will be produced, providing we start with mixtures that are thermodynamically unstable and proceed to form compounds which are thermodynamically more stable.

Of course, as a general proposition, this has been well known for many years. It is reasonable to suppose that the original atmosphere and superficial regions of the Earth contained many of these compounds. But it should be noted that the original unstable mixtures must have been produced by some energetic process. For example, mixtures of ammonia and carbon monoxide can be prepared in the laboratory since there appears to be no method by which they would be produced in a natural Earth environment. This is also true of certain other compounds used by these authors.

The ultraviolet light of the Sun in the high atmosphere produced activated molecules of various kinds, and these activated molecules, containing high free energy, would have engaged in spontaneous chemical reactions on the surface of the Earth. It is also true that electrical discharges could have occurred that would have produced energetic compounds. Such compounds have been studied by Miller, Ponnampertuma, and others, in recent years. It is interesting that many compounds that are characteristic of biological materials have been produced in this way. All such compounds as this could have been present on the earth from the earliest time.

Berkner and Marshall (1964) discuss the protective effect for living organisms of ozone in the high atmosphere. But, in the presence of a reducing atmosphere containing only 1.5×10^{-3} atmosphere of hydrogen, many volatile carbon compounds would be present, and these would absorb the ultraviolet light. In fact, the atmosphere might be opaque to visible light, as well. If the

hydrogen pressure is only 2×10^{-6} atm, the equilibrium ratio of methane to carbon dioxide becomes unity.*

THE VARIATION OF THE ATMOSPHERE WITH TIME

Hydrogen escaped from the Earth continuously from the time the Earth accumulated, and we have assumed that if the pressure is about 1.5×10^{-3} atm of hydrogen at the surface the required amount of hydrogen to produce the oxidation that we have observed would occur in approximately $2\frac{1}{2}$ billion years. This hydrogen comes from the dissociation of water, and the oxygen that is left behind oxidizes carbon compounds to higher states of oxidation; e.g., methane goes to methyl alcohol, to formaldehyde, to formic acid, to carbon dioxide, or the equivalents of these valence states occur in more complicated compounds. Ammonia is oxidized to nitrogen, sulfide is oxidized to sulfate, and ferrous iron to ferric iron. Other elements are oxidized, but their contribution to the required amount of dissociation of water and escape of hydrogen is slight.

There is evidence which indicates that carbon dioxide first appeared in steady concentrations higher than the equilibrium concentration for the reaction of calcium and magnesium silicates with carbon dioxide to give calcium and magnesium carbonates at about 2.5×10^9 years ago. Small amounts of limestone are observed before that date, but massive limestone appears approximately from that time on. It appears then that the state of oxidation of carbon compounds had advanced to a point where appreciable quantities of carbon dioxide existed in the atmosphere.

There is evidence that oxygen must have appeared in the atmosphere about 2 billion years ago. The most striking evidence for this comes from the enormous iron deposits that were laid down in various parts of the world at approximately this time. In Venezuela, for example, there is the great iron mountain Cerro Bolivar where a layer of nearly pure ferric oxide 100 meters thick can be found. But there are other hilltops in Venezuela at the same geologic level which also have some ferric oxide deposits on them. It appears that at least over an area of some 200 km in

*I suspect that the air over some of our cities is opaque to ultraviolet light at times because of small amounts of carbon compounds in the air.

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linear dimensions such deposits existed in Venezuela 2 billion years ago. Similar deposits of iron are found in other parts of the world. McGregor (1927) suggested that this dated the time at which oxygen appeared in the atmosphere. Of course, there must be a way by which iron was transported to these positions. In the absence of oxygen, ferrous bicarbonate would be soluble in water to a slight extent. Hence, it would be eroded out of the igneous rocks and transported by streams to the oceans or to bays. If in these bays algae were present which could oxidize the ferric iron, it would precipitate. It appears that the erosion of the rocks up to that time occurred under a reducing atmosphere, but, with carbon dioxide present, the iron was deposited along with other sedimentary materials in the deep oceans. Such deposits have moved under the continents, just like the ocean bottoms are doing today. At the particular time of 2 billion years ago, the plants were able to precipitate the iron in these lagoons and make these enormous iron deposits. A short time later, the oxidizing atmosphere appeared, and, after that, there were no soluble compounds of iron available. The iron was mechanically deposited throughout the sedimentary materials and was not concentrated in this way. This explanation was presented some 10 years ago (Urey, 1959) and has again been brought forward by Cloud (1968).

Thode, MacNamara and Fleming (1953) observed that S^{34} is concentrated in sulfates relative to sulfides and suggest that this has occurred through repeated oxidation of sulfide by elementary oxygen and repeated reduction by bacteria. They estimate, very approximately, that this began about 10^9 years ago, i.e., again at a time of the order of the 2×10^9 year date.

Another bit of evidence of this kind exists (Ramdohr, 1958), namely that in the dates before 2 billion years ago, uranium was deposited as uraninite UO_2 , whereas, since about two billion years ago, it appears in the sediments in the more oxidized form of pitchblende U_3O_8 . Again, an increase in oxidizing characteristics appeared about 2×10^9 years ago.

THE ORIGIN OF LIFE

Today, it is generally assumed that life originated by natural processes from inorganic material. The complication of living organisms is so great that one marvels that they could ever have

evolved from inorganic material. Possibly our simple judgment in regard to this is due to our inability to appreciate how much chemical experimentation can take place in an ocean during millions of years. However, it is evident that the possibility of complex compounds being present on the Earth is much greater if the atmosphere is reducing than if it is oxidizing. Today, I think it is firmly believed that life would originate in the reducing conditions and would not originate under the present oxidizing conditions. The necessities for the evolution of life are: (1) that water be present, for all living processes as we know them take place in liquid; (2) that we must expect the presence of many complicated compounds in the environment; and (3) very important, that we must expect that there is a source of free energy which produces compounds with a high free energy content, for only in this way do spontaneous chemical reactions take place.

Recent studies show that many biologically important compounds can be produced in a reducing atmosphere by various processes. Recently, extensive studies have been made on the quasi-equilibrium conditions that would exist on the Earth with varying proportions of carbon, hydrogen, oxygen, and nitrogen. These studies show that many complicated compounds will be present, providing the hydrogen pressure is not too high. If the hydrogen pressure is high, methane becomes the only stable compound present in any significant proportions. Even with a hydrogen pressure of 1.5×10^{-3} atm, methane should be the prominent constituent under equilibrium conditions. However, equilibrium conditions are not the conditions that will produce life because, under such conditions, no chemical reactions take place. It would be a dead world and it would remain dead if this were the condition. In a primitive atmosphere, there is always the possibility for high energy compounds to be produced by the action of ultraviolet light in the high atmosphere, or by the effect of lightning in the atmosphere, and there are other minor sources of free energy. Radioactivity is not important, for it is confined mostly to the condensed phases, and thus is not effective in producing carbon compounds of high-energy content. It is also very destructive to life as we know it for the very fundamental reason that these high energy processes break the carbon bonds and destroy the very complicated structures required for living processes. Heat is not important as a source of free energy for we get free energy only when a heat engine operates between two

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different temperatures. If we can heat substances, say to 500°, and then cool them down, chemical reactions will occur spontaneously at ordinary temperatures. But it is quite obvious that on the Earth at the present time high temperature sources are very incidental and not continuous, and, hence, they are not reliable sources for the production of energetic compounds. This situation must have existed in the past. By all odds, the most important source of energy on the primitive earth was the ultraviolet light of the sun and the electrical processes which owe their existence again to the radiation of the Sun.

The biochemical details by which life evolved are exceedingly complicated, and it is not intended that a detailed discussion of this should be undertaken at this point. However, we might point out that modern living organisms, from the most complicated to the most simple, contain deoxyribonucleic and ribonucleic acids and protein materials. The type of protein materials produced is determined completely by the DNA or RNA. At least so far as we can see from the organisms that have persisted to the present time, these compounds are correlated with each other uniquely, and, hence, it appears probable that the origin of life occurred by the evolution simultaneously of DNA, RNA, and proteins, side-by-side. This evolution requires that we should be able to have compounds containing the nucleic acid bases, adenine, cytosine, guanine, thymine, uracil, ribose, deoxyribose, and phosphate in order to produce the nucleic acids. At the same time, we must have present the amino acids, some twenty of which are important in making the prominent proteins of terrestrial organisms. Recently, experiments show that many of these compounds can be produced using energetic processes such as electrical discharges and ultraviolet light. The amino acids are able to persist on the Earth for substantial lengths of time, but it is difficult to produce these except by energetic processes. Probably the phosphate problem is the most puzzling one because the natural phosphates are so insoluble. Calcium, magnesium, and ferrous phosphates have very small solubilities, and one wonders how they could have been available in the primitive oceans in order to facilitate the synthesis of the very important compound DNA and RNA, but, possibly, one part of phosphorus per 10 million parts of water was sufficient, as it is also sufficient for the growth of modern organisms. Miller and Parris (1964) have shown that the answer probably lies in the utilization of solid phosphates by evolving organisms.

When oxygen appeared in the atmosphere some 2 billion years ago, it is probable that most types of organisms existing at that time were eliminated. But some anaerobic organisms have persisted to the present time. For example, yeast is a very common organism, and many anaerobic bacteria are known. And, occasionally, an animal of advanced, complicated structure spends at least part of its life cycle under anaerobic conditions. It is interesting that a fossil microorganism (*Kakabekia umbellata*) was discovered (Barghoorn and Tyler, 1965) in the Gunflint formation which was laid down about 2 billion years ago. Later, what appears to be the same organism or a closely related one was discovered in deposits at Harlech Castle, Wales, in places where human urine was deposited. Such deposits contain considerable amounts of ammonium ion, and this and carbon compounds are required for its growth in laboratory media (Siegel, et al., 1967). If we are able to find an ancient fossil of 2 billion years ago, we can reasonably assume that it was widely distributed in order that even one fossil deposit of such a microorganism could be found at the present time. Thus, it is reasonable to assume that the conditions under which it lived were the general conditions and not those of very specialized locations. In other words, this organism can reasonably be assumed to have lived on an Earth in the oceans of which ammonium ion and ammonia were common, which is precisely the conclusion reached in this paper in regard to the state of nitrogen compounds on the Earth, from its beginning up to some 2 billion years ago. Some may argue that this is not an exact proof of the conditions on Earth 2 billion years ago, and with this I agree. However, the most reasonable interpretation is that *Kakabekia* managed to find very limited areas where biological organisms, e.g., *Homo sapiens*, left biochemical substances which decomposed to produce the ancient ammoniacal conditions under which it evolved.

SUMMARY

We can summarize the conclusions of this paper in this way. The original atmosphere of the Earth was reducing, with free hydrogen in the atmosphere. The atmosphere probably contained substantial amounts of methane, some amounts of nitrogen, and small amounts of ammonia. Also, the oceans contained ammonium salts. The origin of the Earth is generally thought to have occurred between 4.5 and 4.7×10^9 years ago. The loss of hydrogen began

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immediately, and, at the end of approximately 2 billion years, namely 2.5×10^9 years ago, the carbon dioxide pressure in the atmosphere probably became higher than 10^{-5} atmospheres. The concentration of carbonate and bicarbonate ions in the ocean was probably smaller than it is today, and the calcium ion concentration in the oceans may have approached its present value. At this time, probably ferrous iron was also present in the oceans in amounts somewhat less than calcium. Calcium carbonate, magnesium carbonate, and ferrous carbonate were being deposited from the oceans at that time. Approximately 2 billion years ago, green plants appeared, having a capacity of oxidizing ferrous iron to ferric iron, thus resulting in the deposition of the great iron deposits of the Earth. After this time, free oxygen appeared in the atmosphere, and this prevented the erosion of iron from the rocks and its subsequent transport to the seas. From then on, the possibility of the concentrations of iron in large quantities ceased because of the insolubility of the iron in water. For 2 billion years we have had an oxidizing atmosphere, and only those organisms that were able to protect themselves against oxidation processes have survived, with the exception of those organisms (e.g., certain bacteria, yeast, and a very interesting *Kakabekia umbellata*) that have been able to find localized areas on the Earth's surface where reducing conditions exist. It is interesting to note that with the appearance of oxygen and its production by plants, far more energetic organisms have been possible than existed under reducing conditions. No very satisfactory explanation has appeared in the literature to explain the absence of calcareous fossils until the beginning of the Cambrian period and none is attempted in this paper.

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IV

Chemical Evolution and the Origin of Life

Cyril Ponnampерума*

INTRODUCTION

In the evolutionary scheme of things, life may be considered to be a special and very complicated form of the motion of matter. It possibly arose as a new property which matter had not possessed earlier and only occurred at a particular period in the existence of this planet and resulted in its orderly development. It was the result of a gradual process, operating upon the Earth over an inconceivably long span of time. A long chemical evolution was the necessary preamble for the emergence of life.

These ideas are implicit in the writings of Oparin, Haldane, and Bernal.^{1, 2, 3} Oparin alluded to the simple solutions of organic substances whose behaviour was governed by the properties of the component atoms and their arrangement in the molecular structure. Increasing complexity resulted in new properties, and biological orderliness thus came into prominence. Haldane had speculated on the production of a vast variety of organic substances, including sugars, and some of the materials from which proteins are built up by the action of ultraviolet light on the Earth's primitive atmosphere. Bernal theorized on the modes by which concentrations could have been effected on the primitive Earth. Condensations and dehydrogenations would have led to more complex substances making possible further syntheses.

"Even a formulation of this problem is beyond the reach of any one scientist, for such a scientist would have to be at the

*Chief, Chemical Evolution Branch, Exobiology Division, NASA-Ames Research Center, Moffett Field, California; and the Department of Biological Sciences, Stanford University, Stanford, California.

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same time a competent mathematician, physicist, and experienced organic chemist, he should have a very extensive knowledge of geology, geophysics, and geochemistry, and, besides all this, be absolutely at home in all biological disciplines. Sooner or later this task will have to be given to groups representing all these faculties and working closely together theoretically as well as experimentally," said Bernal in 1949 in his celebrated essay entitled, "The Physical Basis of Life."³ The chemist, however, with daring insight could think of the evolutionary process as passing through three distinct chemical phases from inorganic chemistry to that of organic chemistry, and from organic chemistry to that of biological chemistry. Two things, therefore, appear to be necessary for the chemical sequence of events which led to the appearance of the first replicating molecules:

- (1) The origin of the micromolecules or monomers,
- (2) The condensation of the micromolecules into macromolecules or polymers capable of replication.

The purpose of my talk is to outline how experimental work in our laboratory has shown that these two stages could have taken place on the primordial Earth before the appearance of life.

PRIMITIVE ATMOSPHERES

The starting point for any discussion on the question of the origin of life must turn around the nature of the Earth's primitive atmosphere,⁴ for it is this atmosphere which supplied the raw materials. The present rarity of the terrestrial noble gases with respect to their cosmic distribution indicates that a primary atmosphere of the Earth was almost completely lost in early times and that the present atmosphere is of secondary origin. The elements which were later to form a secondary terrestrial atmosphere must have rained out of the primary atmosphere in compounds or have been accumulated as gases during the formation of the Earth. As the temperature of the newly-formed planet increased through the energy of accretion and due to radioactive decay, these compounds were decomposed and the occluded gases released. The chemical composition of the secondary atmosphere must, at first, have been similar to that of the primary atmosphere. Because of its high rate of escape, most of the free hydrogen must have been lost, and the principal constituents of the atmosphere must

have been water vapor, ammonia, and methane. It is this atmosphere of water vapor, methane, and ammonia, and small amounts of hydrogen which will be considered in this discussion as the primitive atmosphere of the Earth.⁵

Although there is some controversy about the true nature of the Earth's early atmosphere, the evidence available from several sources suggests that the primitive atmosphere must have been reducing in nature. The great abundance of hydrogen in the universe is the basic argument in support of this theory. Over 90% of the known universe is made up of free hydrogen. The equilibrium constants further indicate that in the presence of an excess hydrogen the elements carbon, nitrogen, and oxygen must have been present in their reduced form as methane, ammonia, and water. From planetary spectroscopy, we learn that the major planets, Jupiter and Saturn, which have retained their primitive atmosphere have a large abundance of methane, ammonia, hydrogen, and water. The meteorites which have the approximate age of the Earth contain metals in the reduced form. An added argument, which indirectly supports the idea that the primordial atmosphere must have been reducing, is that many of the molecules which are necessary for living organisms cannot be produced unless we have nonoxidizing conditions.

The presence of oxygen in the Earth's atmosphere is intimately related to the evolution of the Earth's primitive atmosphere.⁶ The Earth is unique in our planetary system in having an atmosphere containing free oxygen. The oxygen in the present atmosphere appears to have arisen from two sources: the photodissociation of water in the upper atmosphere by short wavelength ultraviolet light and by plant photosynthesis. Photosynthesis probably evolved when the ozone layer in the upper atmosphere cut out the ultraviolet light from the sun and thus put an end to the photochemical synthesis of organic compounds in the primitive environment. Heterotrophs which thrived on photochemicals available around them were converted to the autotrophs which had to photosynthesize their own food. This change may be diagrammatically represented by the hour glass (Figure 1). Only those organisms that could incorporate molecules such as porphyrins and make use of longer wavelength light were able to pass through the bottleneck. There was a wholesale massacre at this junction. The organisms that survived and developed further were able to evolve into the wide variety of life on Earth today.⁷

TRANSITION FROM REDUCING TO OXIDIZING ATMOSPHERE

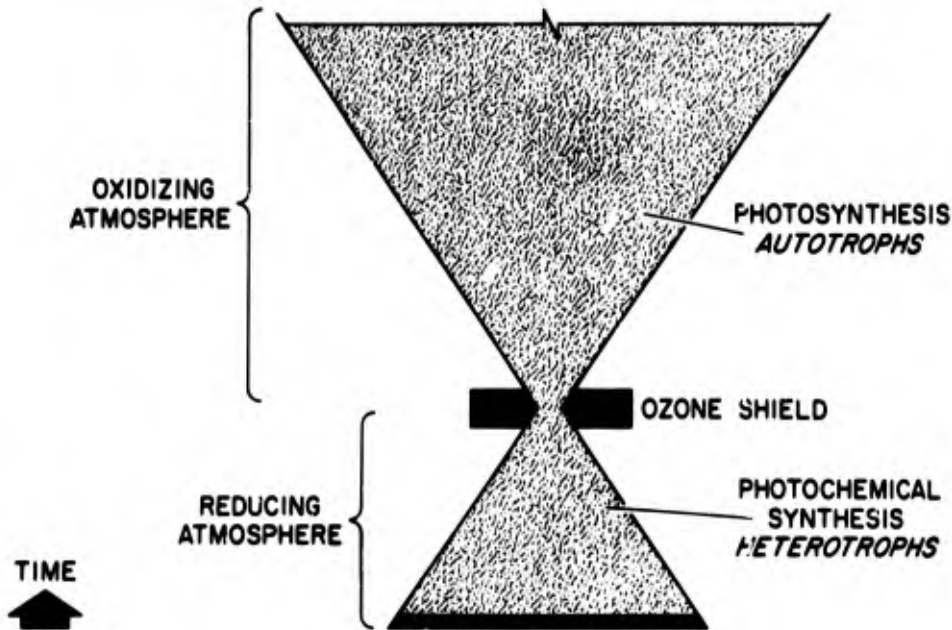


Figure 1

ENERGIES

The energies available for the synthesis of organic compounds under primitive Earth conditions were ultraviolet light from the Sun, electric discharges, ionizing radiation, and heat.⁸ While it is evident that sunlight is the principal source of energy, only a small fraction of this energy was in the wavelength below 2,000 Å and could have been absorbed by the methane, ammonia, and water. However, the photodissociation products of these molecules could absorb energy of higher wavelengths. Next in importance as a source of energy are electric discharges, such as lightning and corona discharges from pointed objects. These occur close to the Earth's surface and hence would more efficiently transfer the reaction products to primitive oceans. A certain amount of energy was also available from the disintegration of uranium-235, uranium-238, and potassium-40. While some of this energy may have been expended in the solid material such as rocks, a certain proportion of it was available in the oceans and the atmosphere. Heat from volcanoes was another form of energy that may have been effective in primordial synthesis.

EXPERIMENTS

In the experiments in our laboratory, we have adopted the simple working hypothesis that the molecules which are important now were also important at the time of the origin of life. We are investigating the abiogenic synthesis of the nucleic acids and proteins. We synthesize the "primordial soup" described by Haldane and proceed to analyze it. I shall now endeavor to show how, in the course of these experiments, we have established that some of the micromolecules of biological significance can be synthesized and that under the same conditions they could be condensed, or polymerized, to give rise to macromolecules.

In experiments starting with methane, ammonia, and water, an electron beam was used to simulate potassium-40 on the primitive Earth.⁹ The gas mixture was irradiated with electrons from a linear accelerator in the Lawrence Radiation Laboratory at Berkeley. In a 45-minute period, the total energy absorbed was about 7×10^{10} ergs per gram. The results of this investigation clearly established that adenine was a product of the radiation of methane, ammonia, and water. The production of adenine is enhanced by the absence of hydrogen. This is to be expected since methyl carbon has to be oxidized in order to appear finally in the purines. In any event, the high concentration of organic matter on the prebiotic Earth probably arose when most of the hydrogen had escaped.

Formaldehyde was formed by the action of electric discharges, or ionizing radiation, on a mixture of primitive gases. Experiments in which formaldehyde was used as starting material have shown that sugars are formed. A preliminary separation indicates that, by far, the highest yield is in the pentoses and hexoses.¹⁰ There is evidence that the biological sugars, ribose and deoxyribose, can be formed by this means. Similarly, hydrogen cyanide, which is readily formed in simulation experiments, gives rise to adenine and guanine by photochemical reactions.¹¹

This brief summary of previous work indicates that micromolecules can, indeed, be formed in simulation experiments. The results from other laboratories have confirmed our findings and have extended the list of compounds so formed.¹² Let us now turn to the question of condensation reactions giving rise to polypeptides and oligonucleotides.

CONDENSATION REACTIONS

Dehydration-condensation reactions are generally involved in the formation of more complex molecules. On the primitive Earth, this type of condensation could have taken place in water solution, in our case the primordial ocean, or in the relative absence of water on the shore of the ocean or the dried-up bed of a lagoon. In our simulation experiments, we have reconstructed both models:

- (1) The condensation reaction taking place in the presence of water, and
- (2) The condensation reaction taking place in the relative absence of water or in a hypohydrous condition.

The condensation reaction taking place in the presence of water will be illustrated by our synthesis of peptides while the condensation reaction in the relative absence of water will be demonstrated by our synthesis of oligonucleotides.

We have two examples of the synthesis of peptides in aqueous solution:

- (1) The photochemical synthesis of di-peptides and tri-peptides from glycine and leucine;¹³
- (2) The synthesis of a polypeptide during the electric discharge through methane, ammonia, and water.¹⁴

When an aqueous solution of glycine and leucine was exposed to ultraviolet light in the presence of cyanamide, the dipeptides glycyl-glycine, glycyl-leucine, leucyl-glycine, leucyl-leucine and the tripeptides glycyl-glycyl-glycine and leucyl-glycyl-glycine were formed.

We have recently found that, in our experiments with electrical discharges on the Earth's primitive atmosphere, most of the aminoacids synthesized were already present in the condensed form. The aminoacids appear to be linked together as soon as they were synthesized. It was only on hydrolysis that free amino acids were detected.

The apparatus used for the experiment consisted of a dumbbell-shaped flask representing the atmosphere and the ocean. The discharge takes place in the upper flask (the atmosphere) and the reaction products accumulate in the lower (the ocean). In a typical

experiment, the flask is evacuated and filled with high purity methane together with C^{14} labeled methane up to a pressure of about $\frac{1}{2}$ atmosphere then, 100 ml of 0.3 normal ammonium hydroxide is introduced through the stopcock, F. The temperature of the lower flask is brought up to 100° with the aid of the heating coil. When complete circulation is established, which becomes apparent when the water condenses on the upper flask and trickles down through the condenser, the Tesla coils are discharged.

After 24 hours of discharge, the upper flask is covered with brown material; organic matter is dissolved in the water contained in the flask below. Radioactivity measurements show that, at this time, 90% of the methane has been converted into organic compounds. Of this, about 45% is in the water fraction. The analysis of the water soluble fraction shows that 18% of it is in the form of cyanide.

Paper chromatography of an aliquot of the "soup" was followed by autoradiography. There was some material at the origin, and several spots were scattered throughout the chromatogram. None of these corresponded to the known amino acids. The use of an amino acid analyzer pointed to the presence of traces of two amino acids. When the starting material was hydrolyzed before being placed on the column of the analyzer, a large number of amino acids were formed with an increase in yield. The retention times corresponded to nine amino acids which are commonly found in protein: Glycine, alanine, aspartic, glutamic, threonine, serine, isoleucine, leucine, and phenylalanine. A few unnatural amino acids appear to be formed, but these have not yet been characterized. The results obtained by ion-exchange chromatography were confirmed by the gas chromatography of the trifluoroacetyl derivatives of the acids.

The evidence so far points to the possible presence of the amino acids in polymeric form in the soup. With the use of a biogel-P column, a fraction having a molecular weight from 186 to 2,000 was separated. This was hydrolyzed, and the acids aspartic, serine, glutamic, glycine, and alanine were identified. The examination of this fraction on electrophoresis as a DNS (1-dimethylaminonaphthalene-5-sulphonyl chloride) derivative showed only one band, suggesting that the fraction separated on the biogel column appeared to be a single polypeptide or a mixture of equivalent net charge.

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In order to establish whether glycine was incorporated into the polymer by a peptide link, the discharge experiment was repeated with unlabelled methane. Glycine labelled with C^{14} was added to the water in the lower flask. Electrophoresis of the end products indicated that the glycine was incorporated. Hydrolysis with the enzyme pronase, released the glycine quantitatively. Similar results were obtained with alanine. In the case of these two amino acids, the incorporation appeared to be via the peptide link.

In the studies on chemical evolution up to now, it has been thought that the individual amino acids had to be first synthesized and then accumulated before the formation of a polymer. Our results on the contrary show that some polymerization had already occurred during the initial reaction between the Earth's primitive atmosphere and natural forces such as lightning. A long period may not have been necessary before the first protein appeared. These short peptides could have acted as the first enzyme in polymerizing nucleotides, which we have already shown can be formed under primitive Earth conditions.

The condensation reactions taking place in the relative absence of water, or in the hypohydrous condition, are exemplified in the case of the oligonucleotide synthesis. Since nucleosides could be formed in aqueous solution, we investigated the possibility of their phosphorylation under hypohydrous conditions. Such a situation could have prevailed on the primitive Earth when organic material may have been deposited on the beds of lagoons and pools which may have fringed the early coastline. An intimate contact between nucleosides and phosphates could have been brought about by a process of evaporation under the action of solar heat.

When the nucleosides adenosine, guanosine, cytidine, uridine, and thymidine were heated with sodium dihydrogen orthophosphate, NaH_2PO_4 , the nucleoside monophosphates were formed.¹⁵ The heating was conducted at about $160^\circ C$. At this temperature, the highest yield of monophosphate obtained was about 18%. This reaction took place at much lower temperatures. Even at 50° , a small yield was obtained, but this required at least 3 days' heating as compared to 2 hours at 160° .

In these initial experiments, several bands were observed in the autoradiograph of the electrophoretic separation. By the combined techniques of autoradiography, paper chromatography,

ion exchange, and electrophoresis, the different isomers of the monophosphates were separated.

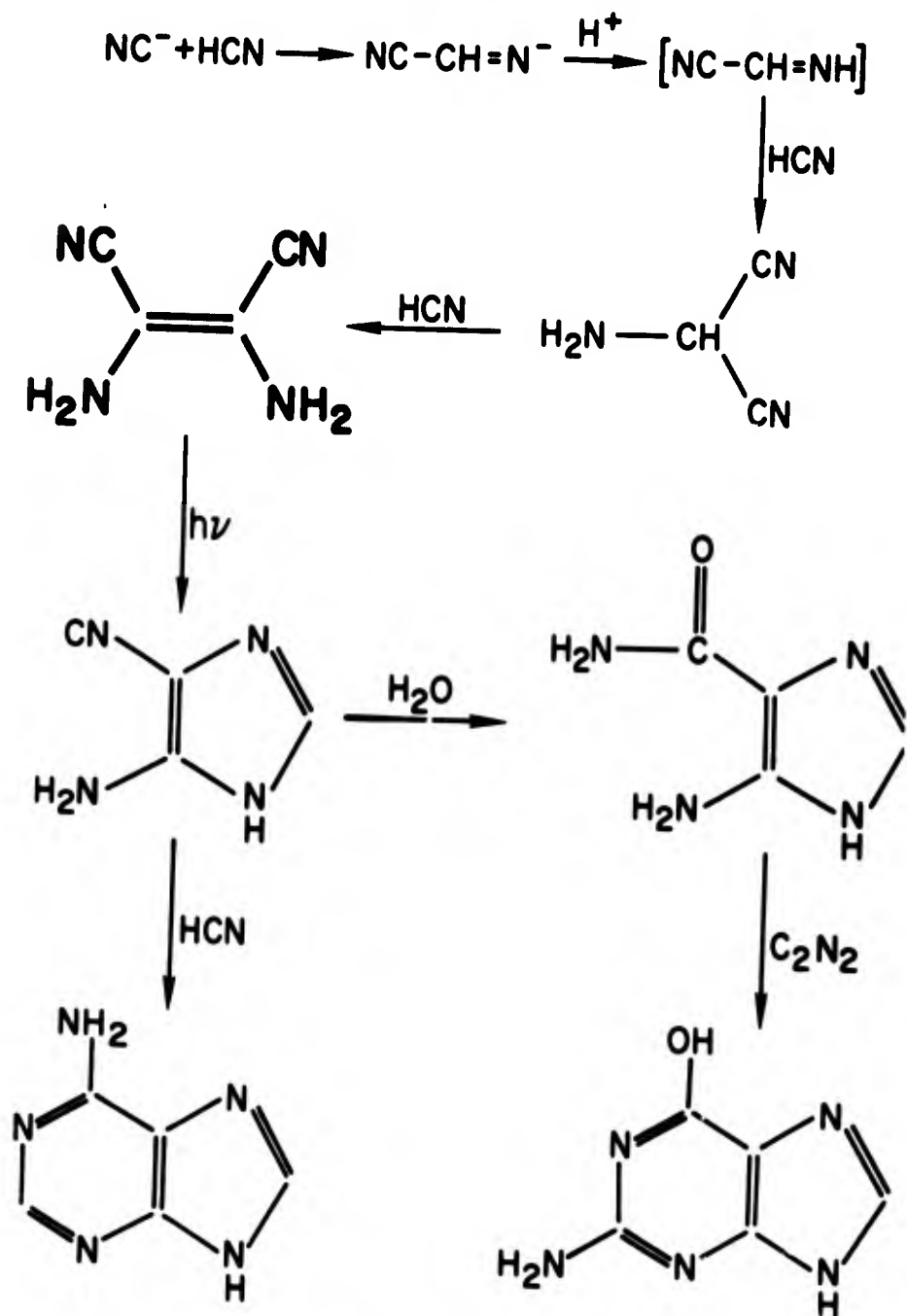
The use of C^{14} labelled nucleosides, and P^{32} labelled phosphate clearly indicated that there were other phosphate containing compounds besides the monophosphate. The electrophoretic mobility of one of these corresponded to the dinucleoside UpU. The identity of this was further confirmed by the use of ion exchange, paper chromatography, and C^{14}/P^{32} ratio studies.

A second compound corresponded to the dinucleotide UpUp. This was similarly identified as the dinucleotide of uridine by combined analytical techniques. We have more recently been able to extend the identifications to the trinucleotides and tetranucleotides. These results clearly indicate that the thermal phosphorylation could result in the synthesis of small polynucleotides.¹⁶

The conditions of these experiments may be considered to be genuinely prebiotic. The temperatures used are within reasonable limits. Although the reaction is favored by the absence of water, it is not completely inhibited by water. We find that water of crystallization does not interfere with the yields. In the case of the mononucleotides, several experiments were done with various proportions of water. We found that the reaction was not hindered unless water was present in large excess. For example, when 2 micromoles of the orthophosphate and 2 micromoles of uridine were heated in the presence of 500 micromoles of water in a sealed tube 5 ml in volume, the reaction still took place although the yield was an order of magnitude less. If dinucleotides, trinucleotides and tetranucleotides can be formed by this process, it is reasonable to expect that several dinucleotides could be linked together by a similar process to give us the beginnings of nucleic acid chain formation.

Recent studies on the pathway of phosphorylation have shown that condensed phosphates are formed when orthophosphates are heated to around 160° . At lower temperatures, partial transformation to linear phosphates was observed. Because of its simplicity, thermal condensation of inorganic orthophosphates at relatively low temperatures is very attractive as a general source of condensed phosphate on the primitive Earth and supports the suggestion that thermal processes may have provided one of the most likely sources of inorganic polyphosphate, a potential phosphorylating and condensing agent in primitive syntheses.¹⁷ We

ADENINE AND GUANINE FROM HCN
TETRAMER



(ORGEL 1966)

Figure 3

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SYNTHESIS OF SUGARS FROM FORMALDEHYDE

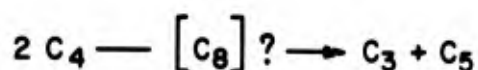
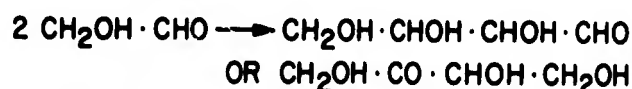
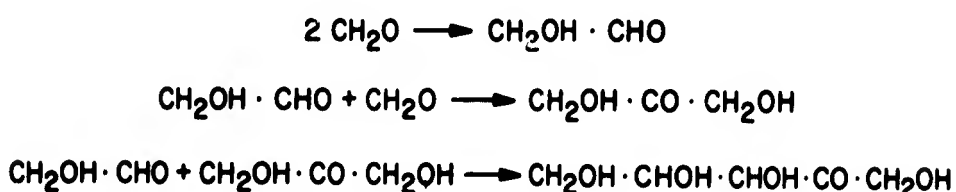


Figure 4

rise to polymers which may have been the forerunners of the nucleic acids and proteins of today.

Recent work on the elucidation of the mechanisms involved in these reactions point to a relative simple chemical pathway for the origin of the micromolecules.

Hydrogen cyanide is formed in copious yield from methane, ammonia, and water. It is the pathway for the purines adenine and guanine (Figures 2,¹⁹ and 3²⁰).

Formaldehyde is an intermediate in the reaction of primitive atmospheres. It is the simplest of the sugars. Condensation reactions with formaldehyde give rise to sugars of biological importance. This was a reaction known to organic chemists since 1861, (Figure 4²¹).

The cyanide and the aldehyde together, by the Strecker synthesis, give rise to amino acids, (Figure 5).

MECHANISMS OF SYNTHESIS

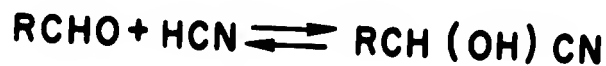


Figure 5

A brief survey of the mechanisms involved in these reactions suggests that all the ingredients necessary for the production of nucleic acids and proteins can be generated from methane, ammonia, and water.

The mechanisms involved in the condensation reactions are somewhat obscure. In the case of the polypeptide, it is reasonable to assume that hydrogen cyanide may be involved since the solution contains 18% cyanide and since previous experiments have shown that cyanide can act as a dehydration-condensation agent. In the polynucleotide synthesis, it seems more likely that the dehydration is mediated by the linear polyphosphates.

The type of synthesis which may be taking place on the planet Jupiter has also been an object of our study. These investigations are of great interest because the present atmosphere of Jupiter approximates that of the early solar nebula. The recent models of the Jovian atmosphere based on the calculations of Peebles and Gallet suggest the presence of liquid water and higher temperature beneath the outer layer of clouds of ammonia crystals.

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The simulation studies have shown that α -aminonitriles which are precursors of amino acids can be synthesized. Some form of chemical evolution may be taking place on Jupiter. Our experiments also lead us to believe that the red colors on the planet may be due to a ruby-red organic polymer formed when a mixture of methane and ammonia is exposed to electric discharges.

The laboratory experiments have shown that, wherever suitable conditions exist, organic compounds of biological significance can be synthesized. These results lend support to the hypothesis of chemical evolution and to our belief in the existence of extra-terrestrial life.

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Physics of the Universe

F. Zwicky*

BASIC OUTLOOK

The coordinators of this symposium have magnanimously asked me to talk about the physics of the Universe. It would be an understatement to say that this is a fairly large order. I therefore suspect that I was not really invited as a specialist to talk about the almost innumerable physical aspects of the Universe, but rather as a morphologist^{1, 2, 3, 4} who visualizes things and events in terms of basic fundamentals, the known number of which, surprisingly enough, is not very great. I shall therefore try to point out and to survey some of these fundamentals and to go into detail only for purposes of illustration.

THE MORPHOLOGICAL APPROACH

Among all of the approaches to the manifold problems of life and the world, this is the most universal. Morphological Thought and Procedure aim at an integral understanding of all communicable aspects of the world and at the development of procedures and methods of construction that will eventually enable us to realize the genius of man, that is, a stabilized world inhabited by men and communities of men who have all achieved their individual and unique statures.

One of the prime requirements for the successful participation in the building of a harmonious and unified world is the knowledge

*Mount Wilson and Palomar Observatories, Carnegie Institute of Washington and California Institute of Technology, Pasadena, Calif.

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of all basic facts relating to things and phenomena on the one hand and understanding of the thoughts, emotions, and aspirations of man on the other. In talking here about the physics of the universe, however, I shall confine myself to a discussion of the properties of matter and space and leave the analysis of the minds of men and their aberrations to another speaker; although I must emphasize that they constitute a complex of problems which actually interest me even more than the physics of the universe.

To state it briefly, the morphologist, in all of his work and his activities, is concerned with the interrelations among objects, phenomena, concepts, and ideas. Furthermore, he endeavours to achieve as an ultimate goal an understanding of all such interrelations. This, in practice, is of course seldom possible, and our procedures then become restricted to what Prof. John Strong has called *Modest Morphology*.⁵ For instance, I may know of one proof of the Pythagorean theorem. The uncompromising morphological approach endeavours to know *all* proofs, which happen to be in this case infinitely many, although these may be grouped into a finite number of classes of the same character. Modest morphology contents itself with two, or with just a few, proofs; the knowledge of which, however, will be useful to evoke resonance of understanding in the mind of one pupil or in another who might not really appreciate the first proof at hand.

MORPHOLOGY OF THE PHYSICS OF THE UNIVERSE

At first sight, it might appear to the morphologist, or for that matter to anybody, that we are concerned here with *all* the interrelations among objects and phenomena. This of course is partly true, and it would suffice as a formulation of the problem if only we were involved individually. For myself, I can observe objects and phenomena, enjoy the experience, interfere as the occasion permits or demands, change the course of events in some measure, and then let it go at that. If, however, objective recording and communication to other individuals is required, the observations which I make must be formulated in some objective and communicable way. A fact as I, and only I, possess it cannot under the circumstances remain such a fact—it becomes but a logical construct to be transmitted to and possibly to be understood by others. Our objective review of the physics of the universe therefore is

not only concerned with interrelations among objects and phenomena but also with concepts and ideas. And, finally, if men decide to work together in changing the world, the morphology of planned action becomes important.

Although all these aspects of the physics of the universe are interrelated, to start with we shall treat them separately as far as this is possible. Ultimately, however, the morphologist aims at visualizing and understanding *all* the basic interrelations among objects, phenomena, concepts, ideas, and human actions.

THE OBJECTS IN THE UNIVERSE^{6, 7}

When man first became conscious of distinct objects in the world, he no doubt, like a child, began to separate and to order them in his mind. In the course of history as well as during the life of every individual, an ever increasing number of objects and of families of objects is thus being established. If you should ask me to follow this historical procedure in my review, however, I shall get nowhere. In order to simplify the task of ordering the objects in the universe and talk about them in easily communicable terms with others, the physicist, chemist, and astrophysicist therefore group them into various categories; some of the most important ones now known or anticipated are the following:

(1) The Hierarchy of More or Less Distinct Objects

(a) *The elementary particles.* These include the protons, electrons, neutrons, neutrinos, mesons, hyperons, and so on; some of which, in the free state, are extremely long lived, while others decay or transform themselves rapidly. For instance the proton is supposed to be stable for periods of over 10^{26} seconds, while the lifetime of the neutron is about 30 minutes, and others decay within minute fractions of seconds. Whatever their lifetime may be, the principal characteristics of these particles are that, as a result of their decay or their interaction with other particles, *all* or *a substantial fraction* of their rest energy mc^2 is being in radiated or absorbed. The investigation of these phenomena constitutes the task of nuclear physics and elementary particle physics.

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Some of the characteristic lengths which enter the theory of elementary particles and nuclear theory are

$$d_{N_1} = e^2/m_e c^2 = 2.8 \times 10^{-13} \text{ cm}$$

and

$$d_{N_2} = e^2/m_p c^2 = 1.6 \times 10^{-16} \text{ cm}$$

where e , m_e , are respectively the charge and the mass of the electron, and m_p is the mass of the proton.

Throughout his thinking such characteristic lengths made up of fundamental physical constants are being associated by the physicist with the various classes of his hierarchy of objects. In some cases, this association is now clearly understood, while it remains obscure in other cases. For instance, we do not yet know in which way the very small length

$$d_G = (G h/c^3)^{1/2} = 4.05 \times 10^{-33} \text{ cm}$$

enters the field of particle physics, if it does at all. In the above equation, G and h are, respectively, the universal constant of gravitation and Planck's constant.

(b) *The atoms.* Neutral atoms are distinct entities consisting of nuclei made up of protons and neutrons surrounded by a number of electrons whose summed-up negative charge exactly compensates the always positive charge of the nuclei. Atoms can be excited or ionized (become charged by losing one or more electrons), emit light, and can be combined into molecules. In contradistinction to nuclear and elementary particle reactions, the energies released or absorbed in these transformations are *small compared with the rest energies* $m c^2$ of the particles involved. The characteristic length most important in atomic physics is Bohr's length:

$$d_H = h^2/4\pi^2 m_e e^2 = 5.3 \times 10^{-9} \text{ cm.}$$

(c) *The molecules.* Analogous to protons and neutrons combining to form atomic nuclei, atoms can combine to build molecules, the difference being that the former are charged. Therefore, with

uranium, nuclei soon reach a limit of growth due to the intrinsic disrupting repulsive forces among the protons. Molecules, on the other hand, could grow indefinitely large were it not for the interference of *extrinsic* destructive effects of all sorts. In addition to the well-disciplined sizes of atoms, based on Bohr's length, an unchecked tendency towards arbitrary sizes enters the field of molecular physics.

(d) *Liquids and crystals.* All matter tends towards aggregation, unless temperature (or kinetic energies of the objects involved) prevents it. On lowering the temperature, a gas or vapor consisting of separate atoms and molecules therefore condenses into a liquid within which the individual particles still have enough energy to exchange places more or less rapidly and thus constitute a chaotic assembly. On lowering the temperature still further, the atoms and molecules get a firm hold and force, so to speak, one another to assume their assigned restricted places from which they can move but little and can completely depart only very seldom. Ideal crystals at very low temperatures thus represent some of the most perfect macroscopic structures known. Ultimate perfection, however, is theirs only in small sizes, since foreign inclusions and mechanical stresses during their growth introduce all sorts of small defects such as mosaic structures⁴ and dislocations.

In parentheses, attention should also be called to the little known fact that, because of the finiteness of the velocity of light, an accurate line-up and spacing of the planes and the elementary cells in crystals may really only be expected within dimensions of Bohr's length, d_{B} , divided by the fine structure constant α , where

$$\alpha = \frac{2\pi e^2}{hc} = 1/137$$

(e) *The range of sizes of liquids, crystals and their combines.* The upper limit of liquid bodies or of solid bodies composed of crystalline conglomerates is determined by the onset of changes due to gravitational forces. We thus can have colloidal particles (or droplets), microcrystals, macroscopic liquid, and solid objects, as well as bodies of the size of the Earth or other planets which may be composed of liquids and solids. But, with the increase of mass, pressures will develop in their centers that will cause various

transformations of matter into denser states—to occur, for instance, the so-called pyknuclear reactions—all of which lead to implosions and explosions and thus become destructive. As for another physical characteristic of the three size ranges of solid bodies, attention should be called to the fact that in microscopic bodies the surfaces play a relatively important part, and the total energy content not only depends on the volume but also on the surface. On the other hand, for macroscopic bodies, the surface energy is negligible as compared with the volume energy. Macroscopic matter is therefore subject to *equations of state* which relate the pressure or specific energy of any part of the object to the local density, temperature, electric and magnetic field, and so on.

(f) *Cosmic bodies.* The most massive solid bodies, such as the Earth and other planets, must be classed as *cosmic bodies*. Generally, however, cosmic bodies are still more massive and include, of course, the stars, the galaxies, and the clusters of galaxies. We shall speak separately about these clusters further on, where we also will discuss the significance of the peculiar fact that, with the clusters of galaxies, the hierarchy ends: there are *no* clusters of clusters of galaxies.

Generally speaking, cosmic bodies are those in which electric and magnetic forces play only a minor role and whose interactions are governed by gravitation.

The transition from macroscopic matter to cosmic matter takes place for solid bodies whose size is about 100 km and whose density is in the order of one gr/cc. At maximum, solid bodies can be charged-up to an electric potential of a billion (10^9) Volts. For greater potentials, the charges would eject each other. Endowed with this charge, two such bodies, 100 km in size, would exert an electric force on each other which is about equal to their mutual gravitational attraction. For larger bodies, the gravitational forces become rapidly more important than any electrical interactions.

(g) *Living organisms.* Attention must be called to the remarkable fact that living organisms are only found in the range of microscopic to macroscopic objects of moderate size. Why these are confined to this group of bodies covering a range of about

10^7 in sizes is not exactly known, although biophysics and biochemistry have already explored a great number of aspects of this remarkable fact. Except for a few incidental remarks, however, we shall not further occupy ourselves with the problems of living matter.

(2) Stars, Galaxies and Clusters of Galaxies^{1, 6, 9}

Since I have occupied myself intensively with these objects in my research, I shall discuss them here at some greater length. My reason for doing so, however, stems especially from the fact that systematic prediction and procedures based on the morphological approach have been particularly fruitful and have resulted in the discovery of many families of entirely new objects. These predictions were based on the simple view that, according to some of the most fundamental laws of modern physics and especially those of the Boltzmann-Gibbs statistical mechanics, matter has a tendency to aggregate either slowly or implosively into ever more compact and massive compounds. And, in so doing, vast amounts of energy are released which cause the dispersion of some matter into the vast cosmic spaces. During the past 30 years the author and other investigators have therefore conducted extended searches which led to the successful discovery of vast amounts of intergalactic matter such as dwarf, pygmy, and gnome galaxies, as well as intergalactic plasmas which give rise to emission of radio waves, X-rays, and cosmic rays.

The quest for compact bodies, on the other hand, led to the conception of neutron stars, ultimate bodies of solar mass and density of hundreds of millions of tons per cm^3 , and to the discovery of pygmy stars and compact galaxies of various descriptions of which the quasi-stellar radio sources (quasars) form but a very small part. Since the spectra of these objects reveal very large *redshifts*, many astronomers have concluded that they are the most distant objects known and that they are receding from us with velocities equal to a good fraction of the velocity of light. Research on the compact galaxies, however, indicates that a considerable part of the red shift may be due to the Einstein gravitational effect. About 3000 compact galaxies have now been assembled in seven lists by the author, and their observation promises to shed much light on the large-scale distribution of matter in the universe and on its evolution.

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It is interesting to note that, in the formation of the ultimate possible stages of cosmic matter (that is, neutron stars*) in extremely compact galaxies, amounts of energy are released which again are comparable to their rest energy, just as it is the case in the interactions of the elementary particles and nuclei. It is, for instance, conjectured that the collapse into neutron stars can account for the enormous energy releases in supernova outbursts, which at maximum light are of the luminosity of about 5000 million suns. Likewise, implosive processes in extremely compact galaxies may release amounts of energy of up to 10^{66} ergs and are capable of causing whole stellar systems, containing millions of suns, to be projected into space with velocities of thousands of kilometers per second.

In the six volume *Catalogue of Galaxies and Clusters of Galaxies*¹³, which the author and his collaborators have been constructing during the past 30 years, about 10,000 rich clusters of galaxies have been listed. Some of these contain as many as ten thousand galaxies, and they represent the largest aggregations of matter known to us. The rich clusters occupy on the average a volume in space the linear dimensions of which are of the order of 150 million light-years. If the force of gravity between two bodies separated by the distance r were strictly proportional to $1/r^2$, we should, from the theory, expect to find clusters of clusters of galaxies. Since these do not seem to exist, we must conclude that the force of gravity rapidly ceases to act when the distances become greater than 150 million light-years.* If this is really true, we must conclude that the general theory of relativity is not quite correct, but needs serious modifications.

*I first suggested the concept of neutron stars in a physics seminar at the California Institute of Technology in 1932 and later worked out the theory of a simple model of throughout constant density¹⁰ for which I derived the following elementary results: First, the (negative) potential energy for this model differs only a few percent from the same model treated by the classical theory of gravitation. Second, the velocity of light on the surface of this neutron star is one-ninth that in empty-field free space. And most important, third, the redshift $\Delta\lambda$ of light of the wavelength λ emitted from the surface to infinity is $\Delta\lambda/\lambda = 2$. This result, derived 30 years ago, promises to be of interest in explaining the fact that the greatest red shifts from the most compact galaxies and the quasars congregate in the neighborhood of the value 2, deviations being easily explainable by varying the model to one with a more realistic density distribution such as those which may be expected in ultimately compact galaxies or *neutron star-studded compact galaxies*¹¹: a concept which I proposed a few years ago¹² which is now being promoted also by others.

*All figures given here for large distances are so-called indicative figures, derived on the assumption that a red shift of 100 km/sec corresponds to 10^6 pc distance.

THE PHYSICAL PHENOMENA IN THE UNIVERSE**Generalities**

In classical physics it has proved convenient to talk about space, matter, and phenomena in space, in order to formulate our various theories about the outer world. We shall first say a few words about space and the "geographical" distribution of the various types of matter in space which we have discussed in the preceding.

Space

Scientists and philosophers of old, including Immanuel Kant, assumed that there is only one type of space, the so-called *Euclidean flat space*, until the mathematicians proved that there are many types of space possible. Whether or not we live in a flat or a curved or a possibly expanding space remains for the future cosmologists to decide on the basis of decisive experiments and observations. Attention should also be called here to the fact that our use of a three-dimensional space in our thinking is not trivial but based on certain performance characteristics of our mental senses.

Animals do not possess these characteristics: in communicating with one another, they must operate in a "space of at least ten dimensions." If they agree to meet in a given spot at a given time, they must transmit ten signals to each other, while we need only four.

Furthermore, it is also not self-evident and not really absolutely necessary that we should formulate our communicable knowledge in terms of a continuous space. We could just as well use a "granulated" space made up of discrete elements. This only to emphasize again that the facts which we formulate for preservation or for transmission to others are really highly logical structures.

The Geography of Cosmic Space¹⁴

The geography of the universe has been explored through the ages in a more or less haphazard way. Luckily, there appeared

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three giants of the mind who opened up the correct vistas for us. At least one more step will have to be performed to inform us about the integral structure of the universe, but this fourth giant to help us out is not in sight.

These three great giants of the past are Aristarchus (320-250 B.C.), Giordano Bruno (1548-1600), and Knut Lundmark (1889-1958) whom I was lucky enough to know and count among my best friends.

Aristarchus conceived the Sun and planets as being bodies in space. He was the first to devise rigorous methods for the determination of the distances of the Moon and the Sun from the Earth, and he thus became the master surveyor of the planetary system. Unfortunately, the dark ages followed and his methods were carried out with precision only 17 or more centuries after Aristarchus.

Giordano Bruno conceived the stars as being bodies outside of the planetary system and occupying the vast space of the Milky Way which he envisioned as an immense galaxy of stars.

And finally, around 1918, Knut Lundmark recognized the existence of myriads of stellar systems or galaxies far beyond the confines of the Milky Way. He also proposed and developed different methods for the determination of the relative locations of the galaxies in cosmic space. As a first result, he derived the distance of Messier 31, the great nebula in Andromeda, to be 650,000 light-years, equal to about six times the diameter of our own galaxy.

Lundmark furthermore suggested a possible relationship between the red shifts in the spectra of galaxies (or their symbolic velocities of recession) and their distances. This velocity-distance relationship, if correctly implemented, promises to furnish important information on the structure of the universe.

The Multiplicity of Physical Phenomena in the Universe

As mentioned before, it is, for communication of knowledge and for teaching purposes, advisable and even necessary to divide the physicochemical phenomena into groups although the delineation

between these may not always be very sharp. For my own purposes, I have generally used the following classification:

- (1) Kinetic and dynamic phenomena
- (2) Elasticity
- (3) Heat
- (4) Electricity
- (5) Magnetism
- (6) Gravitation
- (7) Optical phenomena or electromagnetic radiations in general
- (8) Chemical phenomena
- (9) Nuclear and elementary particle phenomena
- (10) Intrinsic structural behavior of the elementary particles.

To be sure, these categories will not exhaust all the natural physical phenomena possible. For instance, we are certain that there are *gravitational waves* or *shocks* travelling through space. But, since we cannot as yet record them, not much can be said about them. Furthermore, we shall probably find that space has structure all over: for instance, granulation associated with the mysteriously small length,

$$d_0 = (G \cdot h/c^3)^{1/4} = 4.05 \times 10^{-33} \text{ cm}$$

mentioned earlier which we expect to be associated with some sort of zero-point energy of space and with various energy transformations.

It is a most fundamental fact that energy content is associated with the various phenomena which we have enumerated. Considering only the ten phenomena listed, we thus have ten types of energy contents; namely, $E_1 =$ kinetic energy, $E_2 =$ elastic energy, and

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so on until we come to $E_{10} = m c^2$ which is equal to the rest energy of any of the particles involved. It would, of course, be nonsense to talk about these various types of energy if they could not be transformed into one another. For instance, if $m c^2$ could not be transformed into radiation, it would be academic to call it an energy, although dimensionally it would symbolically be $M L^2 T^{-2}$, as the regular kinetic energy. We therefore call energy any intrinsic content of any phenomena mentioned which can be released in one way or another to set a body in motion relative to that system of reference in which it was originally at rest.

The Morphological Totality of Energy Transformations

In quantitatively measuring the intensities of the ten phenomena listed in the previous section, the fact that *energy contents are associated with them* is of prime importance. Two simple examples may be mentioned. First, to measure gravitational force or change of gravitational energy we may put a mass, m_1 , on a spring balance attached to another mass, m_2 , for instance the Earth. The spring is thus being compressed and the elastic energy stored in it measures the change of gravitational potential energy of m_1 . The same can be done to measure an electric charge, e_1 , in terms of another, e_2 , to which it is attached by a spring. Compression of the spring, or storing of elastic energy, is therefore achieved through release of gravitational potential energy in the one case and through release of electrostatic energy in the other case.

Confining ourselves to the ten phenomena (1) to (10) with energies E_1 to E_{10} associated with them, we can thus visualize 100 types of energy transformations $E_i E_k$ with i and k assuming each the value of 1 to 10. If we add the energy of gravitational waves E_{11} and the E_{12} associated with the granulation of space, we shall have $12 \times 12 = 144$ energy transformations.

The study of the energy transformations is of the greatest importance to theoretical, experimental, and applied physics. I am therefore in the process of writing two books which should have been written long ago: namely, one on the Morphology of Energy Transformations and a second on The Morphology of the Devices which are capable of achieving the various energy transformations most efficiently. The first book will contain exactly

300 examples illustrating in a simple way the importance of every one of the 100 energy transformations acting respectively in the microscopic, in the macroscopic, and in the cosmic world.

I cannot emphasize strongly enough that this type of morphological approach not only automatically leads to the visualization and formulation of new problems, as well as to the solution and deeper understanding of old problems but also it is at the same time the Royal Road to new inventions.

THE UNIFORMITY OF OBJECTS AND PHENOMENA THROUGHOUT THE UNIVERSE

Two of the most amazing conclusions which have been derived from astronomical observations and terrestrial experiments are the facts that the composition of matter throughout the visible universe is the same and that the phenomena governing the interactions of the various constituents are the same near and distant as far as we can see. Indeed, the spectra of the most distant objects show that matter there is composed of the same atoms we know of on Earth and that the ratios of the wavelengths emitted by different atoms, ions, and excited states are the same as those on the Earth. Although some investigators still contend that some (half) of the objects in the universe might consist of antimatter (negative protons and positive electrons), this is quite impossible as I have already shown in 1935¹⁵. Indeed, if this were true, γ -rays of 10^{12} to 10^{20} eV would have to be abundant in cosmic rays, but they have never been found. Curiously enough, the build-up of the universe is *therefore fundamentally asymmetrical*, all stationary matter being built of positive protons and negative electrons, and none of negative protons and positive electrons.

The uniformity of the universe is not only evident directly in the structure and the physical characteristic of stars, supernovae, galaxies, and clusters of galaxies at all distances but also more exactly in the equality of the various fundamental constants of nature or, rather, the dimensionless combinations that may be formed with these constants.

For instance the fine structure constant $\alpha = 2\pi e^2/hc = 1/137$ appears to be the same everywhere, as is evident from the ratios

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of the wavelengths of certain spectral lines as observed in terrestrial light sources and the light from distant compact galaxies. Furthermore, the velocity of light and Planck's constant h characteristic for the quanta of this light are the same, irrespective of whether its source is on the Earth or on a very distant galaxy, as I have shown by direct experiment (observing large red shifts with prism and with grating spectrographs on the one hand and comparing the yearly aberration angle of stars and distant galaxies on the other hand)¹.

Finally, experiments have been performed which testify to the equality of the absolute values of the charges of the proton and the electron to one part in 10^{21} , to the independence of their charges up to velocities equal to $0.1 c$ to one part in 10^{17} , to the equality of the inertial and gravitational mass to one part in 10^{22} , to the stability of the proton in a lifetime of 10^{26} years, to the constancy of the ratio $Gm_p m_e / e^2$ between the gravitational and electric attractions of the proton and the electron to one part in 10^9 over the period of a year, and to the constancy of the electric charge with respect to the nuclear interaction strength to 1% in 10^9 years.¹⁶ A number of additional tests, however, will be necessary to ascertain that all dimensionless ratios of the known physical constants and ratios of new constants yet to be found remain invariable with time. It is generally thought that beyond time, length, and mass or momentum there are no other dimensionalities. It is obvious, however, that angle must be used as an additional one, otherwise no space could be constructed at all, and there could not exist any identifiable objects¹. Beyond this, as I have shown from a fundamental analysis of the concept of dimensionalities, several new ones still remain to be introduced if we are to achieve a satisfactory integrated theory of all natural phenomena¹. This then remains the task to be dealt with before we will achieve a unified-field theory and an understanding of the nature and properties of the elementary particles, as well as of large scale phenomena such as the red shift from distant galaxies and the nonexistence of clusters of clusters of galaxies.

BASIC CONCEPTS OF PHYSICAL THEORY

As was said in the beginning, if we are to develop theories, i.e., constructs which are communicable and with which we can transmit information about the universe to one another, we must make

use of certain basic elements of thought and procedure about which all of those interested can agree, e.g., just like in playing chess. Some of the concepts which have been developed in this endeavour are the following.

Strict Causality vs. Uncertainty Principle

Classical physics assumed that the succession of all physical events is a unique and determined one and that all parameters can be measured with any desired accuracy, limited only by the imperfections of our recording devices and our mode of experimentation. Since classical theory did not allow us to bring all phenomena under one hat, quantum mechanics introduced the notion of uncertainty. According to this the position x of a particle and the corresponding mechanical momentum, p_x , can not both be determined simultaneously and accurately as classical mechanics claims. If x is measured with a precision Δx , then the smallest possible error in p_x is given by $\Delta x \cdot \Delta p_x = h$, where h is Planck's constant. Although this has now been accepted as a fundamental principle, I think I have shown that it is not the end of the road concerning the problem of causality¹.

Distant Action and Close Action Theory

A satisfactory theory of electromagnetism can be constructed by starting from the fact that two electric charges, e_1 and e_2 , at rest and separated by the distance r represent a system of the potential energy $e_1 e_2 / r$ or that they exert a force equal to $e_1 e_2 / r^2$ on one another. Any participation of the intervening space may be disregarded. On the other hand, we may think of this space as being the seat of an inhomogeneous electric field, E , representing per unit volume an energy content, $E^2 / 8\pi$, corresponding to the presence of hypothetical stresses first introduced by Maxwell. Or, again, we may consider the Coulomb interaction between the charges as being brought about by the continuous interchange of some "particles"—in this case, of light quanta. Depending on the case at hand, one or the other mode of expressing facts is easier to handle mathematically, more or less easy to communicate and more or less fruitful in enabling us to make new discoveries and inventions.

The Particle Nature and the Wave Nature of Matter

In classical atomic theory, particles were considered somehow as sharply limited tiny objects until de Broglie showed theoretically that with each particle of mass m and velocity v a wave characteristic of wavelength h/mv should be associated, an assertion which was soon verified by Davisson and Germer through reflection-diffraction of electrons on nickel single crystals. Since then, the wave theory of matter, in conjunction with the quantum (matrix) mechanics, has led to the well-known enormous progress in our knowledge of the atomic world.

To laymen, all of these abstract schemes of thought may appear incomprehensible, but in some way they are analogous to the development of the numerous sophisticated languages which men have developed to communicate with one another. And just as one language may be superior to all others in expressing this or that thought, vision, emotion, or fact, the different concepts of the different frames used in theoretical physics also serve different purposes more or less efficiently.

FUTURE OUTLOOK

From the experiences made in the past, it is certain that man's imagination is not powerful enough to devine all of the possible objects (whether elementary, microscopic, macroscopic or cosmic) which still remain to be discovered. But it is certain that the morphological approach will be of the greatest help in the discovery and investigation of new objects and phenomena^{1, 3, 6, 7}. Terrestrial physics of course has been enormously advanced through the construction of powerful elementary-particle accelerators, the invention of the masers, the lasers, and the use of computers, as well as the discovery of the Mössbauer effect and other phenomena that make possible an unheard of increase in the precision of innumerable fundamental experiments. Similar breakthroughs in the recording of neutrinos and gravitons¹⁷ are expected.

The search for intergalactic matter, supernovae, flare stars, pygmy stars, neutron stars, nuclear goblins¹⁸, quasars; blue, red,

and infrared extremely compact galaxies, both variable and stationary—will be immensely helped because of the development of image tubes, photoelectronic telescopes¹⁹, radio telescopes and the possibility of recording, in high altitudes, infrared and ultraviolet radiations, x-rays, γ -rays, and cosmic rays. In sight is still faster and safer recording than that obtained with image tubes, through the development of photographic emulsions containing colloidal particles of explosives that promise to increase the quantum efficiency of light far beyond the limits set by the background noise of electronic devices¹.

I also wish to emphasize again, as I have^{20, 2} been doing for 30 years, when I built the first mosaic objective grating for the 18-inch Schmidt telescope, that the construction of full-size transmission gratings for even the largest Schmidt telescopes is now in sight. Such gratings will allow us to make discoveries of new objects at an unprecedented rate and also to produce plates for the storage of immense spectrographic information on millions of celestial objects which will be invaluable.

And, last but not least, we must not forget the new means of space exploration which are now at hand for the observation of and the experimentation with extraterrestrial objects. Although I am one of the earliest space enthusiasts, who in a small way was actually the first² to start the Space Age with my attempt in 1946 at launching of artificial meteors into space and my successful result on October 16, 1957, I shall always urge all those involved not to go overboard and waste funds and manpower on unnecessarily complicated devices. In other words, what we can do well on the Earth we should do from here. What can be done from high flying balloons should be done from them, rather than from space vehicles. The relative results on the atmosphere of Venus achieved by Prof. John Strong, with high flying balloons, and the outrageously expensive Mariner Spacecraft respectively are clearly cases in point. Furthermore, many observations can be made from moderately high-flying Earth-launched rockets and from orbiting satellites. Unmanned and manned vehicles to the Moon and the planets should only be used for those observations and experiments in physics, chemistry, biology, medicine, and so on, which simply cannot be done in any other way²¹; otherwise the general public and the agencies supporting the various types of space research might, in the end, refuse to provide the necessary funds.

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VI

The Andean Man

Dr. Alberto Hurtado*

There is a discrepancy among historians in regards to the place of origin and the migration path of the early inhabitants of the American hemisphere. But there is definite archeological evidence that the Andean region of Peru has been populated for milleniums. Cardich,¹ a Peruvian anthropologist, has found human skeletons in Lauricocha, near Cerro de Pasco, at an altitude of 4,200 meters. When submitted to radioactive carbon investigations, these skeletons proved to have an approximate age of 9,500 years. More recently, Engel² has observed in Chilca, at about 4,000 meters, remnants of human life dating back 9 to 10,000 years.

Monge³ has pointed out that some aspects of the political, as well as of the administrative, organization during the centuries of Inca Civilization, and also later on of Spanish domain, were directly related to the influence of a high environment on individuals and society. Even at the present time, when the extensive Andean region of Peru has a population of about 6,000,000 inhabitants, social habits and health problems reflect, in large part, the environmental characteristics.

Although there are several factors (such as temperature, air density, humidity and solar radiation) which operate at altitudes over 3,000 meters, it is generally accepted that *hypoxia*, or oxygen deficiency, is the most important one. This condition consists of a lowering of the saturation of oxygen in blood hemoglobin and in a decreased tension of the small fraction physically dissolved in the plasma, as a consequence of the low partial pressure of oxygen in the inspired air. Under these circumstances, there are difficulties

*High Altitudes Research Institute, Peruvian University "Cayetano Heredia," Lima, Peru.



Figure 1. Photograph of a Peruvian Indian native living in Puno, at an altitude of 4,300 meters.

in its diffusion at tissue level and its utilization by the metabolically active cells. When the degree of hypoxia is severe, as it occurs at altitudes which exceed 4,000 meters, there is a need for compensatory processes which are of varied nature: morphological, functional, and chemical. From investigations carried out in recent decades, it has become evident that these adaptive processes reach their highest efficiency in the man born, raised, and living permanently in high environments. These processes have been grouped under the term *natural acclimatization*, in contrast to the term *acquired acclimatization* which refers to the tolerance observed in newcomers after a prolonged time of residence.

In addition to the historical facts already mentioned, this opinion is based on experimental data.⁴ Velasquez has observed that the Indian natives of the Andean zone when subjected, in low pressure chambers, to simulated altitudes, were able to tolerate much higher levels than men who live constantly in lowlands. At 10,000 meters, a large proportion of them retained useful consciousness. We have also found that these natives have a high degree of tolerance to physical activity in spite of the fact that this stress demands a large increase in oxygen supply and consumption.

It is interesting to point out that according to recent observations the degree of hypoxia at a given altitude is not constant. Body posture, sleep, and physical activity introduce a marked variability in the amount of oxygen transported in the circulating blood, from the lungs to the tissues, and this phenomenon is more marked as the altitude becomes higher.

It would not be possible in this brief time to mention and discuss in detail all the adaptive processes which are responsible for the relative *steady state* which characterizes natural acclimatization and its very high efficiency, but some general considerations may possibly give us an appropriate understanding.

The adaptive processes fall into two categories: (1) those which act along the total pO_2 gradient, from inspired air to mixed venous blood, introducing a large economy in the fall of the gradient; and (2) the ones which operate at tissue level, favouring the acquisition and utilization of oxygen.



Figure 2. Native residents playing soccer football in Tielio, Peru, at an altitude of 4,800 meters.

In the first group, we have to consider hyperventilation, reduced A-a gradient for oxygen, polycythemia, modifications in the blood acid-base balance, and changes in the affinity of hemoglobin for oxygen. There is still some controversy concerning the pathogenesis of some of these processes, and this is especially true in regards to the increase of pulmonary ventilation which occurs at high altitudes, at rest and during exercise, both in the resident and in the newcomer. Some investigators are of the opinion that hypoxia *per se* does not constitute a stimulus to the respiratory center activity. From a considerable number of observations, we are inclined to think that this opinion is not exactly correct, although it is evident that the most important factor for the development of hyperventilation is the presence of a hypersensitivity of the center to the stimulation of the blood CO_2 tension. The ventilatory response curve to CO_2 is shifted to the left when plotted against the tension of this gas.

The decrease observed by us in the oxygen gradient between alveolar air and arterial blood is probably related to the increased ventilation, modifications in the ratio with perfusion, the larger size of the alveoli (residual air volume is higher than at sea

level), the greater caliber of the lung capillaries and perhaps some other factors still under investigation.

The polycythemia at high altitudes, known since the last century from the original observations in the Peruvian Andes, is a consequence of a more active erythropoietic activity which has been observed in histological studies of bone marrow biopsies and in investigations of iron metabolism. The precise interaction between hypoxia and erythropoietin still awaits further elucidation. The absolute increases in red cell and hemoglobin volumes are responsible for the higher content of oxygen in the arterial blood, in spite of the reduction in saturation.

The real significance of polycythemia as an adaptive process is open yet for a definite interpretation, because an apparently good tolerance to a high-altitude environment is not infrequently associated with a low level and, at times, even an absence of polycythemia.

The blood acid-base balance in high-altitude residents is characterized by a normal pH, as the low CO₂ content and tension are compensated by a proportional decrease in the bicarbonate.

Our observations seem to confirm that the oxygen dissociation curve is shifted to the right at high altitudes, indicating a lower affinity of hemoglobin for this gas. This favors its diffusion to the tissues.

The proper understanding of natural acclimatization to high altitudes has been greatly facilitated by rather recent contributions which have shown that at tissue level there are important adaptive processes. Early, indirect evidence of this fact came from the repeatedly confirmed observations that natives living permanently in such environment have a much lower lactate and pyruvate accumulation in the blood during severe physical activity.⁵ Some years before, however, an increase of myoglobin in the muscles of dogs born and reared in high places had been demonstrated;⁶ a similar finding was later made in human biopsies, together with the demonstration of significant modifications in the respiratory enzymatic processes.⁷ In addition, a greater number of capillaries per unit of tissue has been observed,⁸ thus facilitating the diffusion of oxygen.

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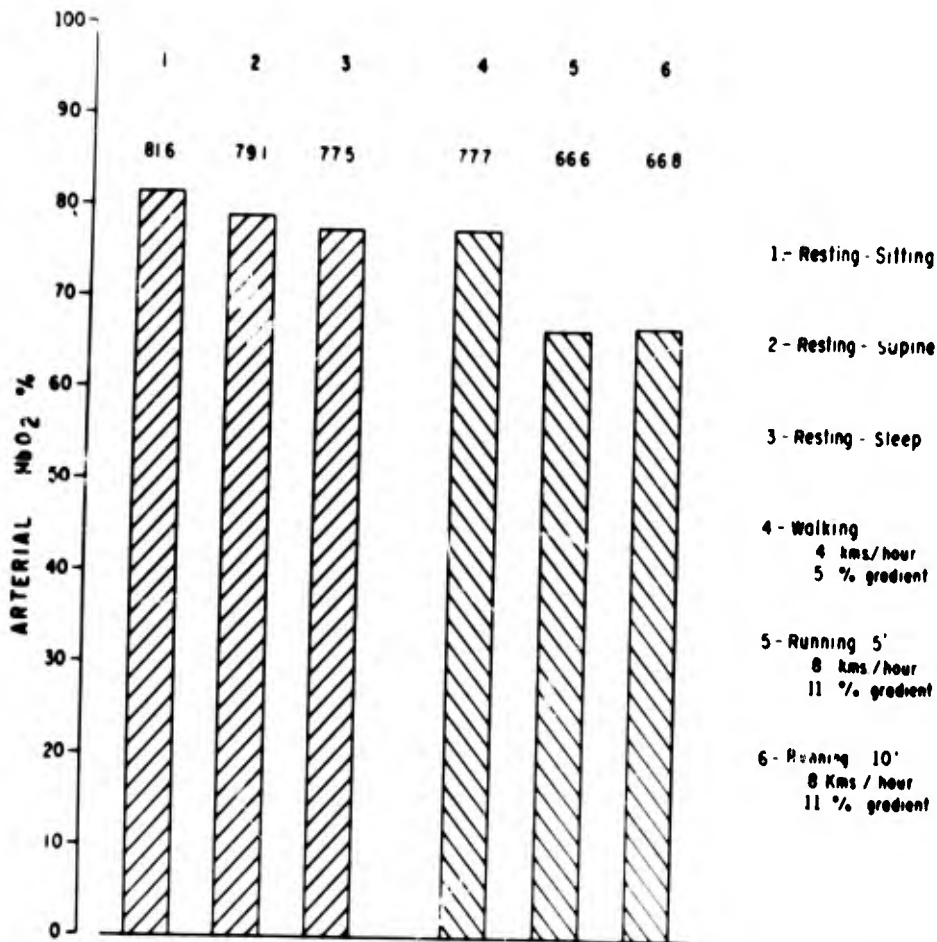


Figure 3. Mean arterial blood oxygen saturation in different experimental conditions.

Observations made in Cerro de Pasco, at an altitude of 4,300 meters.

It is our feeling that this field of investigation, tissue chemistry and cell morphology, has still much to offer in explaining body responses to lowered partial pressures of oxygen in inspired air, especially from the point of view of the real differences in the degree of tolerance which corresponds to natural versus acquired acclimatization.

High-altitude research attracted only the interest of physiologists until recently; but, when attention was directed to the study of permanent populations such as the Andean man, it became evident that such an environment also exerts influence on the

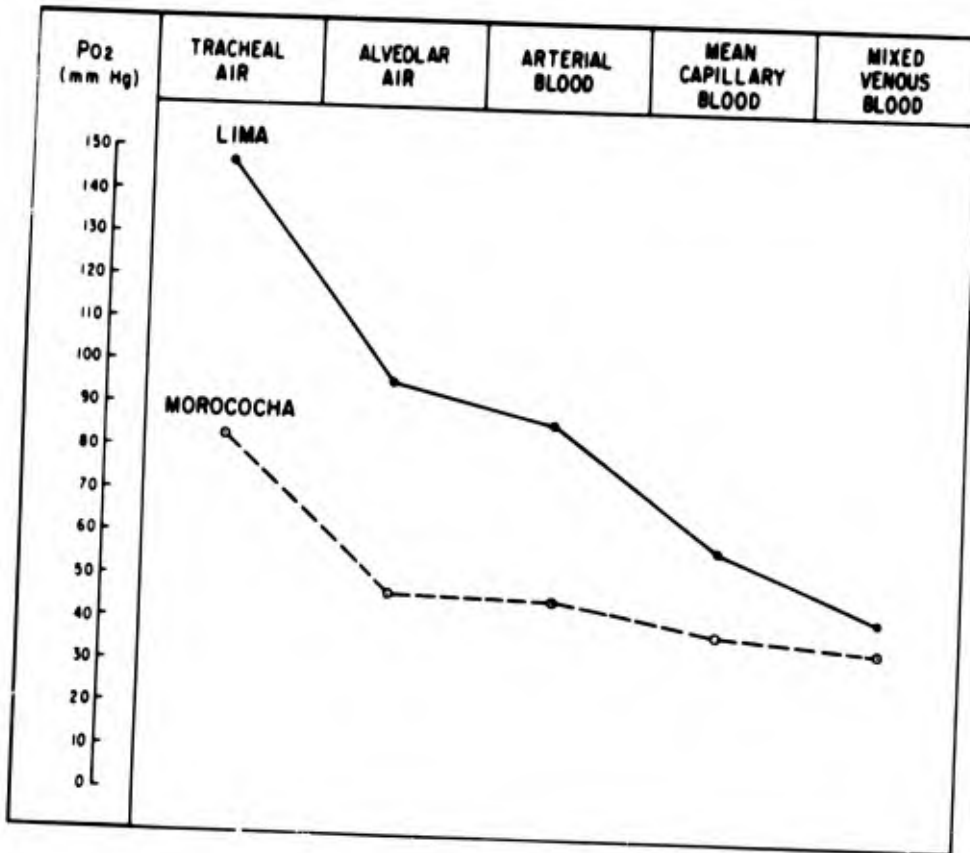


Figure 4. Mean pO_2 gradients, from inspired air at tracheal level to mixed venous blood, in native residents of Lima (sea level) and of Morococha (4,540 meters). Alveolar air, arterial blood, and mixed venous blood (from the pulmonary artery) were obtained simultaneously at rest in the recumbent position. Mean capillary blood pO_2 calculated.

incidence and evolution of certain diseases. Consequently, pathological physiology was added to physiology. The first important contribution in this field was the observation made by Monge⁹, in 1928, that a high-altitude native may eventually lose his acclimatization at any age, developing a symptomatology chiefly related to alterations in the nervous system. Later studies¹⁰ revealed that the pathogenesis of this syndrome, known as Chronic Mountain Sickness or Monge's Disease, is based on the respiratory center's loss of sensitivity to regulatory chemical stimuli. The resulting hypoventilation increases the severity of the hypoxia which, in turn, stimulates further the erythropoietic hyperactivity.

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In 1956, it was originally found¹¹ that residents of high altitudes have a higher level of pulmonary blood pressure, and this finding was later confirmed in a greater number of observations, which included young infants.¹² The significance of this moderate pulmonary hypertension, which has been related to anatomical characteristics of the lung arterioles,¹³ is not well understood. It may contribute to the effectiveness of the alveolar blood gas interface.

Another interesting clinical aspect of high altitudes refers to the not infrequent occurrence of pulmonary edema. The first such case in the literature, reported by us¹⁴, dates back to 1937; since then, a large number of cases have been described, especially in connection with the conflict between India and China in the Himalayan region. Most subjects afflicted were high altitude natives, without previous symptomatology, who returned to the high environment after a brief sojourn at sea level. It is possible that the polycythemic condition and the moderate degree of pulmonary hypertension (which persists for some time after descent) are factors which increase lung capillary permeability in the presence of an acute hypoxia. Physical activity during the first few hours of exposure predisposes to such a clinical episode.

A high-altitude environment is also responsible for modifications in the incidence, evolution, and prognosis of diseases well known at sea level. Reports have been made concerning a higher incidence of liver and gall bladder pathology, intestinal volvulus after surgical intervention, gastric ulcer, etc. Cancer incidence appears to have some clinical peculiarities: One of these is the almost complete absence of leukemia, and this interesting fact has also been observed in animal experimentation.

It is important to mention that silicosis, an occupational disease, constitutes a serious and a frequent problem in the mining industry of the high Andean areas. This high incidence is probably due, along with other factors not known at the present time, to the constant hyperventilation which results in a heavy inhalation of silica particles in a contaminated environment. On the other hand, attention has been called to the low incidence of systemic hypertension, coronary disease, congenital heart defects, diabetes, etc.

In conclusion, a few general remarks are pertinent. A high-altitude environment is an excellent physiological and clinical laboratory which still has much to offer to investigators, in spite of the fertile and active work of recent decades. Acclimatization is largely but not completely understood. Some of the adaptive processes are still under controversy in regards to their pathogenesis, and others demand intensive research. As an example, we may mention the almost complete absence of genetic observations. An exposure which may be rated in milleniums and countless generations must, undoubtedly, be related to inherited traits. The Andean man still awaits for this approach. Further study of him will also give the most appropriate concept of what constitutes acclimatization to high altitudes. Not infrequently such a process is appraised in terms of a few, and even single characteristics, and from the point of view of the variability of what is previously observed at sea level. It seems more logical to think of acclimatization as representing a harmonious integration of many processes of different nature and to define its efficiency in terms of similarity to what is found in the man who is native to this environment, because he is the one best adapted.

It is also worth mentioning that we do not have yet a defined concept on the maximal altitude level compatible with tolerance of the human body. This question has more than a theoretical significance. Not infrequently observations are carried out in low-pressure chambers at simulated levels of altitude which, no doubt, exceed physiological reserves. In such cases, it is incorrect to relate the data obtained to acclimatization; it rather corresponds to deterioration and collapse.

It is worthwhile to insist in the concept that a high-altitude environment is no longer in the domains of only strict physiological research. Hypoxia is not an exclusive characteristic of exposure to a low barometric pressure. In many clinical entities at sea level, hypoxia occurs as a consequence of alterations in the acquisition, transport, or utilization of oxygen and it is responsible for variable symptomatology. It is logical then to assume that the clinician is interested in learning how the human body may best tolerate, or compensate, such a serious condition. The best answer to this useful inquiry may be found in the study of the high altitude native.

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Finally, it seems appropriate here to mention that oxygen administration and utilization problems are also involved in the conquest of space. From a distance point of view, the high altitude resident is far from the sea level inhabitant, but the space traveller is even much farther. But, from a scientific aspect, both have, at least in some degree, several common problems.

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VII

Supersonic and Hypersonic Flight

Raymond L. Bisplinghoff*

The supersonic airplane became a practical reality on October 17, 1947 when Capt. Charles E. Yeager flew the rocket-powered research airplane X-1 slightly faster than the speed of sound. That event was the culmination of an intense period of aeronautical research and development during and after World War II, and it marked the beginning of a new epoch in powered flight.

In the years since the flight of the X-1, aeronautical engineers have almost continuously examined the practicability of commercial aircraft that would fly faster than the speed of sound. Such studies have become more pertinent in recent years with the successful employment by the airlines of high-speed subsonic jet transports.

These studies reflect the traditional evolution of air transportation toward higher cruising speeds. Anyone who has considered this long-term trend has wondered if it would be finally halted at velocities approaching the speed of sound. There now appears to be no valid technical or economic reason why the trend should not continue well into the range of supersonic and hypersonic flight.

In such large and expensive undertakings as supersonic and hypersonic air transportation, technical questions cannot be separated entirely from those of economics and politics. The supersonic transport, or SST, has been the object of considerable public debate in the United States, and that debate promises to become

*Department Head, of Aeronautics and Astronautics, School of Engineering, Massachusetts Institute of Technology, Cambridge, Mass.

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even more intense. It is proper that any undertaking which requires large expenditures of public funds should be questioned and debated and that of its usefulness to, and effects on, society should be assessed fully. As we enter the era of supersonic and hypersonic flight, we enter a period in which public funds will be required on a large scale. It will therefore be an era in which progress will be measured not so much by what can be done technically, but by what projects the elected representatives of the people will be willing to support.

As futuristic as supersonic and hypersonic flight may seem, they actually represent the next step in a development that has taken place over many years. Space stabilized ballistic projectiles such as artillery shells have long operated at supersonic velocities in the atmosphere. World War II stimulated intense research into rocket propulsion and the aeronautics of supersonic flight, and, on October 3, 1942, a German V-2 rocket became the first, actively controlled, fin-stabilized vehicle to achieve supersonic velocities. Thereby, the V-2 demonstrated that a vehicle with active controls could remain stable in flight through and beyond the transonic range. Five years later the testing of the X-1 demonstrated that supersonic manned flight was possible.

Since then, a variety of military aircraft, including the record holding X-15, the A-11, and the B-70 have made supersonic flight seem almost routine. It remained for the French and the British, however, to make the first definite commitment to build a supersonic airplane for commercial service: the Concorde which should be ready for its first flight some time this summer.

The distances between major world cities are of such magnitude that speeds well into the supersonic and hypersonic range can offer distinct advantages to travellers. The graph of Figure 1 shows curves of total trip time as a function of cruise Mach number with range as a parameter.¹ It is based on the assumption that ground transportation and hold times are 2 hours and average accelerations are 0.2 g. With subsonic jet transports, total trip time for the passenger is longer than a working day when distance exceeds about 3,000 nautical miles. When the first generation supersonic transports come into being, a journey of 2,000 to 3,000 miles will require only half a working day. If we accept a half a day as being a desirable trip time, the hypersonic transport can provide

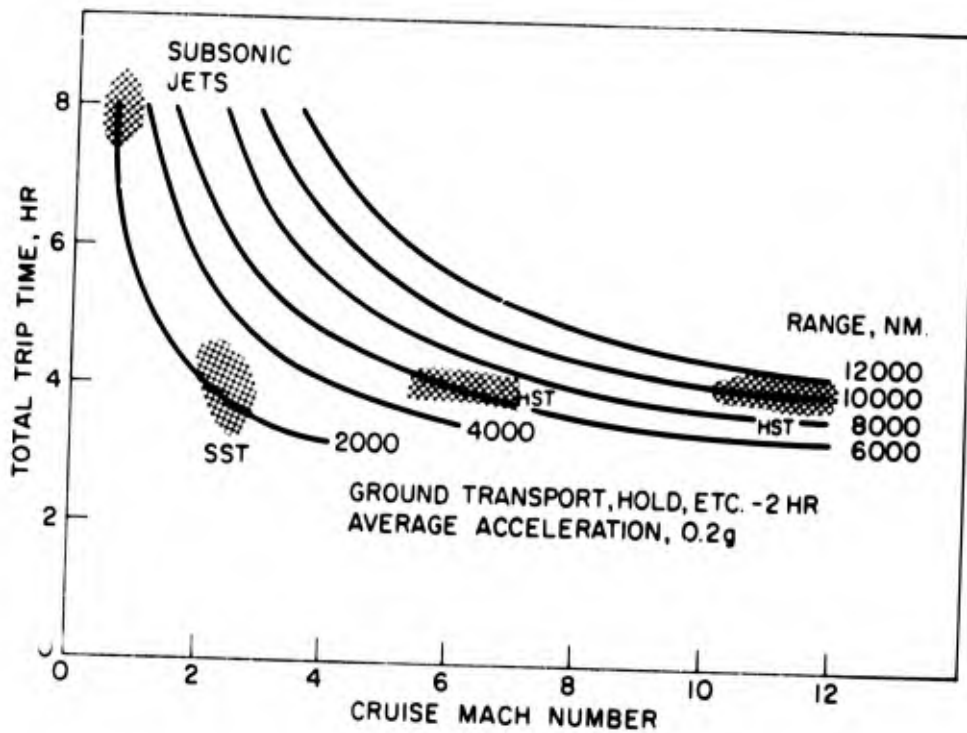


Figure 1. Cruise Mach number.

transportation over many thousands of miles without increasing travel time. A sizeable step beyond the first generation supersonic transport would be the capability to transport passengers hypersonically over 5,000 to 6,000 nautical miles, or from San Francisco to Tokyo, cruising at Mach numbers of five to six. The next stride in capability might be a 10,000 nautical mile journey, or from San Francisco to Melbourne or from New York to Capetown, at Mach numbers of 10 to 12.

The design of every airplane makes use of a principle laid down some 60 years ago by the French engineer Louis Breguet. Breguet showed that the range of an airplane, or the maximum distance it can travel, depends on two main factors: (1) flight efficiency, and (2) the ratio of fuel weight to gross weight, at

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the start of the flight. The following equation is known as the Breguet range equation:

$$\text{Range} = \text{Flight Efficiency} \times \log \left(1 + \frac{W_F}{W_L} \right)$$

where

$$\text{Flight Efficiency} = (M) \left(\frac{L}{D} \right) (\text{Isp})$$

and where

M = Mach number of cruising flight

L/D = Lift-to-drag ratio of airplane in cruising flight

Isp = Specific impulse of engines in cruising flight

W_F = Weight of fuel on board at start of cruising flight

W_L = Weight of airplane at end of cruising flight

Breguet conceived of the flight efficiency as being a composite measure of the aerodynamic and propulsive efficiencies of the airplane. It is represented by a numerical quantity calculated by multiplying the Mach number of flight, *M*, times the lift-to-drag ratio of the airplane, *L/D*, times the specific impulse of the engines, *Isp*. The economic future of supersonic and hypersonic flight is dependent on the success of aeronautical engineers in providing the highest possible value of this quantity.

It is apparent from Breguet's equation that, if everything else remains the same, flight efficiency increases with increasing Mach number. This is one of the principal reasons why very high speed flight is attractive to engineers.

The second component of flight efficiency is lift-to-drag ratio of the airplane. Figure 2 illustrates the variation of lift-to-drag ratio with Mach number over the speed range from subsonic to hypersonic flight based on today's state of technology.^{2, 3} This diagram shows a marked reduction of lift-to-drag ratio in the vicinity of Mach number one and a tendency to level off beyond Mach number five.

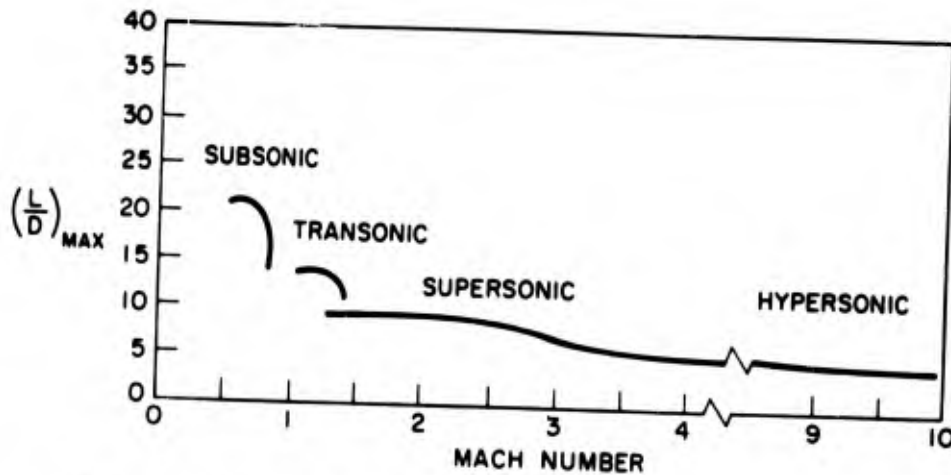


Figure 2. Variation of maximum lift to drag ratio with Mach number.

Since supersonic and hypersonic aircraft must pass through all speeds below their cruising speed during part of each trip, the advantages of variable geometry to optimize the aerodynamic efficiencies over the speed range are evident.

The concept that an overall efficiency of a variety of vehicles could be measured in terms of the product of vehicle velocity times lift-to-drag ratio was suggested by Karman and Gabrielli.¹ They postulated a limit line on a graph of V vs L/D which provides a design envelope. The equation of the line suggested by Karman and Gabrielli is speed in knots \times lift-to-drag ratio = 7500: in other words, the most efficient ships, submarines, and aircraft have about the same product of $L/D \times V$. Large bulk-ore carriers, supertankers, and the new jet transports, as well as the supersonic transport, lie above the Karman-Gabrielli limit line and appear to fall on a line with an equation of $V \times L/D = 10,000$. This extended line passes through a reasonable combination of L/D and V for a large hypersonic airplane at Mach Six.

The third factor in Breguet's definition of flight efficiency is that of the specific impulse of the engines which measures the

pounds of thrust per pound of fuel burned per second. To obtain good specific impulse over the whole range of operating conditions from subsonic to supersonic and hypersonic flight, the engine designer is face with the same incompatible flight conditions as the aerodynamicist. At subsonic speeds, thrust is produced most efficiently by moving a large volume of air at fairly low velocity; at supersonic and hypersonic speeds, it is more efficient to produce the same thrust by moving a smaller volume of air at higher velocity. The former is best accomplished by a turbofan engine, the latter by turbojet and ramjet engines. The problem of the supersonic and hypersonic engine designer is to combine the best features of each. The differences in these engines involve primarily the method by which the air is compressed prior to combustion. In the subsonic and low supersonic range, a compressor is required to raise the pressure of the air to the levels required for the combustion process. Beyond a Mach number of approximately 2.5, the raw air entering the diffuser of the engine generates enough pressure for good operation without an added compressor. It is in this speed range where the simple ramjet engine takes over and provides an ideal method of propulsion up to Mach number of the order of five to seven. Beyond these speeds, the conventional ramjet commences to lose efficiency because of pressure losses in the diffuser and because the high temperatures generated in the diffuser and in the ensuing combustion process tend to dissociate the combustion product gases. The heat stored in these dissociated fragments tends to be lost with a resulting loss in engine efficiency. The latter difficulties led to the proposal that the moving air should not be slowed to subsonic speeds by the diffuser as in the case of the conventional ramjet, but to supersonic speeds. Now the air enters the combustor at supersonic speeds where the combustion process takes place with a lower total temperature rise. This variation in the ramjet principle is known as SCRAMJET, an acronym for supersonic combustion ram jet.

Figure 3, due to Avery,¹ shows the variation which can be expected in specific impulse for various engines over a wide speed range from subsonic to orbital speeds. We observe that the kerosene-fuel turbojet is superior below Mach number three. Beyond three, the kerosene-fueled ramjet and SCRAMJET reduce rapidly in efficiency and degrade to the level of rockets in the vicinity of Mach number of ten to twelve. However, if we use a more energetic fuel, such as liquid hydrogen, and employ the

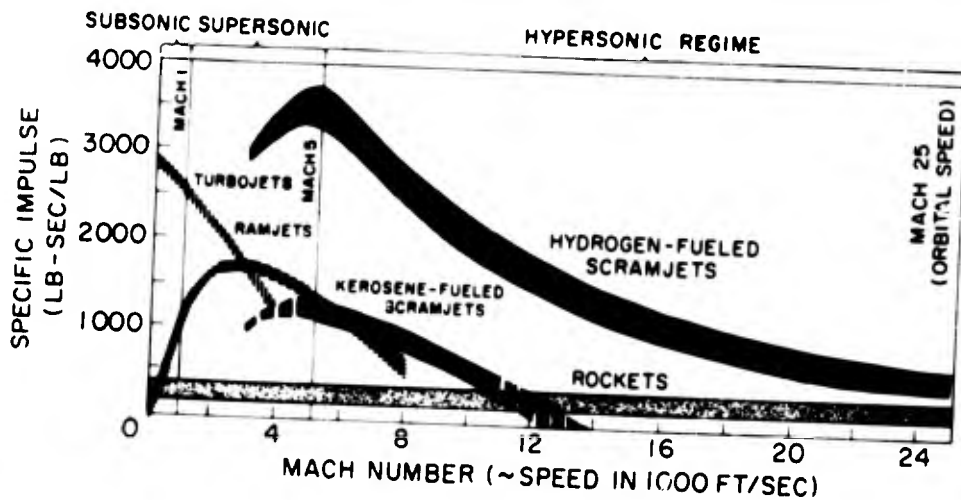


Figure 3. Engine specific impulse (from Avery—ref. 4).

SCRAMJET principle, we can generate very high propulsive efficiencies over the entire hypersonic range, exceeding those of rockets up to orbital speeds.

One of the principal problems of hypersonic flight is that of providing reasonably efficient propulsion from zero speed on the ground to hypersonic cruise. There is a wide variation in the status of engines to accelerate a ramjet to its operational speed. They range from the widely used turbojet and its extension to low Mach numbers to rockets—with a number of concepts or paper designs in between. More work is needed on these conceptual engines to establish a firm technology base. In the ramjet flight regime, there are two possible approaches to acceptable efficiency: One is the so-called dual operation mode or convertible concept where the ramjet employs subsonic combustion from Mach three to six and supersonic combustion above Mach six. The other approach is to upgrade supersonic combustion performance in the Mach three to six range.

What then can be expected for supersonic and hypersonic flight efficiencies and how will they compare with those achieved by today's subsonic jets? Figure 4 shows the results of combining

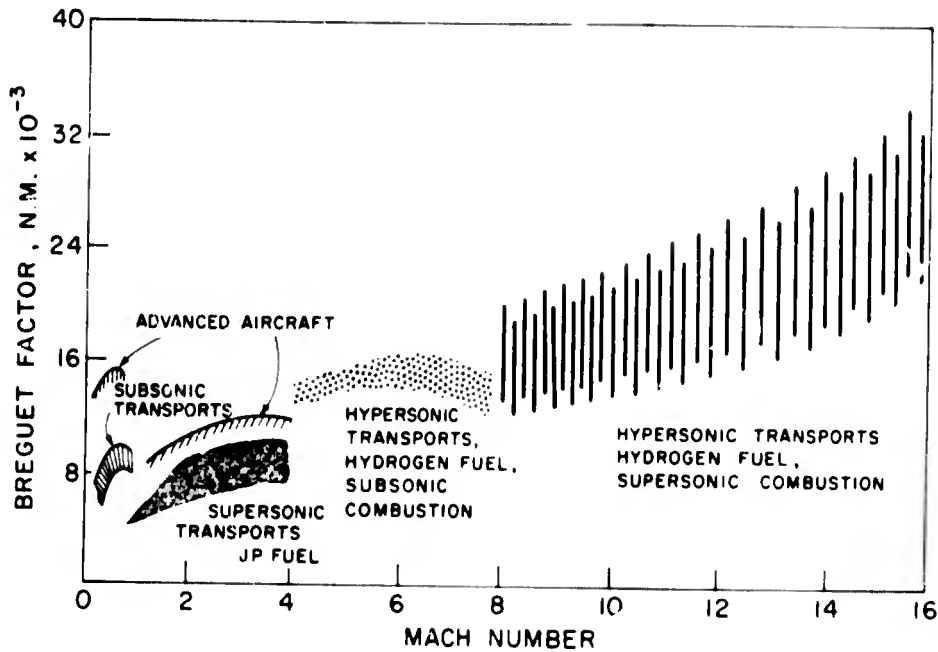


Figure 4. Cruise efficiencies.

the factors assessed above to obtain plots of flight efficiency at various speeds.

The shaded area of Figure 4 illustrates that cruise efficiencies of supersonic transports tend to be slightly lower than, but not too much different from, those of subsonic transports. On the other hand, the hydrogen-fueled hypersonic transport may have very attractive cruise efficiencies. It should be noted, however, that the various areas shown, particularly the large area for hypersonic transports, merely indicate the state of our knowledge what cruise performance may be.

The lower bands of shaded regions in the subsonic and supersonic speed ranges correspond to presently available technologies. The upper band indicated by the note "advanced aircraft" shows what is believed to be possible in the future, based on current research trends.⁵ Very large gains seem to be possible in the high-subsonic speed range where advantage is taken of newer developments in "supercritical" airfoils and aerodynamic interference

technology together with the high by-pass ratio turbofan operating at high turbine inlet temperatures. On the other hand, similar improvements over what is regarded as today's supersonic aircraft technology are not apparent, although a second generation supersonic transport operating near Mach four has some attractiveness.

Cruise performance is not the entire story in obtaining good range and payload characteristics. For supersonic and hypersonic transports, a number of important flight restraints during ascent and descent from cruise altitudes consume significant portions of fuel. Figures 5 and 6 show some of the trajectory constraints for supersonic and hypersonic vehicles, respectively.^{1, 6} Typical cruise

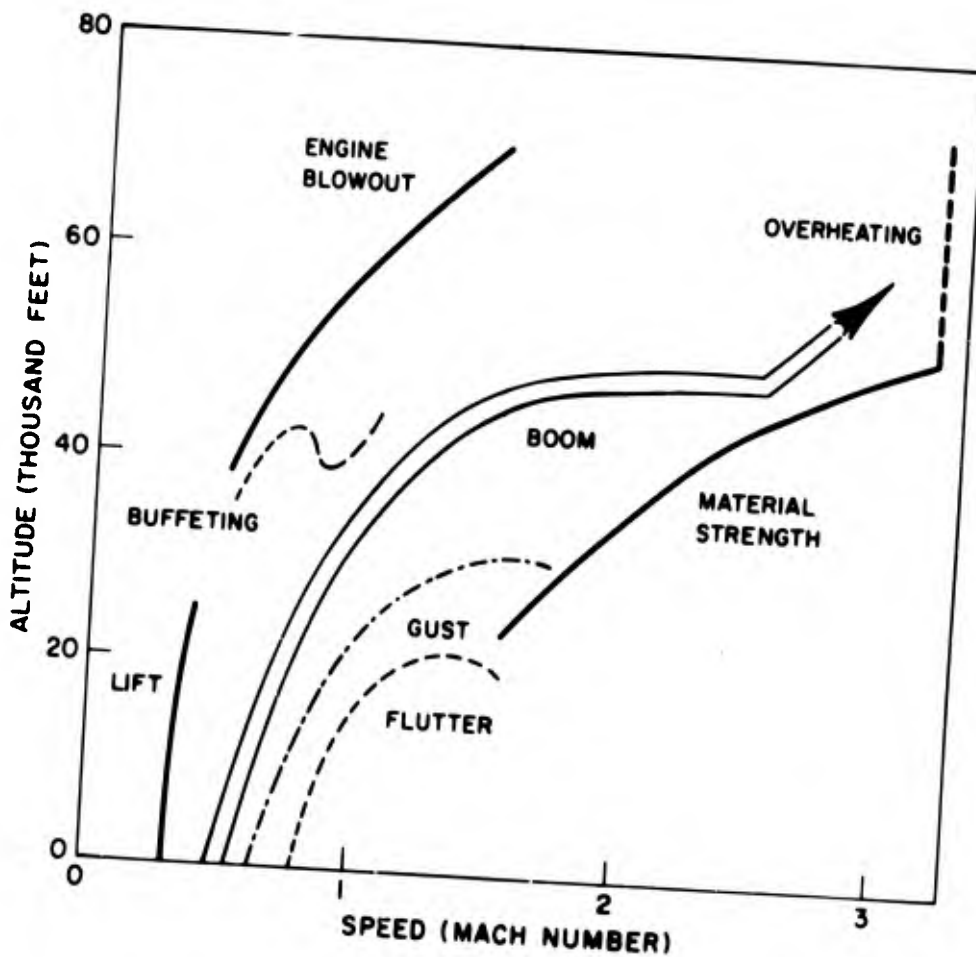


Figure 5. Supersonic vehicle trajectory constraints.

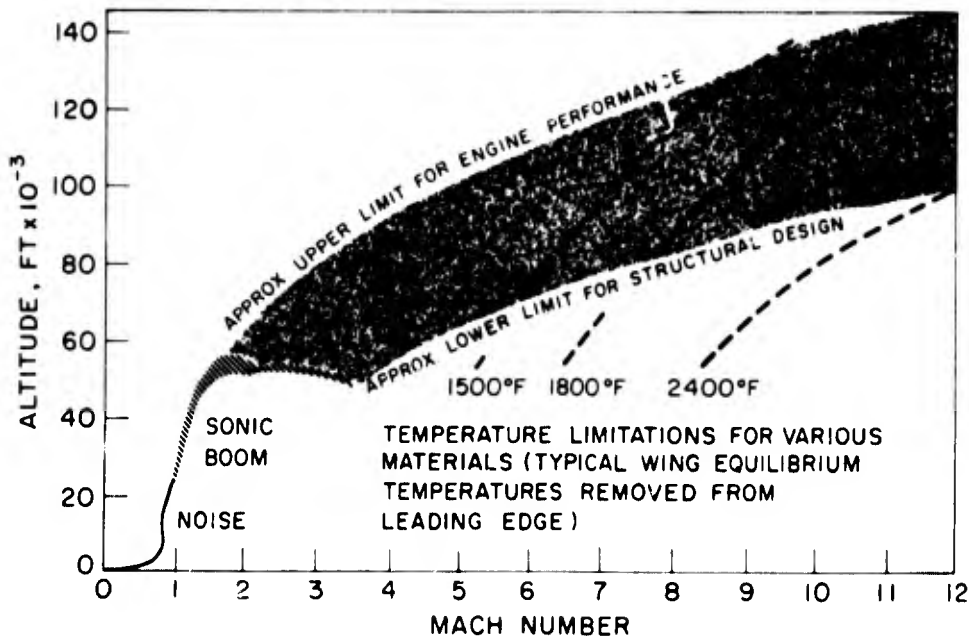


Figure 6. Hypersonic-vehicle trajectory constraints.

altitudes for supersonic transports are in the 60 to 70,000-foot range at speed of Mach 2.7. For Mach six transports, cruise altitudes would be of the order of 100,000 feet. Simple analysis indicates that in both cases, in order to minimize fuel consumed in getting up to cruise, the vehicle should accelerate to cruise speed at low altitude and then climb to the cruise altitude. The trajectory constraint shown, however, indicates that a relatively high altitude climb and acceleration path must be flown because of structural and sonic boom considerations.

As the Breguet equation suggests, flight efficiency is not the whole story in the achievement of range. In order to extend range, a designer must also strive for a high ratio of fuel load to landing weight at the beginning of the flight. This is tantamount to saying that for a given fuel load and payload of passengers and baggage he must reduce the empty weight as much as possible. That has been the perennial problem of the engineer from the earliest days of aviation. William B. Stout, who designed the

Ford Trimotor in the 1920's, liked to say that the aircraft engineers main task in life was to "simplify and add lightness". His advice is no less important today than it was then.

The structural design problem introduced by supersonic and hypersonic flight are exceptionally difficult, and the economic success of these vehicles will very likely swing on our ability to surmount them. The special problems of the supersonic transport can be summarized succinctly by the words: configuration, speed, and longevity. Obtaining a basic configuration which places engines, wing, and landing gear in relative locations such that the load paths are not inordinately long presents a fundamental problem of considerable difficulty.

The principle problems introduced by speed are those of aeroelasticity and aerodynamic heating. At Mach three and an altitude of 70,000 feet, the leading edge of the wing is heated to a temperature of some 550° F. This is well beyond the temperature at which the usual materials of commercial aircraft construction retain adequate strength. The problem of longevity is one of providing adequate airframe safety and serviceability for a period longer than 10 years or some 50,000 hours of flying time. A lifetime of this order is essential if the airplane is to be commercially profitable.

From the structures and materials viewpoint, the feature of overriding importance for the hypersonic airplane is that of temperature. For a transport which will cruise at Machs six to eight, formidable problems exist, with respect to both suitable materials and the efficient structural arrangement of these materials. The use of liquid hydrogen as a fuel sets the lower limit of structural temperature at -423° F. The aerodynamic advantage of sharp leading edges with stagnation temperatures of 3000° to 4000° F makes the problem of cooling very difficult. This large temperature range indicates the many material and structural problems to be expected.

General cooling of the structure is not practical but it may be necessary in localized areas, such as inlets and exhaust nozzles, where the temperatures exceed the limits of the available refractory metals and the use of brittle ceramics is not feasible. Radiation cooling is the simplest and most practical for the greater portion of

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the aircraft. For Machs six to eight, such radiation cooling involves the moderate temperatures of 1200° to 1600° F over most of the aircraft.

The very real advances of the past years in cryogenic materials, developed chiefly for rocket hardware, and in the superalloys, evolved from the gas turbine industry, have led to reliable alloys for the temperature range -420° F to about 1800° F. Major problems exist, however, at the higher temperatures. The chart of Figure 7 offers some perspective for these problems. Its ordinate is compressive yield strength normalized for density.¹ The vertical bands in the figure are estimates of the temperatures that would be encountered by various components. The bulk of the wings would operate in the temperatures shown by the first band while their leading edges, depending on radius, would be in the second band. The aircraft would have a nose cap which would operate within the temperatures shown by the second band.

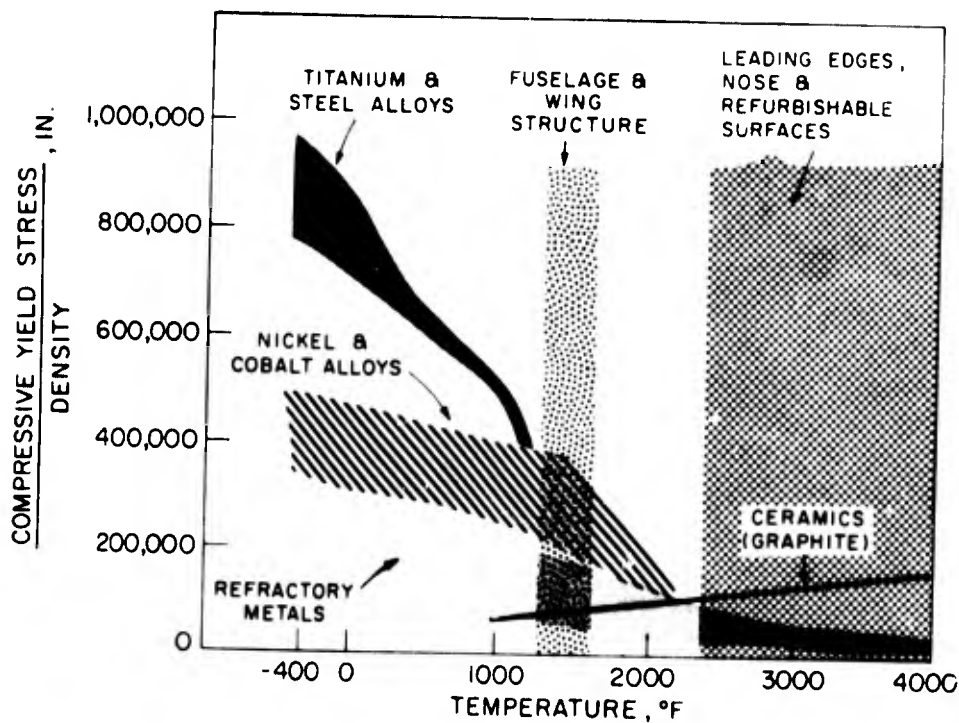


Figure 7. Materials for Mach 6-8 flight.

The figure demonstrates at least two harsh realities: Even at the lower end of the temperature ranges of interest, we do not have available materials that are as strong as those currently being used. This means that there is a premium to be gained through the use of more efficient structures such as sandwiches and honeycombs. Additional development is required, however, to achieve these structures from our best superalloys with the required reliability. Many of the best superalloys are currently available in only cast or forged forms.

At the higher temperatures, it is clear that we must go to refractory metals or ceramics. Both of these categories of materials are unfamiliar to the structural engineer and bring with them formidable problems. One of the worst is that of protecting the refractory metals from rapid and destructive oxidation. Over the past two decades a vast amount of research has gone into the development of both oxidation resistant alloys and protective coatings. Yet today, our best coatings are adequate for only short-flight, one-shot vehicles—not for longtime, multimission, high-reliability airplanes.

Much work remains to be done in this area. NASA is, for example, working on an iridium coating which looks promising on the basis of early results. The present technology of refractory metals compels us to think in terms of refurbishing the highest temperature parts after each, or possibly just a few, flights. We should seek to advance the technology to eliminate this awkward and prohibitively costly procedure.

Analytical studies have been made of a hydrogen-fueled hypersonic transport having a range greater than 5000 miles. Probable structural-weight fractions for hypersonic transports are suggested in the graph of Figure 8.¹ For comparison, the corresponding values for the Mach three supersonic transport and for the subsonic jet are also shown. In addition, two structural concepts are illustrated: the lower being a sandwich structure with an evacuated interior. Both thermal-protection and load-carrying functions are served by this structure. It consists of flat and dimpled sheets joined by welding. Thermal protection is provided by the outer layers of reflective sheets and evacuated spaces. Such a concept shows considerable promise for protection of the liquid hydrogen at -420° F from the external environment of 1500° to

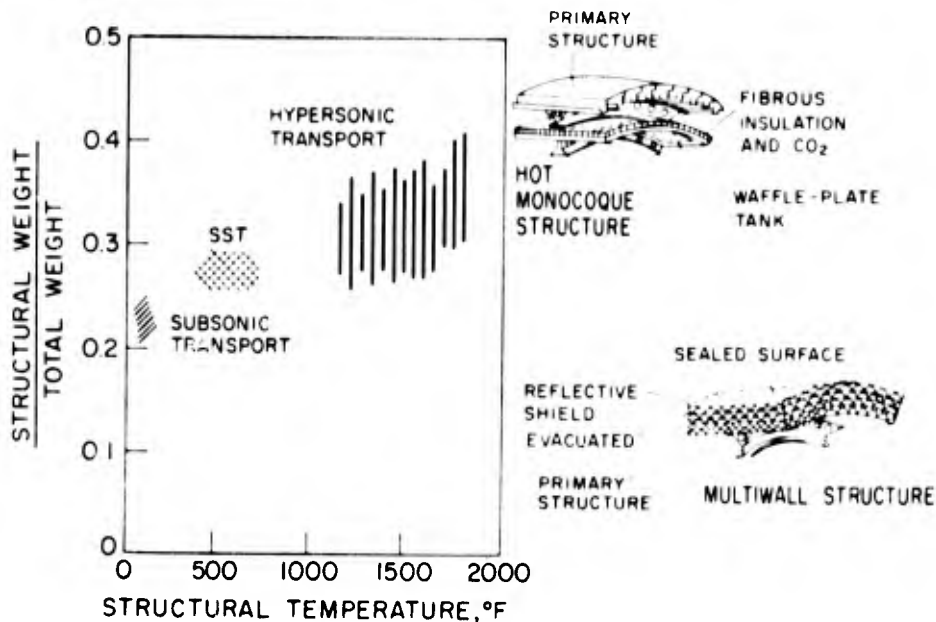


Figure 8. Advanced structures and structural weights.

1800° F. The upper figure illustrates a double-wall structure which employs a carbon dioxide insulation concept.

The structure of the wing will be subjected to sizeable temperature gradients, even in cruise. The lower surface, because of the surface angle of attack, will be hotter than the upper surface, producing sustained thermal gradients. Structural arrangements, such as corrugated panels and pin-jointed trusses, are required to minimize thermal stresses. The use of thin-gauge materials and the presence of thermal stresses—or their elimination by numerous joints—make panel flutter a critical problem for most of the exterior surface. Although the penalty associated with a Mach eight airplane is only slightly greater than that estimated for Mach six, further increases in speed may have very pronounced effects. A Mach eight aircraft approaches the limits of super-alloys and substituting refractory metals may lead to a sizeable increase in weight.

One of the most widely discussed problems facing the designer of supersonic and hypersonic airplanes is sonic boom. The term

"sonic boom" is used to describe the atmospheric disturbance produced when the lower edge of the conical Mach wave produced a supersonic airplane sweeps over the surface of the ground. The zone of the intersection of the Mach cone with the ground is bounded by a hyperbola. The boom is audible simultaneously at all points along the hyperbola, and it is eventually heard at all points on the ground over which the hyperbola sweeps. When a heavy aircraft flies at supersonic speed near the ground, the sonic boom is usually heard as a sharp report. When the sonic boom is produced by an aircraft of modest weight at high altitudes, the effect is more like distant thunder.

NASA's Langley Laboratory has established the variables that govern the pressure changes in the shock wave produced by aircraft operating at low supersonic speeds. This investigation has established that above the speed of sound, increases of speed have comparatively little effect on sonic boom. The chief factors affecting the strength and character of sonic boom are the weight and shape of the airplane and its distance above the ground.

To minimize the annoyance of sonic boom, the supersonic transport will not be permitted the wide choice of altitude and speed pattern now enjoyed by today's commercial aircraft. In order to prevent any sonic boom while it is at low altitudes, supersonic and hypersonic airplanes will be required to climb supersonically to at least 40,000 feet before they accelerate to supersonic speeds. For the same reason, they must decelerate at the end of their trip so that subsonic flight is resumed above 40,000 feet. For both supersonic and hypersonic transports, the maximum sonic-boom intensities will be governed largely by the exit and entry trajectories employed. Sonic boom during cruising flight, however, will be relieved by higher cruising speeds and altitudes. Figure 9, which is constructed for a take-off gross weight of 500,000 lbs, illustrates in a qualitative way the trends in altitude and sonic boom which can be expected with increasing flight speed.⁵ At Mach numbers six to eight, it can be seen that booms with overpressures of 1 lb/sq ft may be achievable. There is, however, a concurrent disadvantage since the lateral speed of the sonic boom on the ground is proportional to altitude and hence greater for the higher flying hypersonic transport.

The authors has considered here only a few of the principal factors of supersonic and hypersonic flight, namely those relating

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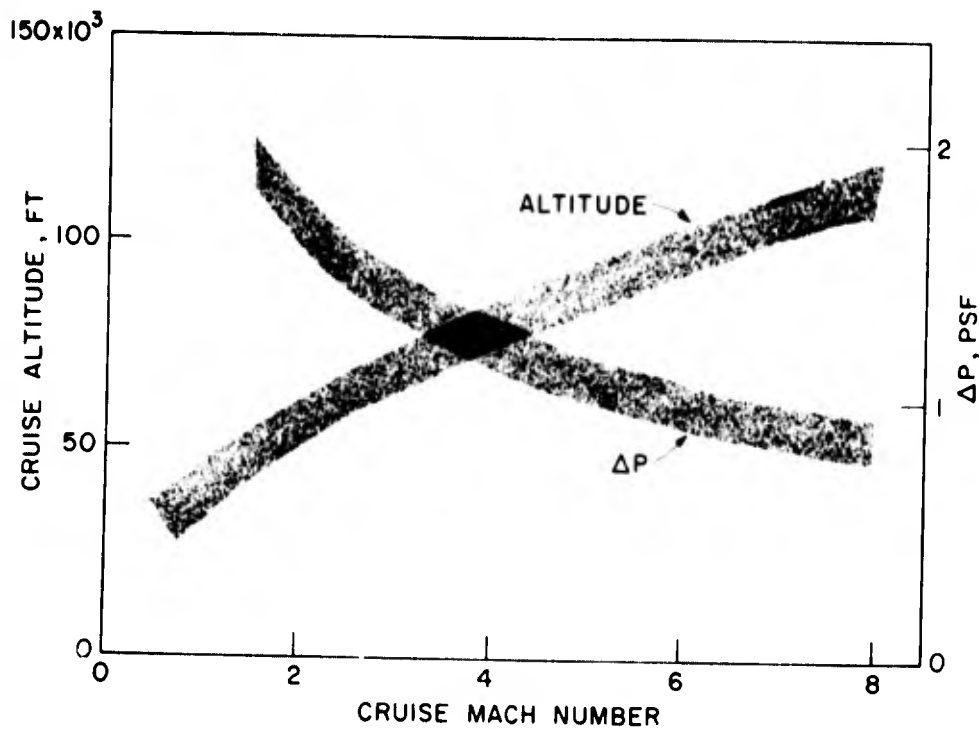


Figure 9. Cruise sonic boom characteristics of supersonic/hypersonic vehicles (from Baals and Foss—ref. 5).

to flight efficiency, range, and sonic boom. There are obviously many others which must also be considered in a practical evaluation of manned flight.

At the present writing, it appears to the author that supersonic and hypersonic commercial air transportation is potentially feasible and economically attractive. However, flight in these speed ranges will not come easy. Although the technologies underlying supersonic flight up to Mach three are evidently in hand, the practical construction of a vehicle which is economically attractive to the airlines requires the solution of exceptionally difficult configuration and design problems. Hypersonic vehicle technology is not yet in hand, and little effort is being expended to get it. When hypersonic vehicle technology is ultimately developed, the same kinds of difficult configuration and design problems now confronting the supersonic airplane designers will require solution.

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Although there are many difficulties to overcome as cruising speeds are increased, structural weight and sonic boom can be mentioned as the two exceptionally severe problems. The author is confident that the former can be eventually overcome by improvements in configuration and structural technology; the latter represents a fundamental and probably ineradicable by-product of supersonic and hypersonic flight. At the present time, there does not seem to be bright prospects for significant reductions in the intensities of sonic boom. The future must be viewed in terms of small reductions obtained through design refinements of conventional aircraft and improvements in aerodynamic, structural, and propulsive efficiencies, together with improved operating procedures.

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VIII

Life Support (Survival) In Space

Col. A. G. Swan*

INTRODUCTION

A strong case is often made for maintaining an environment in space identical to the one on Earth in which we attempt to survive daily.

There have been, and still are, proponents of maintaining air at 760 mm Hg pressure as the spacecraft atmosphere. Similarly, there are some who support providing an artificial gravity for spacecraft. Indeed, sea level air and 1 g have been thoroughly validated, as evidenced by a world population of approximately 3.5 billion people¹ and countless other living creatures. Today, however, we are seriously concerned, particularly in heavily industrialized areas, about the concentrations of contaminants in our 1 atmosphere of air. Without even referring to survival or support of life in aerospace flight, we are continually aware of the necessity to maintain tolerable limits within our Earthbound environment. In 1966, on our highways, we had over 53,000 people killed and about 2 million¹ injured because limits of tolerable impact were exceeded. Many of these casualties could have been avoided if adequate protective restraints were available and had been in use.

Rapid changes in our atmospheric pressure, temperature, and moisture content, certainly not enough to cause concern from the hypoxia or bends standpoints, have destroyed much of human life and property in the form of tornadoes, hurricanes, floods, ice

*Director of Research and Development, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas.

and snow storms. Sustained heat waves have likewise taken their toll.

Hospitals and nursing homes contain literally thousands of humans in prolonged bed confinement which is a qualified analog of weightlessness. Cardiovascular systems and mineral metabolism undoubtedly undergo adaptive changes under such conditions, but these do not seem incompatible with life. Rehabilitation of the cardiovascular and musculoskeletal systems appears practical when the initial bed-confining causes permit.

Fire, as essential an ingredient as it is to our present advanced state of technology, has been a tremendously destructive as well as constructive force throughout its existence. Industrial and residential fires destroyed almost 8,000 lives and approximately a \$1½ billion in property last year in this country.¹ Even with the marvelous advances in the field of nutrition, it has been estimated that one-fourth of the world's population is dying of malnutrition.² These examples, of course, could continue without good purpose. The point is that we are not without problems in our "ideal" environment on Earth; it lacks reliability, consistency, and predictability. It is easy to make predictions when a thorough environmental history is known and these predictions are applied to large masses of people. It is extremely difficult to apply precise predictions regarding individual *survivability* in an environment which can vary through large extremes. Of course, the latter is the case when applied to the small number engaged in spaceflight.

With modern methods of systems analysis, reliability forecasting, and the philosophy of redundancy in life support equipment, we can predict the internal environments of aircraft, spacecraft, and pressure suits with great confidence. With proper hazards analyses, we can effectively plan for or even avoid most life support systems' emergencies. Experience, which is a great factor in continually improving our ability to preclude or successfully deal with emergencies, enhances our ability to predict life support systems' failures.

There is perhaps the tendency to conclude that, because we have evolved in an atmosphere of air with the other terrestrial conditions, this is the ideal sort of environment. We know entirely too little to say that this is, in fact, the "best" environment for

Table 1

MAN'S ENVIRONMENTAL REQUIREMENTS IN A SPACE VEHICLE

PRESSURE CONTROL	760 - 187 mm Hg
OXYGEN PARTIAL PRESSURE CONTROL	425 - 100 mm Hg
CARBON DIOXIDE PARTIAL PRESSURE CONTROL	8 - 0 mm Hg
TEMPERATURE CONTROL	24 - 20° C
RELATIVE HUMIDITY CONTROL	70 - 40 %
MICRO-CONTAMINANT CONTROL	NON - TOXIC

man. With temperature extremes ranging greater than -60° to $+120^{\circ}$ F in inhabited regions of the United States, alone, with highly variable moisture contents and considerable variations of pressure and oxygen contents in various inhabited areas of the world, it is most difficult to even determine which climate is most conducive to longevity. If the selection of a model atmosphere is desired or indicated, hopefully a more objective approach will be pursued than just "sticking with" the one we have. (See Table 1.)

We must not judge too severely the spacecraft environments which have been used and which are planned for use today. To the contrary, we must be adaptable enough in our thinking, and hence in our planning, to vary the individual characteristics of the environments in order to accomplish the mission assigned for any given space venture.

For the purpose of this discussion the term "environment" should be more clearly defined. Primarily reference is made to:

- a. The atmosphere; its pressure, composition, and temperature

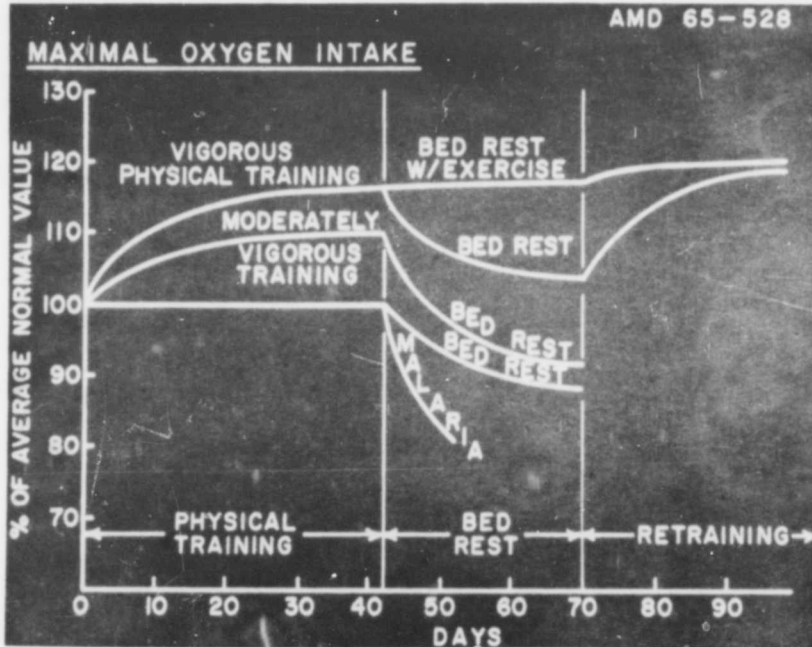


Figure 1

- b. The gravitational forces
- c. Solar radiation.

All of these are important to man's survival—be it on Earth or in space. Of these, the validation and selection of the atmosphere most easily lend themselves to laboratory investigation. The gravitational forces, ranging from a resultant zero in orbit to 8 g or greater on launch and reentry, have been the subject of many speculations, studies, and symposia—as have the nature and identification of solar radiation hazards. Although tremendous progress has been made in each of these areas since the First International Symposium held in San Antonio in 1951, there is still a real scarcity of data regarding the interaction of these various environmental entities. This information will undoubtedly come to us as longer duration manned and animal space flights are experienced.

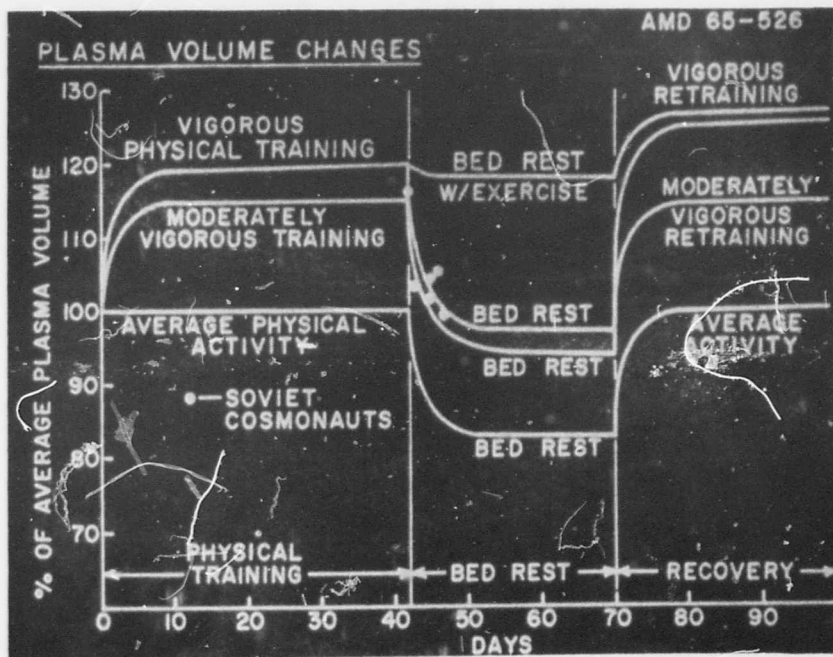


Figure 2

WEIGHTLESSNESS

The weightlessness condition remains one of the primary environmental concerns of future spaceflight. Extensive research has been reported using bed rest, other types of inactivity, cast immobilization, and water immersion techniques. Each of these techniques has undesirable features, but the validation of man's ability to adapt to this condition has resulted from United States and Russian spaceflights. Cardiovascular deconditioning and alteration in mineral metabolism are certainly most prominent among the physiologic problems identified with man as a spacecraft occupant. Figures 1, 2, and 3 depict changes in maximal oxygen intake, plasma volume, and heart rate following tilt table testing, which occur in human subjects when exposed to bed rest. The state of initial physical conditioning is also considered by showing the influence of vigorous and of moderately vigorous physical training prior to exposure to bed rest. These can be easily compared to a control or to subjects not pre-exposed to physical

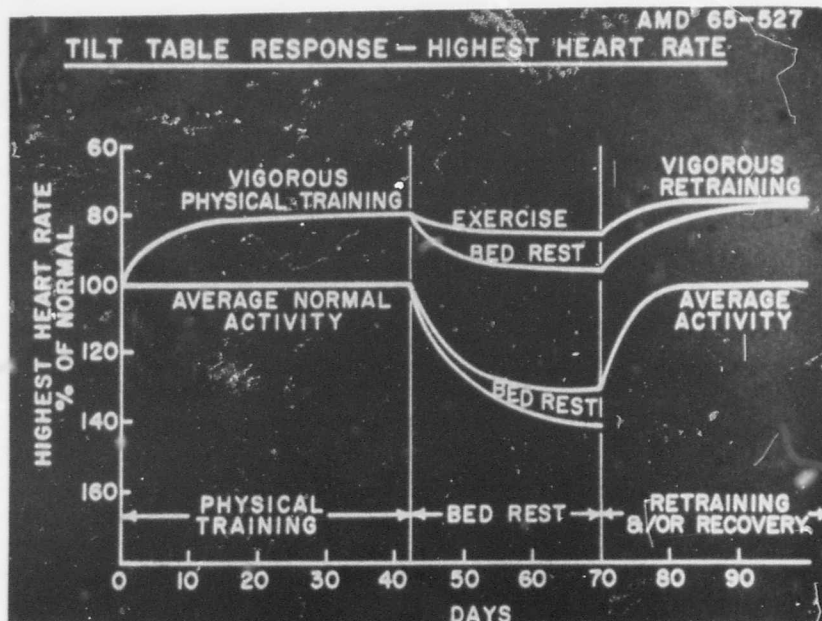


Figure 3

training. The average physical activity conditions will be seen on the charts in Figures 1, 2, and 3 at the 100% point on the ordinate. These physiologic changes can be further noted by following the activities through a post-bed-rest or retraining phase. Of particular importance is the resistive type of protective effect of prior conditioning and the restorative type of protective influence offered by exercise during the bed-rest phase.

In Figure 4, the changes in calcium metabolism are followed prior to, during, and after, approximately 7 weeks of immobilization by plaster casts: similar to the technique one would use to allow broken bone rehabilitation. While there remains some controversy regarding the extent of demineralization in spaceflight and the most effective countermeasure for it, it is safe to generalize that changes do occur such as occur in bed rest, cast immobilization, or other prolonged inactivity. It is also safe to generalize that a considerable elucidation on this subject can be expected in the near future from the sophisticated research presently in progress. The research represented in Figures 1 through 4 has been

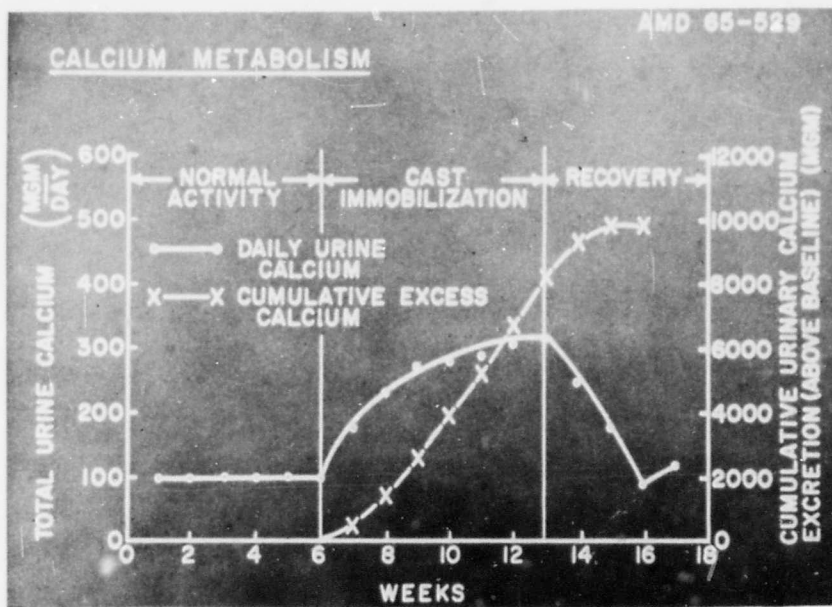


Figure 4

summarized in this very excellent fashion by Dr. John W. Ord of the USAF Aerospace Medical Division. The introduction of mass measuring devices for large (man) and small (biological samples) item measurement is now a reality. Such devices have been developed by Dr. William E. Thornton and his associates, also of the Aerospace Medical Division. These devices work with great accuracy and can be produced as hardware qualified for spaceflight. (See Figure 5.) This will provide the capability to study on-board activity with considerably greater fidelity than has been possible in the past. The availability of lower body negative pressure devices (see Figure 6), total body exercisers and variable gradient pressure garments make the development of physiologic countermeasures to weightlessness impairment an exciting and promising area of research with a high probability of beneficial results accruing. Figure 6 shows a lower body negative pressure device, one of the promising techniques being evaluated as a possible weightlessness countermeasure. It is encouraging in the protection give the cardiovascular system in particular. Other

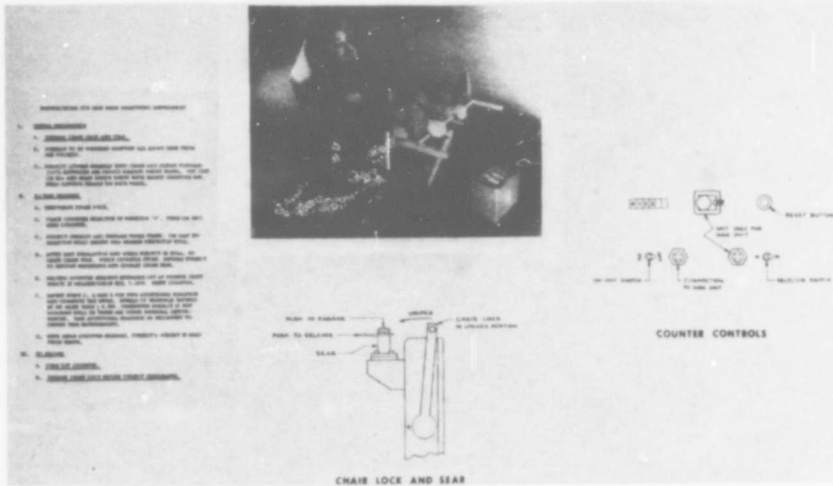


Figure 5. Prototype hardware of a mass measuring device for use in future spaceflight.

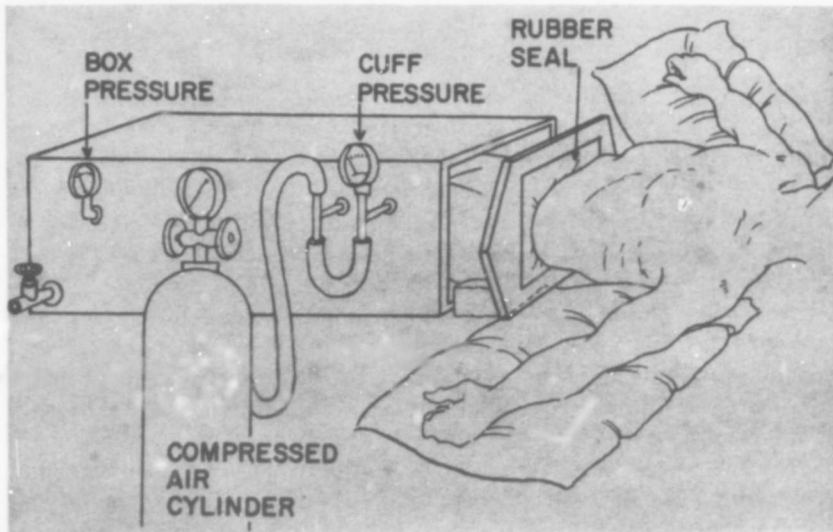


Figure 6. A procedure for producing and measuring negative pressure applied to lower portion of the body.

Table 2

POSSIBLE WEIGHTLESSNESS COUNTERMEASURES		AMD 65-523
DIFFERENTIAL PRESSURES TO BODY REGIONS		POSITIVE PRESSURE TO BODY
		PRESSURE BREATHING
		EXTREMITY VENOUS CUFFS
		LOWER BODY SUCTION
MUSCLE EXERCISE	STATIC	ISOMETRIC EXERCISE
		STANDING-WALKING, FORCE LOADED
	DYNAMIC	ISOTONIC EXERCISE
		FORCE LOADED, ISOTONIC EXERCISE
ACCELERATION	LINEAR	DOUBLE TRAMPOLINE OR POGO STICK
	RADIAL	ON BOARD CENTRIFUGE
		STATION ROTATION
	REFLEX STIMULATION	DIFFERENTIAL TEMPERATURES
		DRUGS
		ELECTRIC MUSCLE STIMULATION

possible countermeasures are shown on Table 2, and a relative grading system from 0 to 4 (0 being least effective and 4 being most effective) is shown in Table 3. In any event, these and similar devices should be thoroughly explored before the costly and complex means of providing artificial g is seriously undertaken.

ATMOSPHERE SELECTION

The potential atmospheres which provide an engineering choice³ are listed as follows:

- 14.7 psia - 760 mm Hg - Air, ambient composition
- 10.0 psia - 520 mm Hg - Air, ambient composition
- 7.0 psia - 365 mm Hg - 46% O₂/54% N₂ (He, Ne, Ar, ?)
- 5.0 psia - 258 mm Hg - 71% O₂/29% N₂ (He, Ne, Ar, ?)
- 5.0 psia - 258 mm Hg - 100% O₂
- 3.7 psia - 191 mm Hg - 100% O₂
- 3.0 psia - 158 mm Hg - 100% O₂

Table 3

AMD 65-524 EFFECTIVENESS OF WEIGHTLESSNESS COUNTERMEASURES							
PRESS. BREATH.	EXTREMITY CUFFS	LOWER BODY SUCTION	FORCE LOADED ISOMETRICS	RESIST. LOADED ISOTONICS	LINEAR OSCIL. ACCEL.	RADIAL ACCEL.	
DISPLACEMENT OF MOBILE STRUCTURES		1	0	1-2	1	1-2	2 / 3-4
DISPLACEMENT OF FLUID IN ELASTIC SPACES		2-3	2-3	3-4	1	3-4	2 3-4
BODY SYSTEM LOADING CIRCULATORY MUSCULOSKELETAL METABOLIC THERMAL		1	0-1	2-3	2	3-4	3 2-4

VALIDATION STUDIES COMPLETED

No. of Exps	Subject (Total)	Environment	Duration (Days)
2	4	7.34 psia, 42% O ₂ /58% N ₂	30
2	4	5.0 psia, 97% O ₂ /2% N ₂	14
2	8	5.0 psia, 99% O ₂ /0.3% N ₂	30
1	4	13.5 psia, 33% O ₂ /67% N ₂	30
2	4	7.0 psia, 46% O ₂ /54% He	15
1	4	13.5 psia, 28% O ₂ /69% N ₂ /3% CO ₂	4
1	4	3.8 psia, 63% O ₂ /26% N ₂ /11% CO ₂	4
2	5	13.5 psia, 20% O ₂ /78% N ₂ /3% CO ₂	5
1	4	7.0 psia, 68% O ₂ /29% He	56

(References 4 through 11)

From the potential atmospheres, a large number of variations have been investigated, and a general conclusion can be drawn that none of the altered atmospheres shown above cause functional difficulty in man for the times shown. More recently, the National Aeronautics and Space Administration with a contract to the McDonnell Douglas Company has completed a 60-day experiment using human subjects under conditions of 258-mm Hg total pressure, with approximately 68% oxygen and 32% nitrogen. No problems during this experiment were noted from the physiologic evaluation of the subjects; at least no functional physiologic impairment could be detected. This experiment served not only to validate this atmosphere for a 60-day period but also to validate the capability to regulate such an atmosphere for the 60-day period with a prototype spacecraft environmental control system.

Dr. B. E. Welch and associates, at the USAF School of Aerospace Medicine, have not only been active in validating primary atmospheres but also have given much consideration to the effects of increased carbon dioxide partial pressures in the primary atmospheres as shown in Tables 4 and 5. The effects shown in Table 5 are particularly important when the failure of a carbon

Table 4

CHRONIC CARBON DIOXIDE STUDIES IN MAN			
PCO ₂ (mm. Hg)	PB	Duration	Investigator
7-8	Ground Level	30 Days	USSR
11-12	Ground Level	42 Days	USN
15	Ground Level	30 Days	USSR
21	Ground Level	5 Days	USAF
21	200	4 Days	USAF
30	Ground Level	5 Days	USAF
30	Ground Level	10 Days	USAF

Table 5

<u>DETECTION OF ELEVATED CO₂ PARTIAL PRESSURES</u>	
<u>Pco₂</u>	<u>Effect</u>
0 - 8 mm Hg.	No noticeable effect.
8 - 15 mm Hg.	Barely noticeable. \dot{V}_E increases slightly. Arterial pH measurably lower, but adapts. No subjective or objective effect on work.
15 - 21 mm Hg.	Noticeable. \dot{V}_E increases 3 - 5 l/min. Aware of increased V_T . Decreased pH initially. Returns toward normal with increase in HCO_3^- . Maximum exercise effort subjectively more difficult. Headache.
21 - 30 mm Hg.	Very noticeable. \dot{V}_E approximately doubled due to increased V_T . Decreased pH with an ill-defined return toward normal. Sub-maximal effort subjectively more difficult. Headache.

Table 6

COMPOUNDS SPECIFICALLY PRODUCED BY MAN

Carbon Monoxide	Methanol
Hydrogen	Ethanol
Methane	Methyl ethyl Ketone
Hydrogen Sulfide	Acetic Acid
Ammonia	Acetaldehyde
Acetone	Mercaptans

dioxide removal system aboard a spacecraft could yield such concentrations in the environment for a prolonged period. It is important to know the maximum allowable exposure to trace contaminants from both the time and concentration standpoints. Many trace contaminants may now become a problem with more effectively sealed cabins, particularly for the longer missions. The sources of these contaminants can be from man himself, from the materials carried with him, and from equipment malfunctions. The major products produced by man are shown in Table 6.

OXYGEN TOXICITY

Final conclusions as to the possibility of cellular changes resulting from breathing higher than normal partial pressures of oxygen, which may not be identified by functional test, are not yet clear. Breathing 258 mm Hg pure oxygen has been associated with reversible changes in red blood cell mass in man. This has been reported from the Gemini spaceflight program.¹² At this time, there exists controversy as to the structural changes in lung tissue, changes in cellular processes, which may occur at increased oxygen pressures even at total pressures as low as 258 mm Hg, have been reported.^{12, 13} In any event, more carefully planned research is in order.

RAPID DECOMPRESSION

During the past few years, earlier work by Hall, Hitchcock and others has been confirmed and carried further by Koestler¹⁴ and associates. Chimpanzees have been exposed to decompressions from 179 mm Hg to less than 2 mm Hg in less than 0.8 second and have remained at the near vacuum for 5 to 180 seconds. The performance of these animals has returned to normal limits within 4 hours. It is believed that previous restrictions which have been applied on the recompression times required for both spacecraft and large environmental simulators can now be reevaluated. Figures 7 and 8 show the experimental animal and equipment used by Koestler and his associates from the Aerospace Medical Division's Aeromedical Research Laboratory at Holloman AFB, New



Figure 7. Experimental animal and performance measuring equipment prior to being placed into a decompression chamber.

Mexico. Figure 8 shows the extensive array of performance parameters which are measured to give the sophisticated performance index which Koestler et al. used. His results are further shown in Figure 9 which plots the actual and the predictive results regarding the elapsed time during which performance was totally impaired. Figure 10 shows the data plotted in similar fashion regarding both actual and predicted times for recovery of performance to the level recorded prior to the rapid decompression.

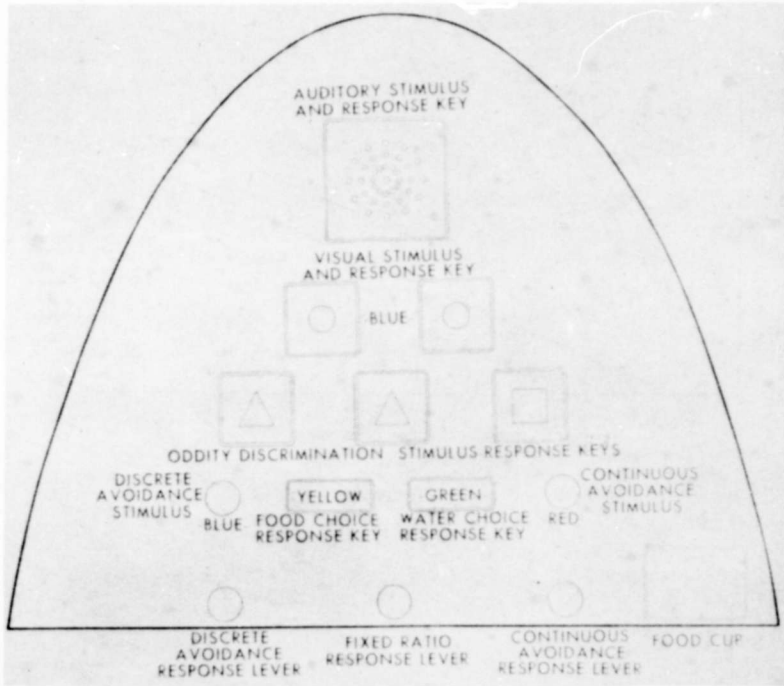


Figure 8. Front view of the performance panel located in front of chimpanzee as shown in Figure 7.

Table 7 tabulates the same information shown in Figures 9 and 10 and shows the exposure times and times of useful consciousness as well.

FIRE HAZARDS^{15, 16}

The increased likelihood of fire in high oxygen concentrations has long been known. The awareness of this as a hazard has certainly been sharpened as the result of recent tragic accidents using increased concentrations of pure oxygen in tests and investigations. The development of fireproof clothing and other equipment for use in spacecraft and in simulators has been given more consideration during the past 1½ years than at any previous time. Material made from glass fibers is the most successful

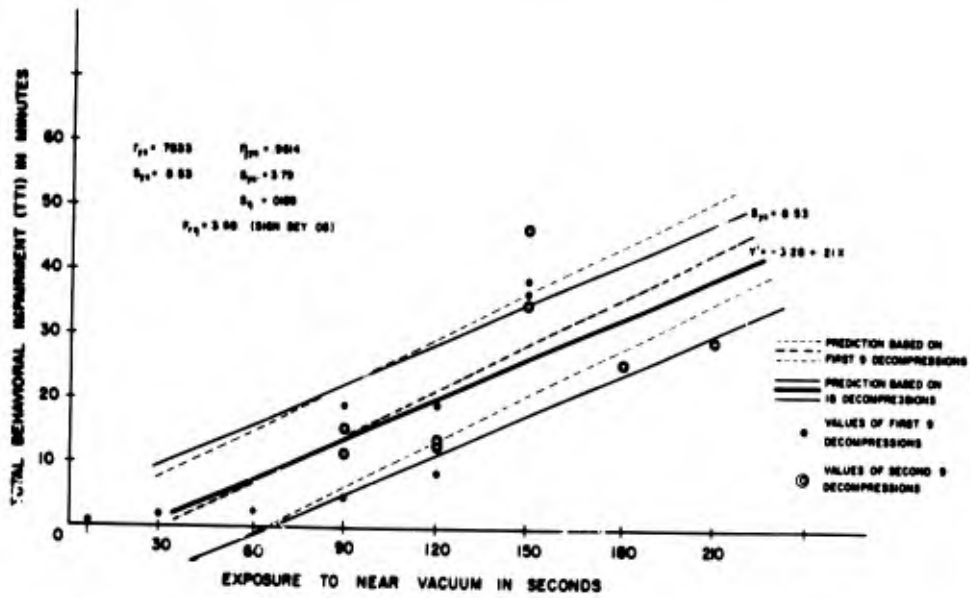


Figure 9

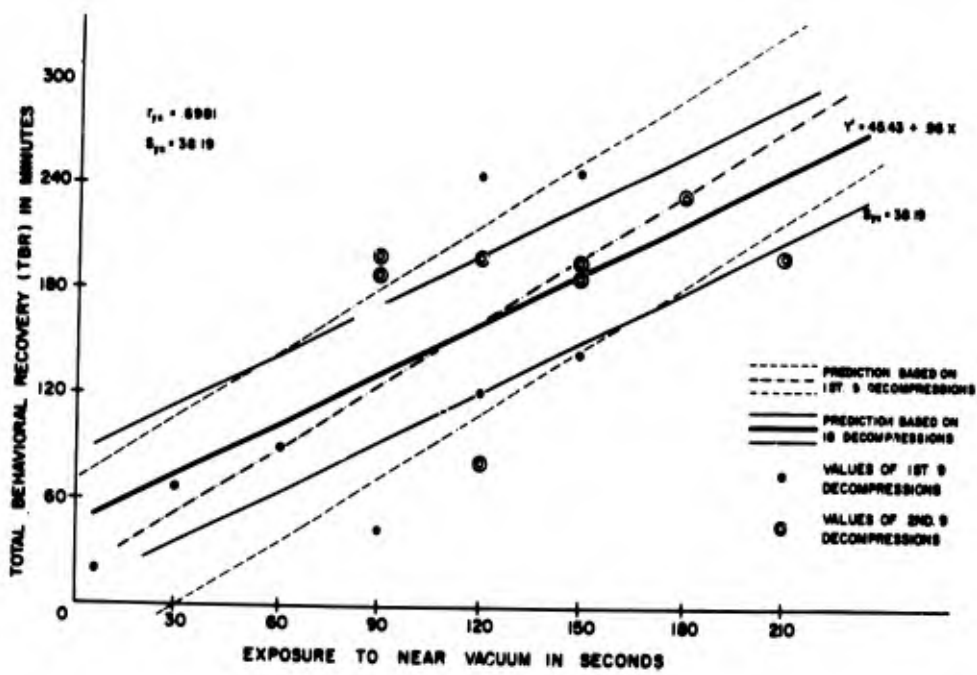


Figure 10

Table 7

Summary of Rapid Decompression Effects

RD Experiment	Exposure Time to < 2 mm Hg (seconds)	TUC Time of Useful Consciousness (seconds)	TTI Time of Total Behavioral Impairment (minutes)	TBR Time of Total Behavioral Recovery (minutes)
1/05*	5	11	.42	20.00
2/30*	30	Not Available	1.80	67.00
3/60*	60	16.9	2.48	90.08
4/90*	90	11.3	18.93	163.02
7/90*	90	12.5	4.82	43.00
12/90	90	3.6	Not Available	Not Available
13/90	90	6.5	11.63	199.00
16/90	90	8.0	15.67	188.75
5/120*	120	10.1	8.56	245.02
8/120*	120	9.5	19.07	121.75
10/120	120	29.6	13.73	81.75
15/120	120	10.4	12.97	198.50
6/150*	150	29.7	36.56	144.02
9/150*	150	8.0	38.69	247.00
11/150	150	10.0	46.50	187.00
14/150	150	1.5	34.83	197.25
17/180	180	11.1	26.70	234.25
18/210	210	10.2	29.25	199.25

* Decompression test previously accomplished under Contract T-27210-G.

development for protective clothing at this time. A new fireproof rubber has been developed by a NASA contractor which offers much promise. Perhaps the most important effort has been in the greatly improved hazards analyses which have been performed to minimize the ignition sources and the presence of flammable materials in the high oxygen concentration areas. The use of ultraviolet detection with automatic water spray systems has been widely adopted for fire extinguishment in environmental simulators. The use of chemical extinguishers and inhibitors for fire protection in high oxygen concentrations is still under study, particularly for aircraft and spacecraft application. Table 8 shows

Table 8

FLAME SPREAD RATE (in sec)

Material	Air 760 mm Hg	70% O ₂ -30% N ₂ 258 mm Hg	70% O ₂ -30% He 258 mm Hg	100% O ₂ 258 mm Hg
Wood	.025 ± .025	0.18 ± .03	0.27 ± .03	0.35 ± .03
Paper	.08 ± .01	0.55 ± .05	0.74 ± .06	0.90 ± .07
Cotton Fabric	.10 ± .01	1.8 ± .2	1.2 ± .2	3.2 ± .2
Foam Cushion	.14 ± .01	6.1 ± .5	6.0 ± .6	13 ± 1

flame-spread rate for some of the highly combustible, but often used materials, in some of the more important atmospheres.

CONCLUSIONS

In the progress since the Third International Symposium on Bioastronautics and the Exploration of Space, the oxygen-helium atmosphere for flights up to 60 days has been validated.¹⁰ We have raised more questions than we have provided answers for in the area of oxygen toxicity. The likelihood of successfully recovering man after brief exposures to near vacuum is viewed with much greater confidence. Our ability to avoid fire in space or space-simulated conditions has greatly improved. These items, briefly discussed, indicate either significant technical advances or greater knowledge upon which to assess their involvement. Today we are in a much improved position to predict performance of life supporting systems, to identify potential hazards, and to realistically prepare for emergencies. These, along with the tremendously important space flight experience and the many technical advancements, improve the probability of man's survival in prolonged spaceflight. With today's knowledge and with the capability to terminate a flight in a matter of hours if conditions demand, it seems perfectly feasible to undertake manned flights of 30 to 45 days.

We should not delay, however, in attempting to obtain animal flights for 90 to 180 days, giving particular emphasis to the study of cellular effects caused by the total space environment for

prolonged periods. We should further investigate, with dispatch, oxygen toxicity hazards as being an integral part of future atmosphere validation and selection programs. Intense efforts should be applied to investigating the use of fire inhibitors as components in the spacecraft atmosphere. The ultimate means of evaluating and validating the total space environment for man will come, of course, only through the use of orbiting spacecraft with man. There are many important laboratory and inflight observations yet to be made in the course of such a validation.

In retrospect, the way man's ability to survive in space has been determined thus far seems to be a relatively good one. It has essentially been one of vertical launchings; then limited parabolic flights, with animals preceding man; and, finally, orbital flights of increasing duration, first with animals and then with man. Many of the formidable problems facing manned spaceflights at the time of the First and Second International Symposia either have been solved or have ceased to be immediate problems. The progress since the Third International Symposium on Bioastronautics and the Exploration of Space, although only a few years ago (1964), is encouraging. The prospects between now and, hopefully, the Fifth International Symposium offer exciting and profoundly rewarding prospects.

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IX

One-Man Propulsion Devices and Their Application On Earth and In Space

Maj. Gen. Don R. Ostrander*

Man for thousands of years has been intrigued with the possibility of systems in which he himself provided either (or both) the power for flight and the means for stabilized flight. After the turn of the 20th century, however, the trend in aviation shifted from "man-centered" flying to "machine-centered" flying--toward powered machines which were designed to be as nearly as possible aerodynamically stable without man in the loop.

Then, in the mid-1950's, there was renewed interest in "man-centered" personal mobility systems. Although the old dream of flying machines, in which man provided his own power, never materialized, simple control systems in which he is an integral and indispensable component of the aerodynamic control loop have proven feasible. In general, three different approaches were investigated during the 50's and early 60's: flying platforms, which the pilot controlled by shifting his weight; one-man helicopters; and Earth and space rocket-powered propulsion systems in a variety of configurations.

Bell Aerosystems Company, then Bell Aircraft Corporation, began studies of rocket-powered individual propulsion devices in 1953. Mr. Wendell F. Moore, who is still with the company, did the pioneer work in this area, culminating in 1957 with the first tethered test of such a device.

*Vice President, Planning, Bell Aerosystems Company, Buffalo, New York.



Figure 1. Tether Test Rig.

Figure 1 shows one of the early tests. This was a nitrogen gas tether test rig which was fabricated of steel tubing with two under-arm stirrups to lift the operator. It had two downward pointing rocket nozzles and the nitrogen gas was supplied from an external source through a flexible hose. It was used to obtain basic data

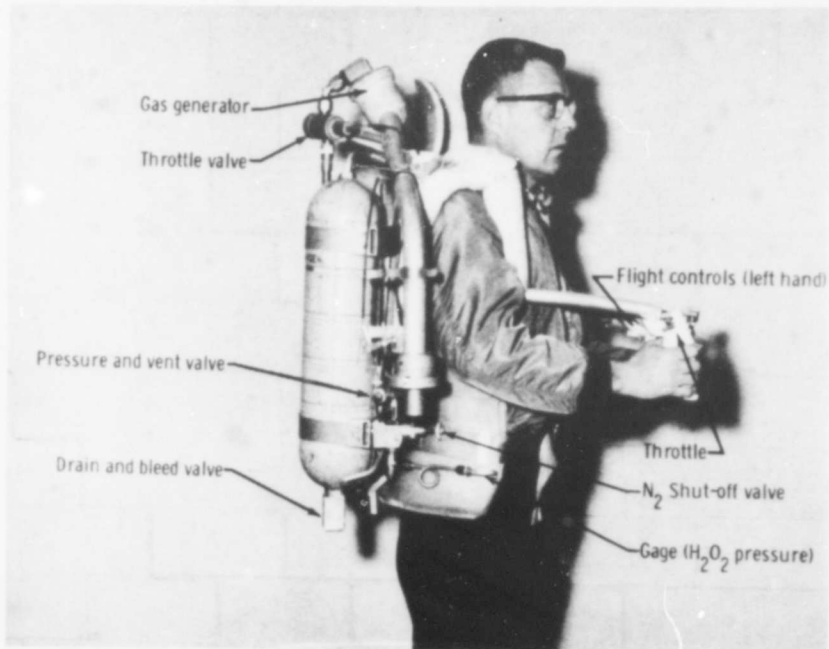


Figure 2. Small Rocket Lift Device (SRLD).

on system stability and control, to determine optimum location of the nozzles, and the best position for applying the lift force to the operator's body.

In August 1960, the United States Army Transportation Corps Research and Engineering Command, awarded Bell a contract to demonstrate the feasibility of manned free flight by such a device. The feasibility configuration shown in Figures 2 and 3 was designed around off-the-shelf hardware and is remarkably similar to the unit that has been demonstrated around the world. Lift was provided by a 300-pound thrust hydrogen peroxide gas generator located behind the pilot's neck and supplied from pressurized tanks on the pilot's back. Insulated tubing carried the rocket exhaust gases to the nozzles located outboard of the pilot. The system was mounted to a fiberglass corset molded to fit the operator's body, and lift was applied primarily by lift rings which fit under the operator's arms.

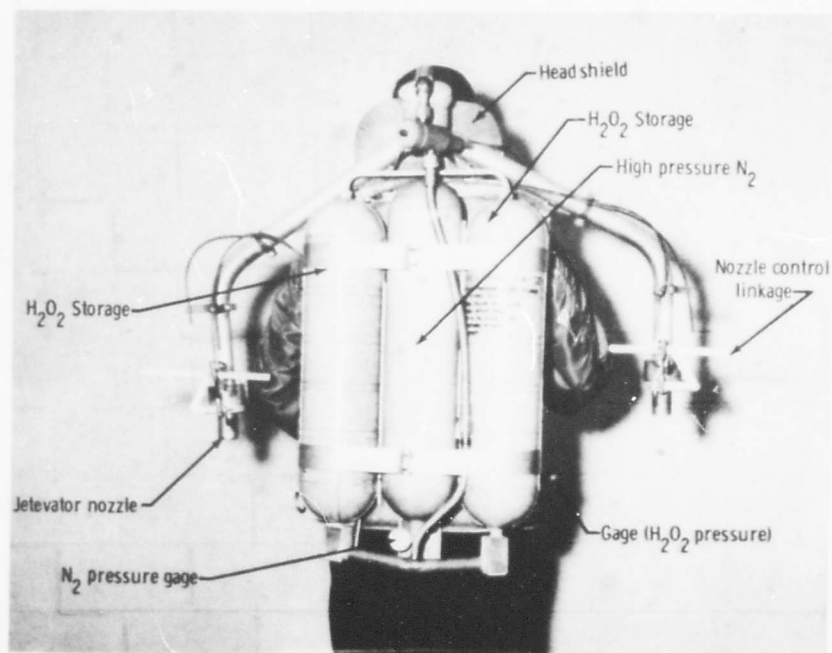
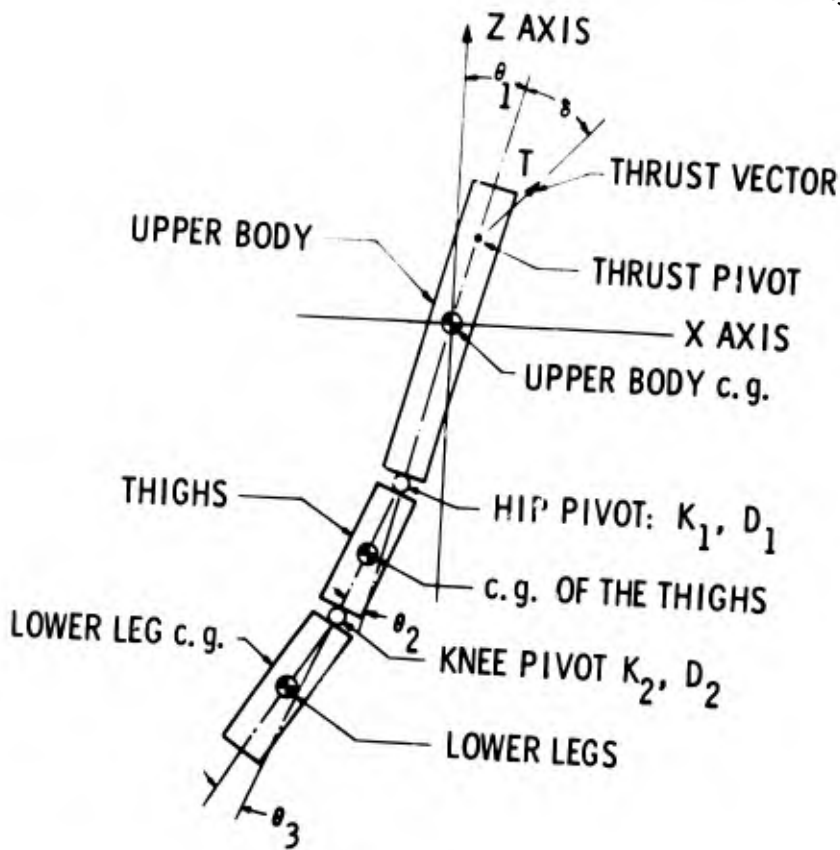


Figure 3. Small Rocket Lift Device (SRLD).

Concurrently with the empirical testing of the control system on the tether rig, mathematical models describing the flight dynamics of the system were developed, and the equations of motion representing pitch, translation, and vertical motions of both the upper and lower body of the operator were programmed on a computer and simulation studies investigating system control were then initiated. Figure 4 is an example of one of the three-body models used for developing simulator models. Later, rigid body models proved to be sufficient, since motion of the lower legs had a minimal effect on the control equations.

As a result of these studies, and the continuing test flights, one change was made in the system to enhance stability and control. In the original feasibility unit, the two rocket nozzles had been gimbaled with three degrees of freedom such that they could be rotated to produce pitch, roll, and yaw control moments. Because of the sensitivity of the device, the pivot behind the operator's



- δ = Thruster angular displacement with respect to the upper body
- T = Thrust
- θ_1 = Angular displacement of upper body from the vertical
- θ_2 = Angular displacement of middle body from the upper body
- θ_3 = Angular displacement of lower body from the middle body
- K_1 = Torsional spring constant acting at the pilot's hips
- K_2 = Torsional spring constant acting at the pilot's knees
- D_1 = Damping exerted by the pilot at the hips
- D_2 = Damping exerted by the pilot at the knees

Figure 4. Three-Body Model of the SRLD Man-Machine System.

neck was changed to permit lateral (roll) and fore-aft (pitch) control by movement of the handles, but jetevators were incorporated in the exhaust stream at the nozzle exhaust for

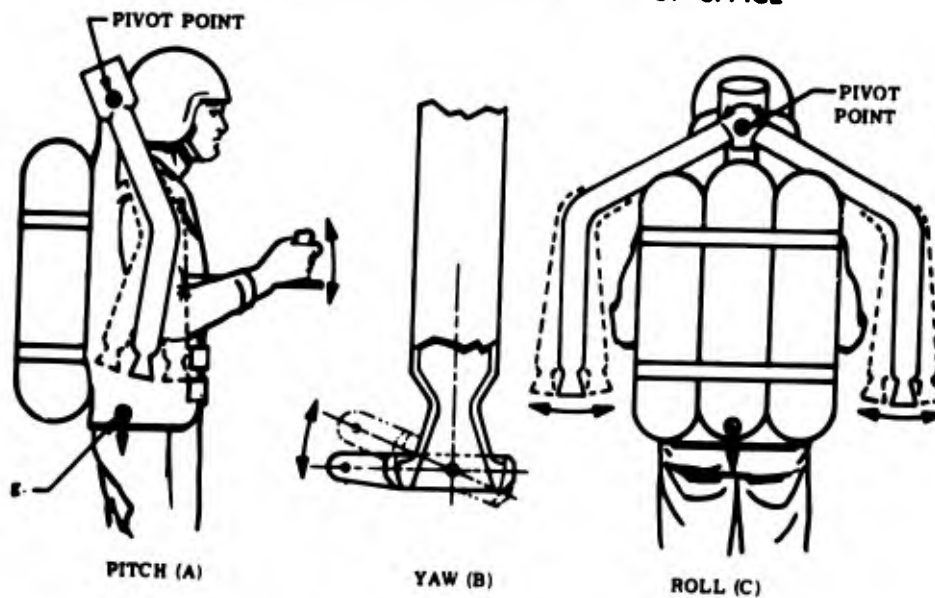


Figure 5. Attitude Control System.

yaw control. This current method of attitude control is shown in Figure 5.

Pitch and roll are controlled by appropriate movements of the control lever arms rotating around the pivot point, but yaw is controlled as shown in the center figure by jetevators activated by a rotary hand grip on the left lever arm. Throttle control is provided by a rotary hand grip on the right arm rest.

On April 20th, 1961, after thirty-six tethered flights with the feasibility system, Harold Graham, a Bell Rocket Test Engineer, successfully completed the first free flight of the system. This 13-second flight was made at an average altitude of approximately 18 inches, a velocity of approximately 8 mph, and covered approximately 112 feet (8 feet less than the first flight of the Wright brothers). In the approximately 7 years since the initial flight, over 3,000 flights have been completed under a wide range of operational conditions, including flights at a velocity in excess of 60 mph and at distances of over 800 feet.

This rocket-powered system, with a flight duration of only about 21 seconds, obviously has limited operational application. In order to turn the system into one which meets meaningful mission



Figure 6. Jet-Powered Individual Life Device.

performance requirements, Bell is presently under contract to the United States Army, and the Advanced Research Projects Agency for the development of a new backpack unit using a small turbojet power plant. Figure 6 shows a mockup of this jet-powered version.

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Table I. Potential Mission Areas For Individual Propulsion Device Application

Civilian

- | | |
|---------------------------------|---|
| 1. Rescue | 5. Transportation into inaccessible terrain |
| 2. Forestry service operations | 6. Emergency medical assistance |
| 3. Fire fighting | 7. Coast Guard operations |
| 4. Police work and riot control | |

Military

- | | |
|--------------------------|---------------------------------------|
| 1. Wire laying | 5. Clandestine operations |
| 2. Liaison | 6. Forward observers |
| 3. Amphibious assault | 7. Reconnaissance |
| 4. Passage over barriers | 8. Base perimeter control and defense |
-

The configuration is basically the same as in the rocket-powered version. Unfortunately, the performance is still classified but the improvements are significant, and we can now talk about range in terms of miles rather than yards. This now becomes a feasible device, both for operational military use, as well as for a variety of potential civilian applications. Table I shows some potential missions for such a device which we have investigated in quite some detail.

Subsequent to the first flights of the belt version, we have devised a variety of alternative configurations. Figure 7 shows the flying chair. The seat itself is simply a light plastic chair, which our engineers borrowed from one of the offices. The propulsion unit is mounted on the back of the chair.

Figure 8 shows what we call the Rocket POGO, in which the propulsion device is mounted on a vertical rod, or pole. The operator merely steps on the foot rest, slips his arms over a pair of lift bars, and takes off. Our pilots say that this configuration is as easy, if not easier, to fly than the belt version, and it has the advantage of quick mounting and dismounting. It is of particular interest to this discussion because of its potential application, or the application of similar configurations, to Lunar Flying Vehicles which will be discussed later in this paper.



Figure 7. Flying Chair.

Finally, we have developed and flown a two-man POGO (Fig. 9), which may have application for rescue missions on Earth and also serves as a test vehicle for studying two-man lunar flyers.

This long background of experience in small lift devices here on Earth has lead us naturally into applying the same technology

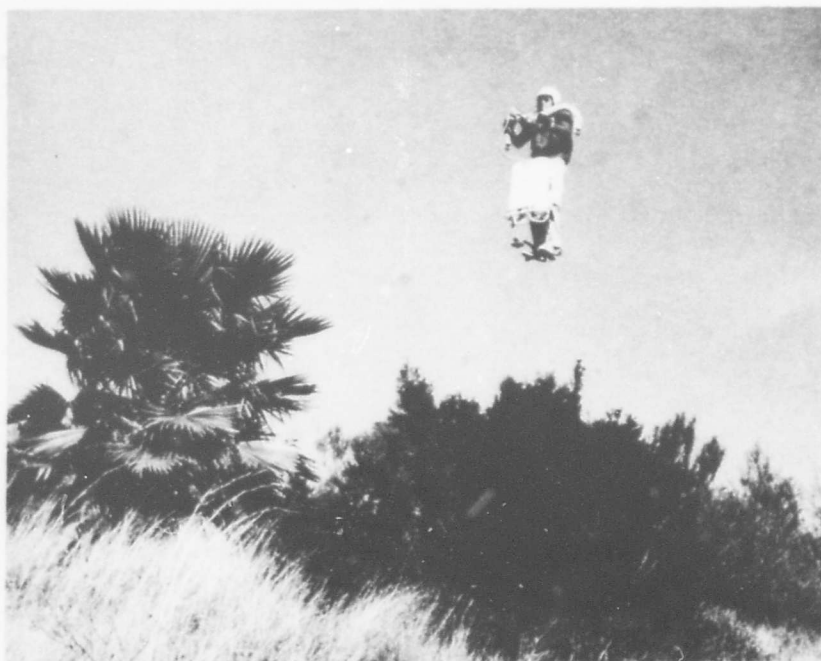


Figure 8. Rocket POGO Vehicle.

to individual mobility devices for use in space, either on or over the surface of the Moon, or for extravehicular activity in orbit. Turning first to lunar propulsion devices, there is a variety of missions which might be accomplished or supported by lunar flyers. Some of them are listed in Table II.

Surface Exploration

The initial lunar landings involve numerous short excursions from the lunar module for general scientific observations, collection of soil and rock samples, and gross measurements of the physical characteristics of the lunar surface. While these tasks can be accomplished by the walking astronaut, or by various types of lunar crawlers, the availability of a lunar flyer would considerably enhance the radius of operation and reduce the total extravehicular time required.

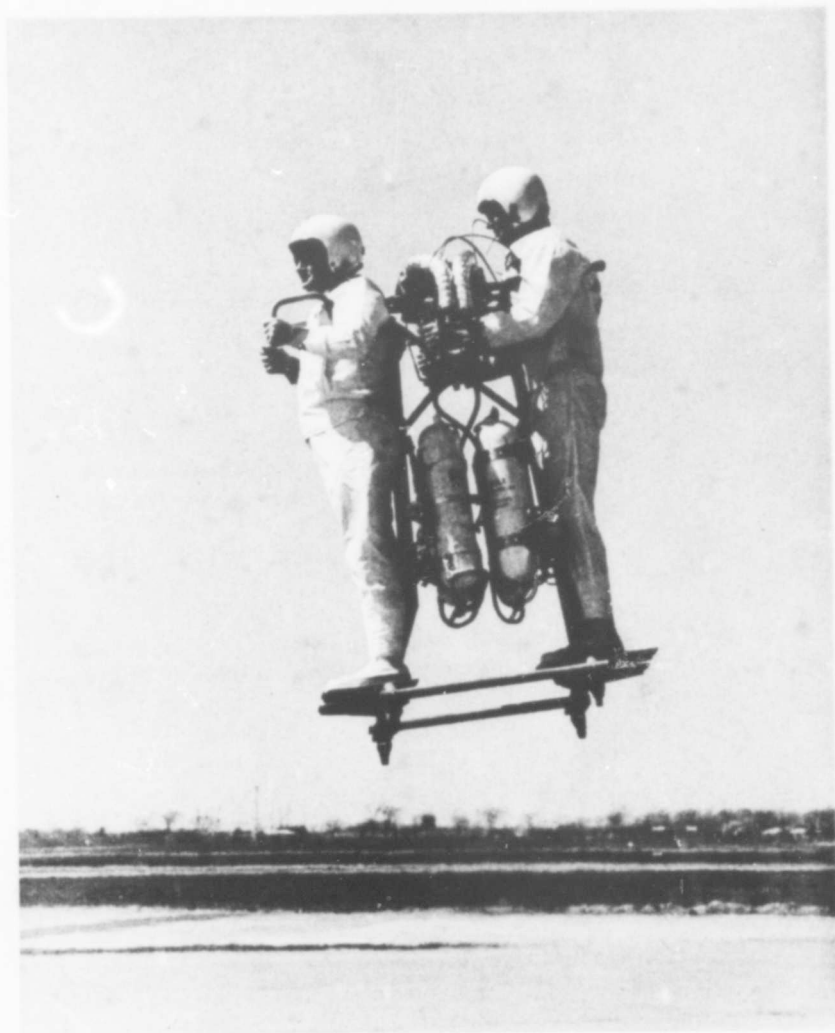


Figure 9. Two-Man Rocket POGO Vehicle.

Emplacement of Scientific Instruments

Instruments could be emplaced at greater distances from the lunar module. This, of course, would allow a greater range of selection of monitoring sites, as well as a greater number of separate sites.

Table II. Potential Missions For Lunar Flyers

Surface exploration
Emplacement of scientific instruments
Transportation into inaccessible areas
Remote sensing
Surveying/mapping
Rescue

Transportation into Inaccessible Areas

Deep crater and lunar rille exploration is of considerable interest for lunar surface study. The accessibility of these locations to a walking astronaut, or one riding in a surface vehicle, is limited.

Remote Sensing

A lunar flyer offers considerable potential for remote sensing across the complete electromagnetic spectrum, which would provide not only direct scientific information, but also additional reconnaissance information to guide subsequent detailed exploration.

Surveying/Mapping

A flyer could be utilized for quick and accurate surveying/mapping of areas which are out of the line of sight of the lunar module.

Rescue Mission

Lunar flyers could be utilized in conjunction with surface vehicles as a means of return to the lunar module in the event the surface vehicle should malfunction, or for rapid rescue of a walking astronaut. In addition, it is feasible to employ a simple propulsion unit with sufficient ΔV to escape from the lunar surface gravitational field and inject the astronaut into lunar orbit, where he could be retrieved by the parent spacecraft.

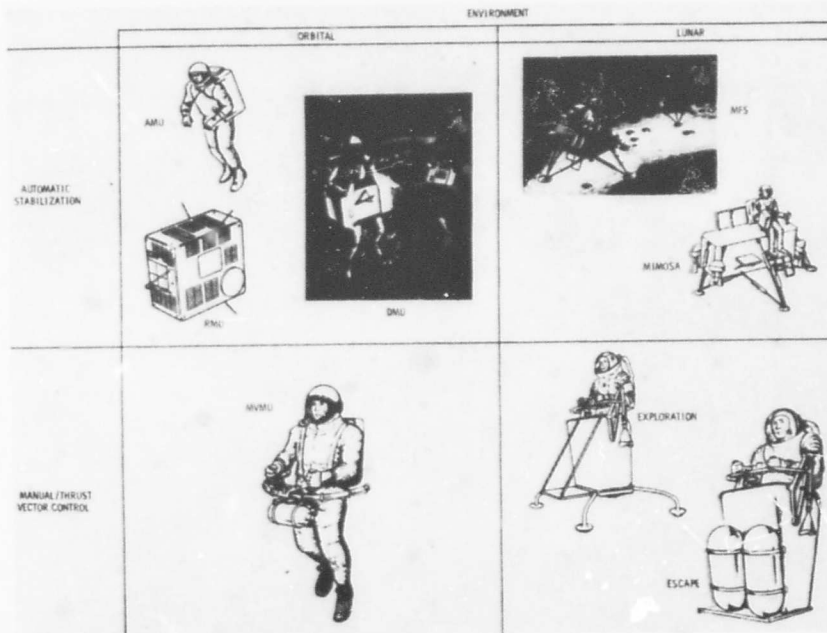


Figure 10. Spectrum of Maneuvering Aids.

There are basically three control system concepts which have been proposed for use with space propulsion devices, whether they be used for lunar flying, or for orbital operations. They include those vehicles which are controlled by shifting body weight (i.e., kinesthetic control); vehicles which have stability augmented control systems of one kind or another; and those controlled by manual thrust vector positioning, such as derivatives of the Rocket Belt or Rocket POGO. Bell Aerosystems has concentrated largely on the latter two classes.

Figure 10 shows some of the variations in configuration which we have studied. On the right-hand side are some of the Lunar Flying Vehicle concepts we have worked on. At the upper right are one-man and two-man automatically stabilized versions. These use orthogonally mounted attitude control thrusters with on-off attitude commands generated by a 3-degree-of-freedom sidearm controller. The configurations shown would be capable of approximately a 15-mile radius round trip, or a 50-mile one-way flight. They could carry up to 300 pounds of scientific equipment, and



Figure 11. Lunar Flying Vehicle Mockup.

would be powered by four 100-pound thrust bipropellant rocket engines. At the bottom right are one-man versions of thrust vector control devices.

Figure 11 is a closer view of a mockup of one of these devices; a more sophisticated version of the Rocket POGO device. They

would also be powered by bipropellant rocket engines. The shield is provided to protect the astronaut and the propellant tanks from the lunar and rocket plume environment.

The design requirements and operating characteristics of a rocket lift device for lunar use will, of course, differ in several aspects from that of a similar vehicle on Earth. We have been studying these differences over the last few years, and Table III lists some of the major contributing factors.

The absence of an appreciable atmosphere on the moon is a significant factor. We ran a series of simulator runs in which atmospheric drag effects were eliminated along with X-axis, and found that experienced Rocket Belt operators did, in fact, tend to over-accelerate. We found, however, that they quickly learned to compensate in their control movements, and we don't anticipate any serious problems.

The second and third effects are interacting and must be considered together. Lunar vehicle systems will have masses and inertias comparable with their corresponding Earth designs; however, the 1/6 g field on the Moon requires a corresponding six times reduction in system thrust. These effects combine to dictate reduced attitude control powers and translational accelerations. The slower response tends to improve controllability, because it in effect gives the operator more "think time."

There was initially some concern about the effect of a full-pressure suit on operator control. In order to investigate this effect, as well as the effects of reduced gravity, Bell conducted, under contract to NASA, a series of 1/6 g flights during May and June of 1967. These flights were conducted at Langley Research Center, using the large outdoor Lunar Landing Research Facility

Table III. Factors Affecting Lunar Operation of Rocket Lift Devices

Absence of aerodynamic drag effects
Mass and inertia effects
Reduced gravity effects
Full pressure suit effects

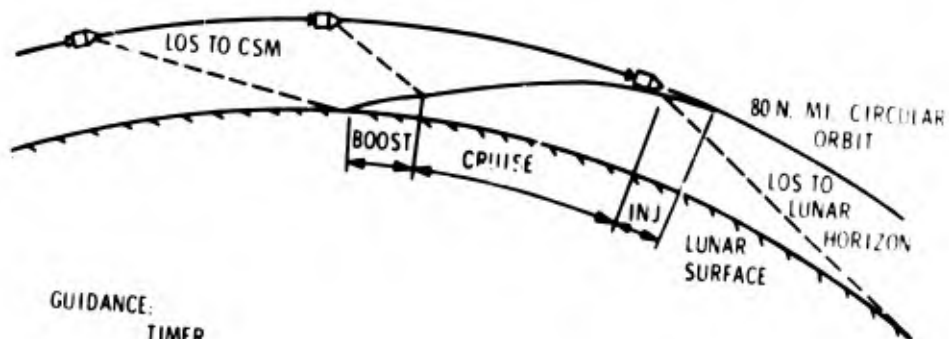
and a constant tension suspension system designed to support five-sixth of the weight of the gimbal, vehicle, and operator assembly. Two pilots were used; a Bell pilot who had previously flown over 700 flights in this type of vehicle in earth g environment and a pilot from NASA-Langley who had made 58 previous flights. The flights started with shirtsleeve operations; then the same maneuvers were repeated in the Apollo soft pressure suit; and later in the hard suit.

The test results can be summed up by saying that both pilots found it easier to fly under $1/6$ g than 1 g, and the hard suit condition was the easiest of the three. The vehicle controls were somewhat oversensitive in pitch and roll, since they hadn't been optimized for the reduced g condition, but this is relatively easy to correct.

As mentioned earlier, it would be possible to use this type of vehicle for emergency escape to lunar orbit. Two such vehicles, with a dry weight of 146 pounds each, which would use propellants from the LM Descent stage, could be carried on the LM vehicle.

Figure 12 shows one typical guidance technique and nominal trajectory for such a mission. After a short vertical ascent, the astronaut would pitch the vehicle to acquire the Command and Service Module in its lunar orbit in the crosshairs of a simple visual sight and would maintain the crosshairs on the Command and Service Module throughout the boost phase. At a pre-determined time, thrust would be reduced to a preset low level for the cruise phase. At a second predetermined time, injection into orbit would be initiated by pitching the vehicle to acquire the lunar horizon. At the same time, thrust would be increased to a preset injection phase magnitude. Horizon tracking would be continued until a third preset time when thrust would be terminated, placing the astronaut in the required orbit for retrieval by the Command and Service Module. This nominal trajectory requires a total ΔV of 6,792 ft/sec, which is easily obtainable from the propellant load on the vehicle. The total ascent flight time is 11.3 minutes. Error analysis indicates that a lunar orbit can be achieved with sufficient accuracy so that the Command and Service Module can perform the retrieval within its ΔV budget.

Turning now to orbital maneuvering aids, these also break down generally into two classes: those incorporating some form of



GUIDANCE:
 TIMER
 VISUAL SIGHT
 THREE FIXED THRUST PHASES
 ORBITING CSM AND LUNAR HORIZON AS REFERENCES
 OPEN LOOP ASCENT TECHNIQUE

ΔV :
 6792 FT/SEC (PLUS OUT-OF-PLANE 100 FPS / DEG.)

ASCENT TIME:
 11.3 MINUTES

RENDEZVOUS AND DOCK
 CSM ACTIVE

Figure 12. Escape to Orbit Technique and Nominal Trajectory.

stability augmentation; and those using simple thrust vector control.

We have done work on both types. The upper left-hand quarter of Figure 10 shows an Astronaut Maneuvering Unit using orthogonally positioned thrusters and rate gyros in each axis for stabilization. Beneath it is shown an unmanned version, a Remote Maneuvering Unit incorporating a TV camera and other sensors, which can be remotely controlled from the parent spacecraft, or by commands from Earth tracking systems. On the right, an artist's concept illustrates a combination of two—a Dual Maneuvering Unit which we designed under contract to the USAF Aero Propulsion Laboratory, which could be used in either the manned or unmanned mode.

At the bottom left is shown a Manual Thrust Vector Control Maneuvering Unit (MVMU). Figure 13 is a closer view of this configuration. This unit is attached directly to the astronaut's body with a quickly removable harness arrangement and employs

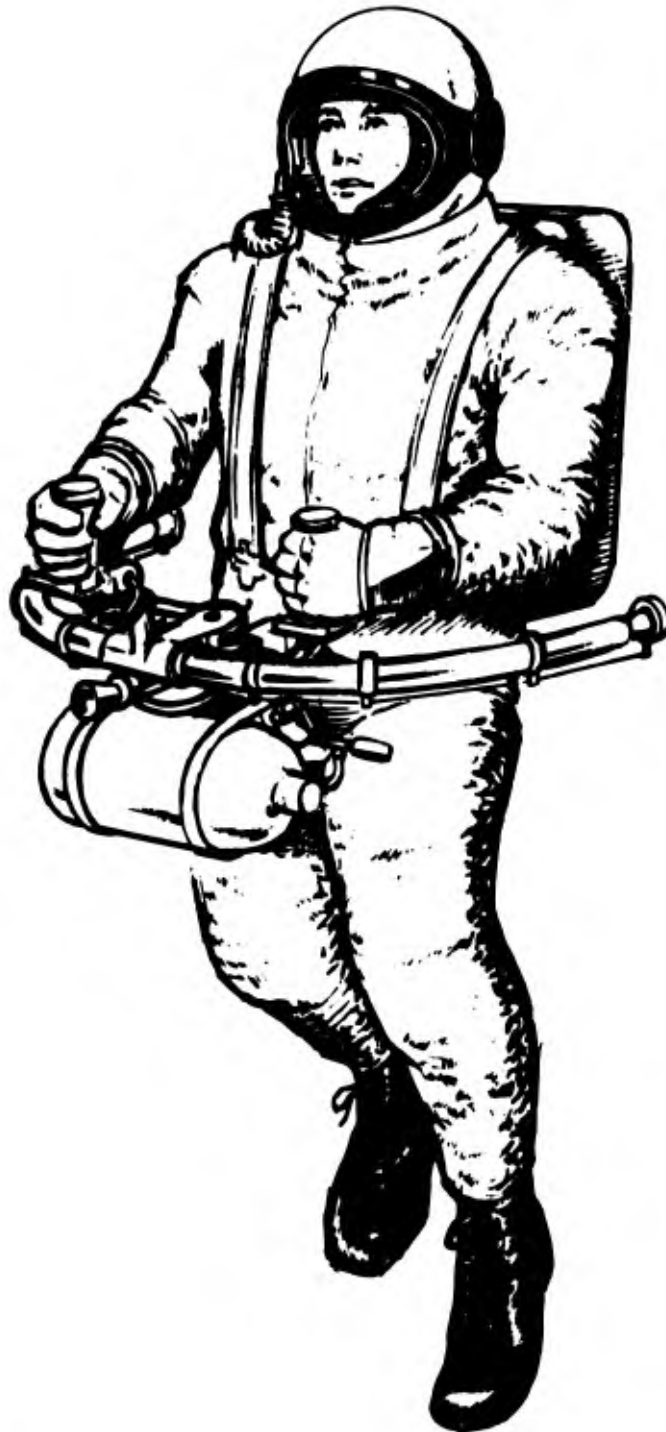


Figure 18. Manual Thrust Vector Control Maneuvering Unit (MVMU).

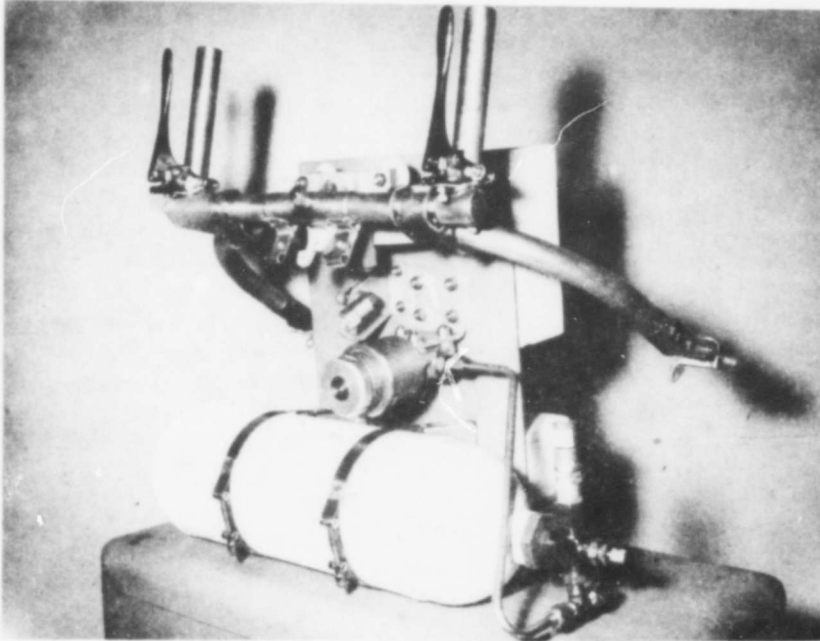


Figure 14. MVMU Test Unit.

three thrusters: two firing forward, and one rearward. In this respect, it is similar to the hand-held thruster unit used on Gemini flights 4 and 10. Control in the three axes is obtained by moving the hand controllers in much the same manner as described earlier for the Rocket Belt.

Figure 14 shows a prototype unit of the MVMU which is cold gas powered and which has been used for Earth testing. It is made of off-the-shelf components and is not a flight weight system. The flight weight system would be simplified and could be hydrazine powered.

The choice of which type of a system to use for a given orbital mission (stability augmented or thrust vectoring devices) depends upon the range involved, the time available for the maneuver, and the type and amount of instrumentation and supporting equipment available. In over-the-surface operations, either on Earth or on

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the Moon, the operator has a combination of visual, dynamic and vestibular cues to determine his flight trajectory. In orbit, the vestibular and dynamic cues are largely absent, so the operator must depend largely upon visual cues for determining his thrusting actions. These cues may be derived from a variety of sources, including the star background, the horizon, or the target vehicle. Analytical studies, simulation, and our limited orbital flight experience all indicate that at short ranges the pilot is able to maneuver with respect to a target object simply by aiming and thrusting in the direction he wishes to travel. As separation distances increase, however, these visual cues become less useful. The maximum safe range of operation has yet to be determined. Because of the large number of potential orbital missions, it is doubtful that any one system will be optimum for all areas of application.

After 15 years of work in the area, Bell Aerosystems is convinced that, while there is still much work to be done in this field, these individual mobility devices have proven their feasibility and have significant potential, both on earth and in space.

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X

Manned Space Stations

Dr. Robert R. Gilruth*

GATEWAY TO OUR FUTURE IN SPACE

Space stations orbiting the Earth have long been the dream of space engineers and scientists. There have been many concepts and designs proposed, and many reasons have been given for their use. One of the problems has been the difficulty of dealing with the very multitude of uses and the infinite variations of designs.

During the last few years, however, several things have happened to help clarify the picture: First, the recent development of the Saturn V rocket has provided one of the major building blocks for space station design. Secondly, we now have a far greater knowledge of the environment desirable for working and living in space; and, thirdly, the programs of the work in science and technology to be done in a space station have been studied in considerable depth with the result that the use requirements can now be better defined.

In this paper, I will discuss why the space station concept is attractive and what I believe are the basic design requirements, describe briefly our present Earth orbital plans as contained in the Apollo Applications Program, and conclude with some speculations on what future Earth orbital space stations could be like.

WHY SPACE STATIONS?

So much has been written, both in the science-fiction field and in technical documents about space stations, that it is useful to

*Director, Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas.

MANNED SPACE STATION

- A LOCATION IN SPACE WHICH IS DEVELOPED TO SUPPORT MEN AND OPERATIONAL AND EXPERIMENTAL EQUIPMENT ON A PERMANENT BASIS IN ORDER TO TAKE ADVANTAGE OF THE ECONOMICS OF SIZE, CENTRALIZATION AND PERMANENCY
 - POWER BASE
 - VOLUME BASE
 - LOGISTICS BASE
 - EXPERIMENT EQUIPMENT BASE
 - COMMUNICATION BASE
 - DATA REDUCTION BASE

Figure 1

SPACE STATION ADVANTAGES

- PERMANENCY
 - REUSE, REFURBISHMENT, AND MODIFICATION OF OPERATIONAL AND SCIENTIFIC EQUIPMENT
- LOGISTIC CENTER
 - CENTRALIZED SPACE LOCATION AND STORAGE CAPABILITY PERMITS EFFICIENT LAUNCH SCHEDULES FOR OPERATIONAL AND EXPERIMENT SUPPORT SUPPLIES
- POWER CENTER
 - PERMANENCY AND LARGE SIZE MAKE LARGE POWER SOURCES USEFUL AND TECHNICALLY FEASIBLE
- PERSONNEL CENTER
 - INCREASES RATIO OF EXPERIMENT TIME TO HOUSEKEEPING TIME AVAILABLE
- ALLOWS SPECIAL DISCIPLINE MEMBERS IN THE CREW
- FLEXIBLE CREW ROTATION PATTERNS CAN BE ESTABLISHED

Figure 2

state what we mean by space stations. I have presented a fairly concise definition in Figure 1. It is important to note that, as the definition states, a space station is not so much a "thing" as it is a location in space which is developed to support men and equipment on a permanent basis in order to take advantage of the economies of size, centralization, and permanency. In other words, a space station is a "base" in space, equivalent in function to those used in many forms of terrestrial exploration, for example, those in the Antarctic. As the chart indicates, the base has six important characteristics: it is a central location for power, volume, logistics, experimental equipment, communications, and data reduction. Such a definition encompasses schemes in which all of these things might be located within a single volume, or alternately where there may be several devices which are orbiting the Earth in close proximity with one another. An example of this latter form would be a station which consists of a large living center surrounded by free modules containing telescopes, earth sensors, and specialized scientific satellites orbiting close enough so that they could be tended or serviced intermittently by personnel from the living quarters.

In Figure 2, the next chart, I have indicated the features from which we expect to profit by creating a space station program wherein all the individual missions contribute directly to the success of the total mission. First, as the chart indicates, we are seeking the economic benefits which will accrue from the achievement of a longer lifetime of the objects we place in space. Both the equipment required to support man and to run the station, and the basic scientific equipment which we place in space can operate for long lifetimes. With proper logistics support, these items can be reused, can be refurbished where wearout phenomena or random failures have occurred, and, perhaps more importantly, can be modified to take advantage of gains in technology or changes in experimental objectives. As will be noted later on, experimenting with permanency is one of the major goals of our Apollo Applications Program.

The creation of a permanent place in space to which we return again and again allows us to centralize the storage of expendables and equipment and to make maximum use of a limited number of logistics flights. Since logistics flights are the largest single cost element in any orbital program, this is an extremely important economic advantage of space station operation.

APOLLO APPLICATIONS PROGRAM

● OBJECTIVES

- ESTABLISHMENT OF MAN'S BIO-MEDICAL AND OPERATIONAL CAPABILITIES TO FUNCTION IN SPACE FOR EXTENDED PERIODS
- ESTABLISH MAN'S ROLE IN THE OPERATION OF COMPLEX SCIENTIFIC INVESTIGATIONS IN ASTRONOMY AND EARTH OBSERVATION

● CHARACTERISTICS

- MAN'S FIRST EXPERIENCE IN SPACE WITH ADEQUATE VOLUME AND SUPPORT EQUIPMENT
 - FIRST COMPREHENSIVE MEDICAL MEASUREMENTS CONTINUOUSLY FOR EXTENDED PERIODS
 - FIRST PROGRAM PLANNED PRIMARILY AROUND EXPERIMENTAL AND SCIENTIFIC OBJECTIVES

Figure 3

This logistic advantage is also important for the economical transportation of the crew, but there are other advantages to creation of a personnel "center" in space besides the economies of logistics. First, when we have achieved a crew size of about 11 or 12 people, we begin to realize the economy of large size since only a small percentage of total crew worktime will have to be spent on the functions of operating and maintaining the station, thus making available a greater percentage of time for the accomplishment of experimental objectives. The economies of specialization are also available as the concentration of a large number of people allows most of them to be specialized for individual experimental functions. This will relieve the considerable cross-training problems which are inherent in small crews. The concentration of personnel in a permanently established volume makes it feasible to provide relatively large amounts of volume devoted to personal comfort and convenience and to establish, throughout the station, living conditions which are more Earth-like than we can afford in smaller space vehicles. This will be important in the selection and training of crews and in their efficiency in space operations as well.

In addition to the above advantages, which are primarily operational in character, there is one system which will definitely benefit from the economics of permanency and large size: the power system. The large size of the space station enables us to develop the structure necessary to support either the large panels required for solar cells or to provide the separation, shielding weight, and radiator areas required for large nuclear systems. The capability of a space station to carry power sources of 20 to 50 kw or even 100 kw will be its most important technical contribution, since the availability of power is the basis of all system design and is fundamental to the capability of nearly all experimental equipment.

APOLLO APPLICATIONS PROGRAM - A MODEST BEGINNING

We have long recognized these intrinsic advantages of space stations and the Apollo Applications Program is designed to explore them in a modest way. Figure 3 presents a chart of the basic Apollo Applications objectives and characteristics. The primary goal of the Apollo Applications Program is the establishment of man's capability to function in space for significantly long periods of time and to establish man's role in conducting complex investigations in space. The "wet launched" workshop will contain sufficient volume (almost 4,000 cu ft per man compared to Apollo's 120) and support equipment so that the astronauts will be able to function and live in a manner more like that of the Earth's environment than has been the case to date with the closely packed spacecraft. This is to be accomplished by outfitting an S-IVB booster stage so that it can be entered by the astronauts after depletion of hydrogen and made into livable quarters. This "workshop" will be visited over a period of time by a series of Apollo Command Service Module flights.

Figure 4 presents a view of the initially launched workshop with a Command Service Module attached, and it shows the tubular docking adapter mounted at the front end of the S-IVB stage and connected with the airlock. The interior of the hydrogen tank has been outfitted with equipment originally stored in the docking adapter in a series of rooms mounted on the middle floor which was initially installed in the hydrogen tank. The power source (6-kw solar cells) is shown extended from the mounting pods on the side of the S-IVB.

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AAP ORBITAL WORKSHOP - INITIAL MANNING

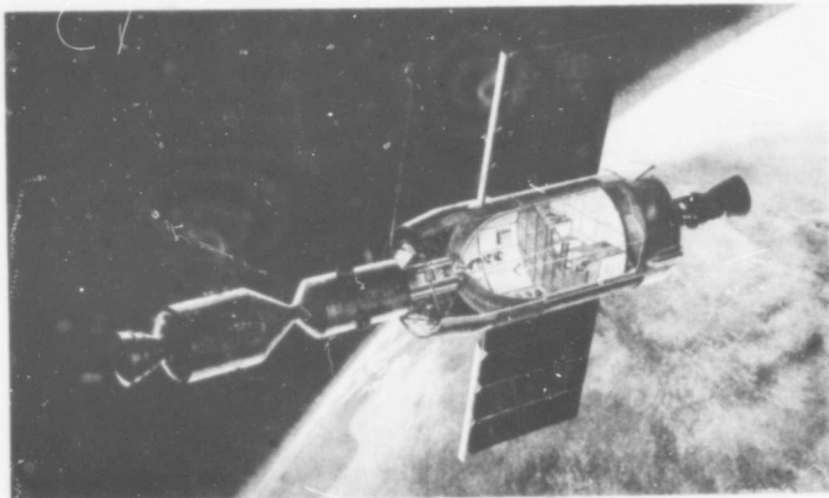


Figure 4

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**S-IVB WORKSHOP MOCKUP SLEEPING
AND FOOD PREPARATION CUBICLE**

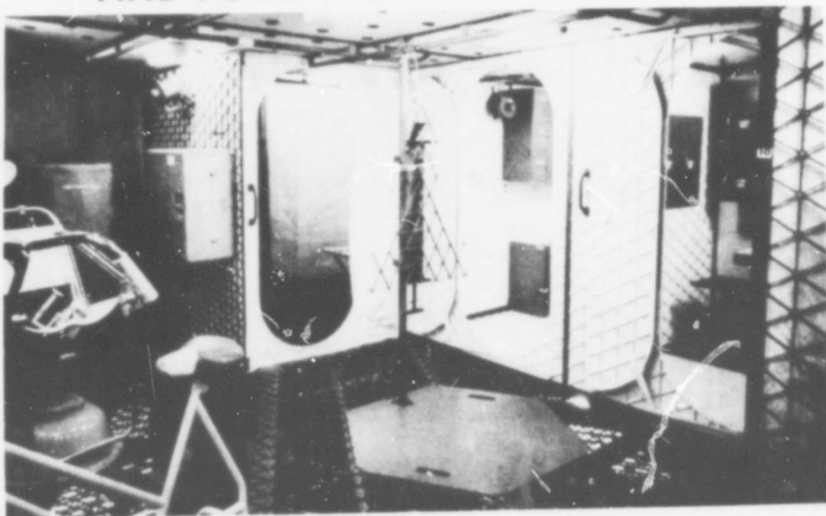


Figure 5

The next two pictures are taken inside a full-scale mockup at the Marshall Space Flight Center. Figure 5 shows the doorways leading into three of the four rooms on the main deck. These rooms will be used for sleeping compartments, waste management, and food preparation. These are all elements in one of the major test programs associated with the wet workshop; namely, that of ascertaining the habitability characteristics required to support astronauts in space.

Figure 6 shows equipment for one of the elements of the very thorough medical test programs which will be another main feature of the Apollo Application mission. This is the ergometer, which is the bicycle-like device in the foreground of the second picture. Also shown are three subjects, one seated in a Barany chair which is another piece of test equipment for medical experiments. This second picture shows more clearly the area outside of the rooms equipped with experiments which have been brought into the area from their stowage place in the docking adapter.

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S-IVB WORKSHOP MOCKUP EXPERIMENT AREA

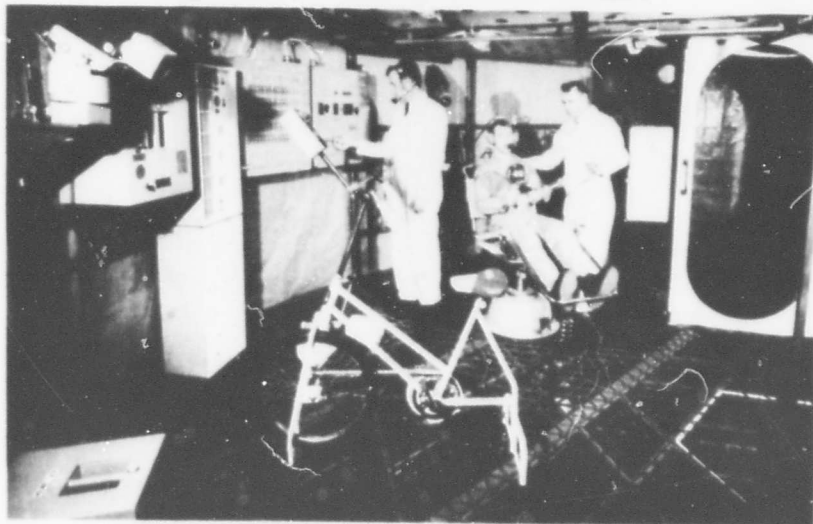


Figure 6

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AAP ORBITAL WORKSHOP WITH LM/ATM SOLAR EXPERIMENT ATTACHED

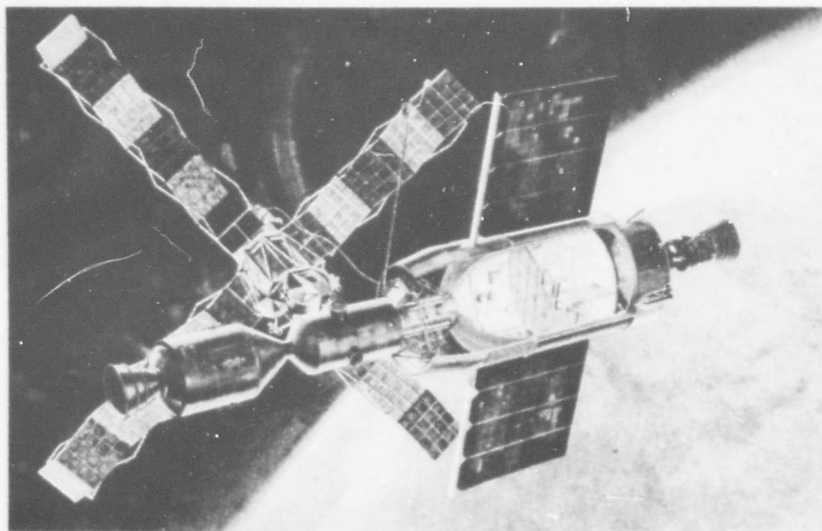


Figure 7

The Apollo Applications Program also will include a major science experiment, a solar observation experiment which will be launched and rendezvoused unmanned with the wet workshop and which will be docked by an astronaut located in the docking adapter, using remote control. A view of this experiment located on the workshop is shown in Figure 7. This experiment will provide us with two very important steps toward our future space station programs. First, it will be our first chance to link man with a really complex scientific experiment and thus to explore his capabilities to function with such devices. Secondly, we will be developing techniques and equipment for sending experiments and supplies to a space station in an unmanned mode. This mode may be an important method for logistic supply in the future.

It is apparent from this brief description that the wet workshop will be fulfilling the role of a prototype space station. It will provide a generous living volume, the essential power and communications systems, and it will be operated over a period of time. Thus,

our "modest" beginning will be clearly laying the groundwork for the development of future space stations by giving us basic data on man, the systems, and some of the experiments which will define our future programs.

In creating the wet workshop we have been forced, however, to neglect what may be one of the major requirements for successful operation of a space station: artificial gravity.

THE ARTIFICIAL GRAVITY PROBLEM

The Apollo Applications program wet workshop program, as now envisioned, will provide us with a good base from which to evaluate man's performance in space at zero-gravity. In this section I will discuss some of the things we have been thinking about concerning the need for artificial gravity and for a test program to define its characteristics. As noted earlier, I have discussed some general reasons why we feel that space stations are advantageous in developing an economic program for the beneficial exploitation of space, and one of the main advantages I noted was that it could provide an Earth-like environment which would enable a wide segment of our scientific community to be potentially available for space work. This leads me to discuss what I believe is a very important aspect of space station requirements; namely, the need that the station be designed to provide a high level of artificial gravity. The principal reasons for this are indicated in Figure 8. First, note that our concern is not that man will not be able to adapt to zero-gravity over the period of time that he is likely to be a crew member aboard a space station (3 to 6 months). The problem is one of providing relatively normal living and working conditions. This will be important for crew comfort and adaptation to living conditions and will, therefore, increase their basic efficiency and task effectiveness.

As noted on the chart, the environmental factors affected by artificial "g" can be divided into three types: those connected with processes involving fluids; those connected with locomotion and orientation; and those including general man/machine interfaces. By providing gravity, fluid processes such as those associated with personal hygiene, cleaning, food preparation, chemistry, all can be performed in a manner identical to that which we are accustomed to here on Earth. With the establishment of normal

ARTIFICIAL GRAVITY

- NORMALIZES ALL PROCESSES INVOLVING FLUIDS
 - WASHING AND PERSONAL HYGIENE
 - FOOD PREPARATION
 - CHEMISTRY
 - CLEANING
- NORMALIZES LOCOMOTION AND ORIENTATION
 - HANDS-FREE WALKING
- 'NORMAL' MAN/MACHINE INTERFACES
 - MINIMIZES SPECIAL TRAINING AND MAXIMIZES EFFECTS OF EARTH TRAINING
 - PERMITS USE OF 'STANDARD' EXPERIMENT AND OPERATIONAL EQUIPMENT

Figure 8

gravity relationships, the ability to walk with the hands free will provide the basis for an environment which needs little or no training for adaptation. Artificial gravity will also provide normal man/machine interfaces with all types of equipment--both operational and experimental. Again, this would eliminate the need for special zero-gravity training and would maximize the effectiveness of Earth training, especially for the more complex repair, refurbishment, and modification tasks we can expect in the future. This advantage is a major feature of an artificial gravity station. As a corollary to this, artificial "g" will permit the use of equipment developed for use in Earth laboratories but otherwise applicable to space station tasks.

For all of these reasons, we conclude that the characteristics of artificial gravity are important objectives for a near-term Earth orbital activity and I will discuss some of the parameters which should be studied by special experiments before we can be firm about a conceptual design which would meet the space station objectives.

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ARTIFICIAL GRAVITY ENVELOPE

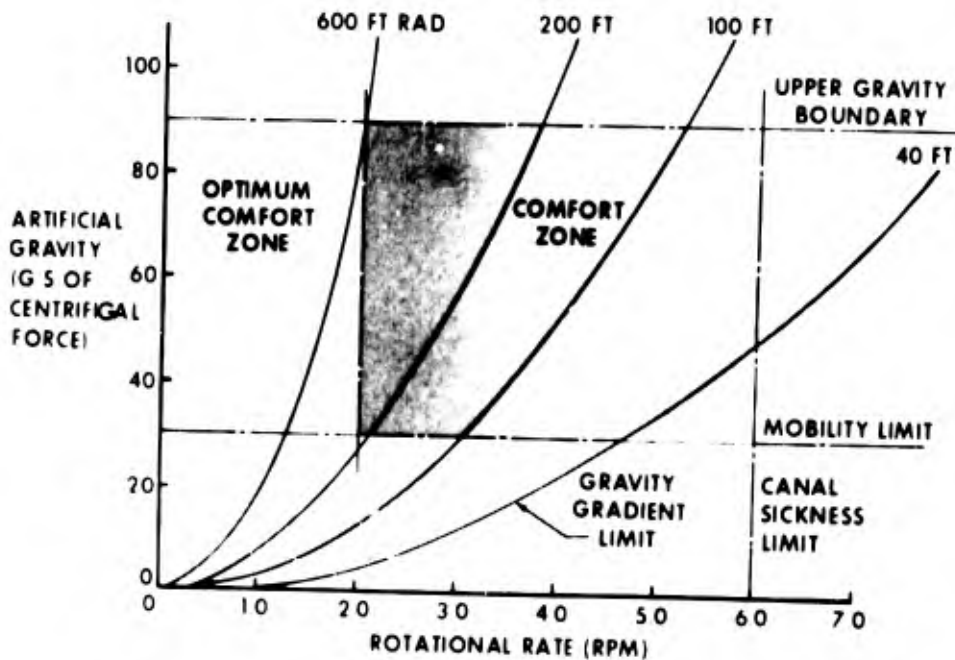


Figure 9

As you will note in Figure 9, artificial "g" has two important parameters for any given level: the rate at which the vehicle is rotated, and the radius at which the man is stationed. We have indicated on the chart a so-called "comfort zone," namely, an area which ground-based tests have indicated man can tolerate without serious problems of adjustment. Parabolic airplane flights have indicated that most of the problems of locomotion and fluid transfer are overcome by gravity as low as three-tenths g. Since rotational simulators on the ground have indicated that the average person can adjust to 4 rpm, we are led to a minimum rotational arm of about 50 feet. However, these ground tests are limited because they always have a 1-g field affecting the results, and we cannot be certain that when that field is nonexistent that the rotational forces will not affect the subconscious adaptation mechanisms more strongly. Thus, we are interested in even lower rotational rates and higher gravity forces. We would like to investigate radii as high as 200 feet and gravity as high as 1-g. These considerations have led us to examine a system shown in

ARTIFICIAL GRAVITY EXPERIMENT

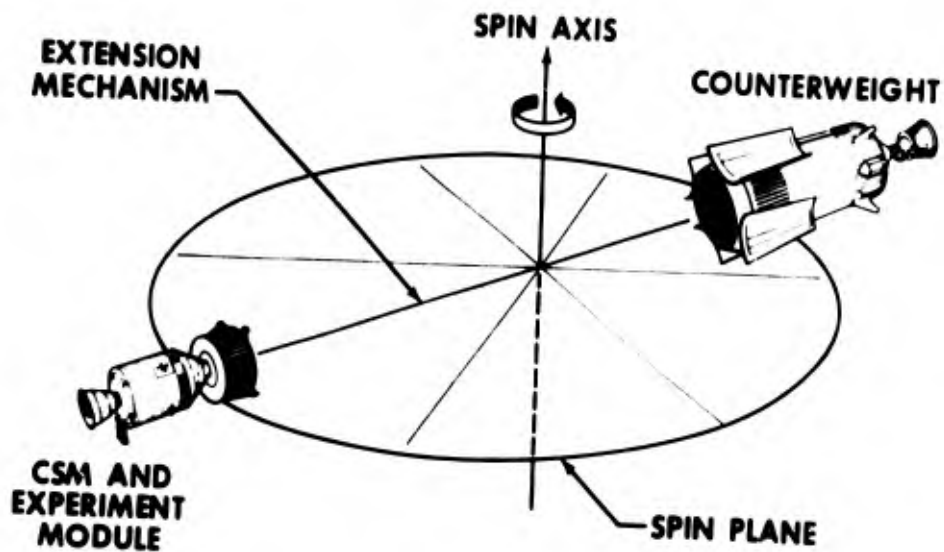


Figure 10

FUTURE EXPERIMENT EXAMPLES

- OBSERVATIONAL EXPERIMENTS
 - ASTRONOMY
 - EARTH SENSING
- ON-BOARD EXPERIMENTS
 - BIO-MEDICAL
 - BIO-SCIENCE
 - PHYSICS

Figure 11

Figure 10; namely, the rotation of an Apollo spacecraft with an experiment module, both tethered to an S-IV rocket stage in such a way that various radii can be achieved by the system. With this type of experience, we can be ready to construct the type of space accommodations which we feel will be necessary to meet the comfort and work requirement of the future space activity.

THE NEXT STEP — EXPERIMENTS AND APPLICATIONS

Any discussion of a future space station program must be preceded by an understanding of the types of experiments which will likely be a part of that program. NASA has recently spent considerable effort in studying experimental programs for space stations as given in Figure 11. The results of these studies can be classified under two general headings: observational experiments which include astronomy and Earth sensing; and on-board experiments such as bioscience and biomedical experiments and high energy physics.

ASTRONOMY

The sciences which make use of the observational advantages of Earth orbit will benefit most obviously from space station operations. Astronomy, especially, can be expected to produce dramatic results from being able to observe outside of Earth's dirty and shimmering atmosphere.

Figure 12 is presented to give a feeling for some of the engineering work that has gone into the sizing and design of astronomy experiments. The chart presents, in hard outline, modestly-sized telescopes of the 40-inch objective type, which are the optical equivalent of land-based 120-inch telescopes. Even these are large enough to require a significantly large space station as a base; but these are just a beginning. Telescopes of 120-inch diameter have been seriously proposed by the National Academy of Sciences as an objective for space astronomy. A conceptual design of a 120-inch telescope is shown in the background at the same scale to give a feel for the size of things to come. Such a telescope would probably be flown adjacent to a space station and visited periodically for service and data retrieval.

ASTRONOMY

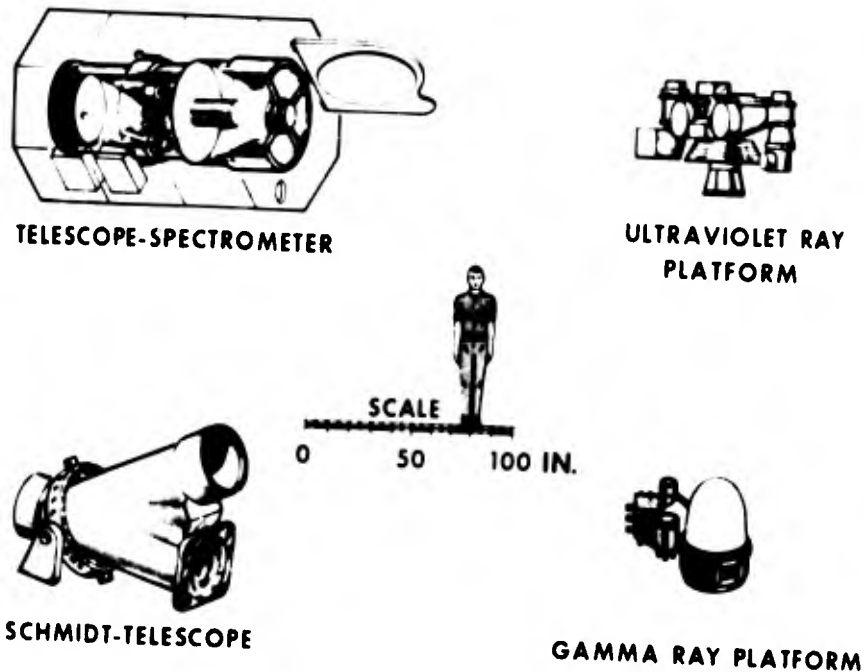


Figure 12

EARTH SENSING

The development of remote sensing equipment for the observation of the Earth's surface, and probably subsurface, will be one of the major tasks of the manned space base.

To date, our principal experiments with Earth observation from space have been primarily photographic. As many investigators have shown, these photographs taken with simple equipment give us dramatically new and astonishingly useful views of our home planet.

My next two charts are photographs taken on our last Saturn V flight. This chart, Figure 13, covers approximately 10,000 square miles in the El Paso-Juarez area and includes the pure white sands of the White Sands National Monument. It is a clear example of the detail which is obtained with space photography. The communications system in the international metropolitan area is clearly

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**WHITE
SANDS
EL PASO
AREA
APOLLO
PHOTOGRAPHY**



Figure 13

seen. The agricultural utilization along the valley of the Rio Grande can be viewed over a large area. Unique volcanic features are seen to the west of El Paso. Snow covers the higher peaks of the Sacramento Mountains to the east of Alamogordo. The unique capabilities of space photography result from the broad synoptic view of large features which can be seen in a single photograph. Large mountain systems can be visualized in a single photograph, and important geophysical relationships are established over areas of up to 250 miles square. To obtain the same information by conventional aircraft and photomosaic techniques would require hundreds of photographs to be secured, all under different and changing conditions, and a cumbersome assembly would be required.

The next photograph, Figure 14, indicates another use for space observation—oceanography. It shows quite plainly the eastern edge of the Gulf stream for a distance of about 50 miles. Techniques are being developed for routine observation of the ocean; the measuring of its temperatures, sea state, and currents.

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GULF
STREAM
AND
SEA
STATE
APOLLO
PHOTOGRAPHY



Figure 14

But photography covers only a very small part of the information the Earth is sending into space. Figure 15 shows a concept of electromagnetic Earth sensing equipment which would have the capability of measuring the Earth's surface over nearly the entire electromagnetic spectrum. The large variety of experimental equipment which will be of interest in this area of investigation can easily be seen; and again, the rather significant size of the sensors is noticeable. There is little doubt that this field of endeavor holds great promise for future applications of direct benefit to a wide variety of professions and occupations, as well as to the scientific community in general. It will probably be so useful that we will want to spread its benefits to other nations, especially those nations which are just emerging into the world of modern industry and agriculture. This use of our space abilities may well become a great force for international cooperation and I, personally, look forward to the day when our space station crews will contain representatives from all the nations of the world.

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Figure 15

BIOMEDICAL AND BIOSCIENCE EXPERIMENTS

On-board experiments can take a great many forms. Some will take advantage of the limitless vacuum of space; these may well involve manufacturing processes in the long run. Some will be in space to utilize the unique environment of zero-gravity. The zero-gravity environment is of special interest to the biomedical and bioscience researcher since it will undoubtedly open new avenues in research on the growth process in animals and plants. Figure 16 shows a typical laboratory with animal colonies and plant farms. It also shows some biomedical experiments, and again we can expect that the zero-gravity environment will help immeasurably in the investigation and understanding of fundamental principles.

PHYSICS

It is interesting to recall that the study of the fundamental particles of nature began with observations made from the natural cosmic radiation that exists in space. These initial experiments

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BIOLOGY LABORATORY

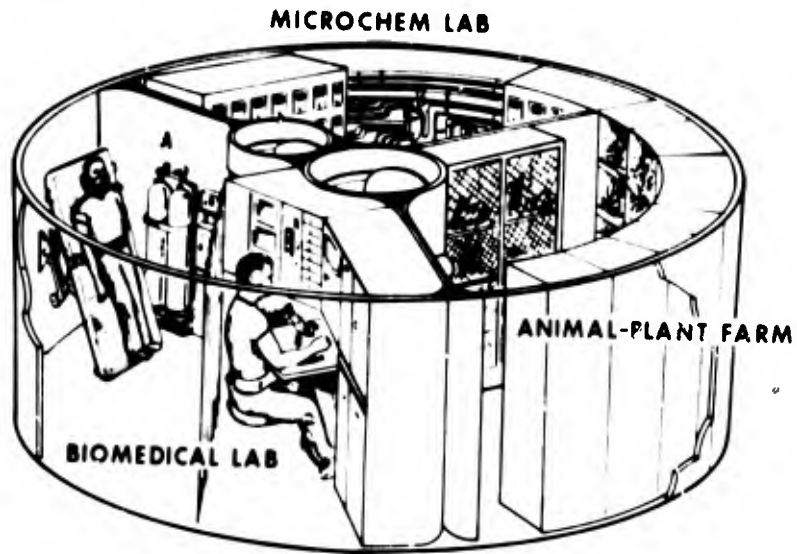


Figure 16

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HIGH ENERGY COSMIC RAY LAB

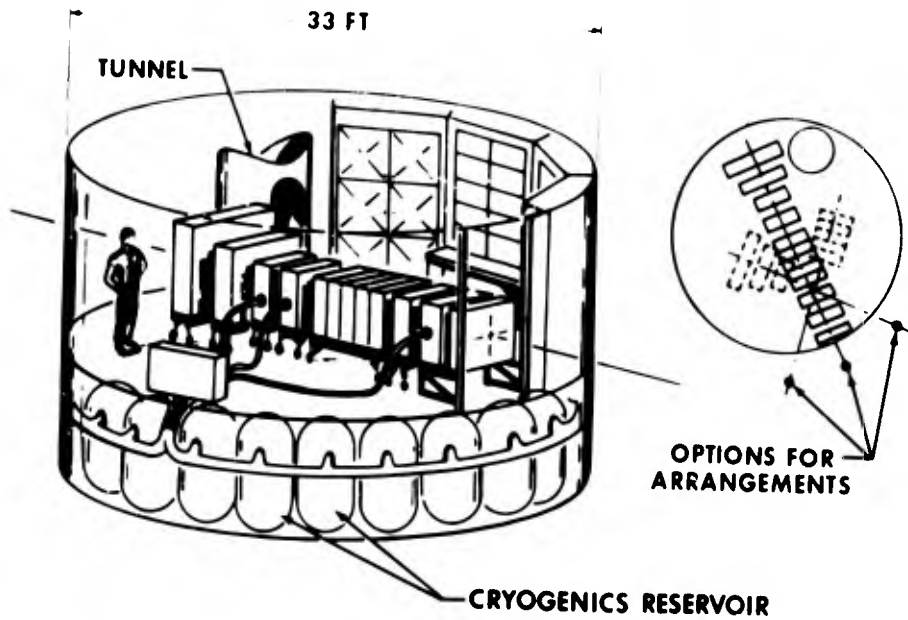


Figure 17

were made from balloons and mountain tops. Our space station capabilities will open the way for a return to the natural environment as a primary source of high-energy particles. By placing a large cosmic ray facility in a space station, such as is shown in Figure 17, we will extend the basic particle energy available for investigation by three orders of magnitude (from 70 BEV to 70,000 BEV). We can expect to increase our knowledge significantly about the nature of the fundamental particles in matter just as our recent increases in energy capability have so changed our simple electron-proton-neutron picture of the atom. But equally exciting will be the clues that the nature of cosmic rays will give on cosmological questions—questions such as the possible existence of antimatter in the universe.

The operation of such a laboratory will be a very complex affair, using the most advanced techniques for recording and analyzing data. Because of these problems and because of the large size and complexity of the cryogenically cooled superconducting magnets which will be at the heart of the laboratory, the presence of highly trained scientists will be a necessity for such a space laboratory.

THE NEXT STEP — SPACE STATION CONFIGURATION

Having examined the types and general characteristics of possible experiments, we can now proceed to examine what one of the first operational space stations might be like. In Figure 18, I have listed some general space station characteristics which I believe will be required to meet the type of experiment program discussed above. The first characteristic listed on this chart is that the station shall have an Earth-like environment. This means, principally, that the station will be designed for 10-14 psi (air) atmosphere system ($O_2 + N_2$ and possibly with trace elements) and for $\frac{1}{2}$ to 1 g of artificial gravity in the major living and operational areas of the station. We must, of course, include a counter-rotating laboratory operating at essentially zero-gravity. The station should have the capability of accommodating at least a fifty-man crew initially, with the prospect of being able to expand its capabilities to at least 100 by additional launches. We must certainly plan to operate the station at higher inclination than those conducted to date in our space flights. Our studies have shown that about 50° inclination, or somewhat higher, is a good compromise for operational and experimental reasons. This inclination provides a near

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LARGE SPACE STATIONS- GENERAL CHARACTERISTICS

- EARTH-LIKE ENVIRONMENT
 - 10 - 14 PSI AIR LIFE SUPPORT SYSTEM
 - $\frac{1}{2}$ TO 1 'g' ARTIFICIAL GRAVITY
- COUNTER ROTATING ZERO 'g' LABORATORY
- 50 MAN CREW - EXPANDABLE TO 100 BY ADDITIONAL LAUNCH
- HIGH INCLINATION $\geq 50^\circ$
- ATTACHED AND STATION-KEEPING EXPERIMENT MODULES

Figure 18

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THE MILLION POUND SPACE STATION ROTATING NEAR A 120 IN TELESCOPE MODULE

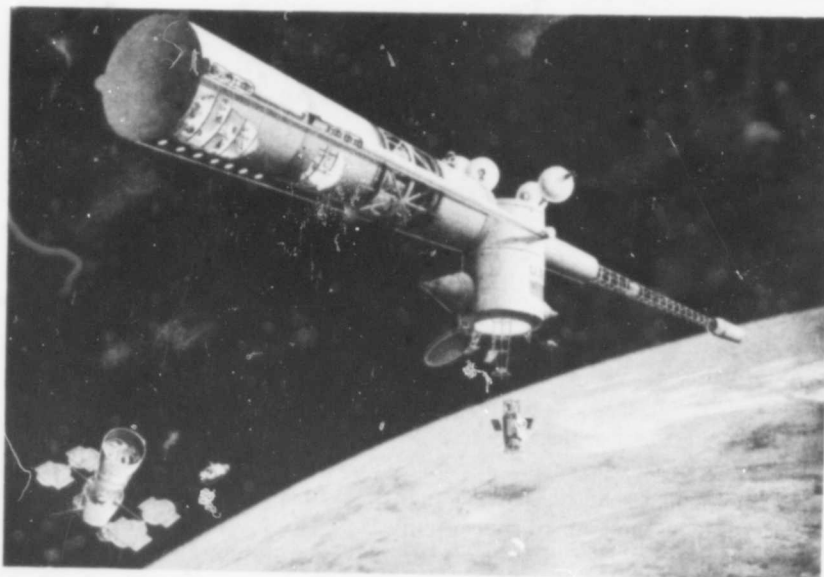


Figure 19

minimum of radiation background, which is important for minimizing its effects on the crew and on the sensitive film used in astronomical observations. It is sufficiently high to cover the majority of the occupied land masses, even though it leaves out some of the more developed countries in Europe. It would include, of course, all of the United States except Alaska, and within the continental United States is where the majority of ground sites will be located to test orbital observation techniques.

The final general characteristic noted is that the station will have both attached and station-keeping experimental modules. For example, in the astronomical area we can expect attached telescopes up to 40 inches in diameter, while the proposed 120-inch telescope would be mounted in a separate module flying near the station in a station-keeping mode. This will mean the development of a technique for visiting such a device for operational adjustments, data-gathering, and repairs. Small experiment modules will also probably be clustered around the station, and a hangar will be provided so that these modules can be brought back into the station for servicing by the station crew.

In order to stimulate your imagination, I have prepared some details of a space station of this advanced concept which is shown by an artist's drawing in Figure 19. As noted in the next Figure, No. 20, the station would be large, having a 240-foot radius to the rotational "g" living quarters; as much as a 375-foot radius to the spinning balance and power section on the other end of the rotational segment. The station would be launched in three parts by three Saturn V rockets and assembled in space. It would have a gross weight of about one million pounds, and we can expect to carry as much as 100,000 pounds of experiment weight. The volume in the living quarters would be about 50,000 cu ft—while the zero-gravity laboratory could contain as much as 45,000 cu ft. The large radius would permit us to achieve nearly 1-g at 3.5 rpm, and thus that becomes the maximum rotation we would need. Since the station will have a rather large inertia, it would require 7,000 pounds of fuel to spin up to its 3.5 rpm, and, in that condition, will have sufficient inertia that it will remain essentially fixed in inertial space.

The enormous stability of a large rotating station of this type has unique advantages for the observational devices located on it,

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LARGE SPACE STATIONS-SPECIFIC CHARACTERISTICS

- SIZE
 - 240 FOOT RADIUS TO LIVING QUARTERS
 - 375 FOOT RADIUS TO POWER AND BALANCE SECTION
- WEIGHT
 - 1,000,000 POUNDS TOTAL WEIGHT
 - 100,000 POUNDS EXPERIMENT WEIGHT
- VOLUME
 - 50,000 CUBIC FEET LIVING AND OPERATIONAL QUARTERS (ROTATIONAL 'g')
 - 43,000 CUBIC FEET ZERO 'g' LABORATORY
- ROTATION
 - 3.5 RPM

Figure 20

since it gives them a firm base which can be reacted against with conventional mechanical or hydraulic drives. In addition, its fixity with respect to inertial space is exactly suited for astronomical observations. The directional and tracking problems of Earth sensors are somewhat more complex, but this is partially compensated for by their less stringent accuracy requirements.

We have shown the station in operation with a 120-inch telescope floating nearby. This figure shows some of the fundamental features of the station. Note especially the hangar with a small satellite being taken into it for maintenance. The telescopes are mounted to the zerogravity nub on the top surface; the Earth sensors are mounted in a similar fashion on the bottom part of the hub.

It is interesting to note that the on-board experiments would be located in both the hub and in the artificial "g" volume. Basic biomedical/bioscience zerogravity experiments would be in the

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ORBITAL BUILD-UP

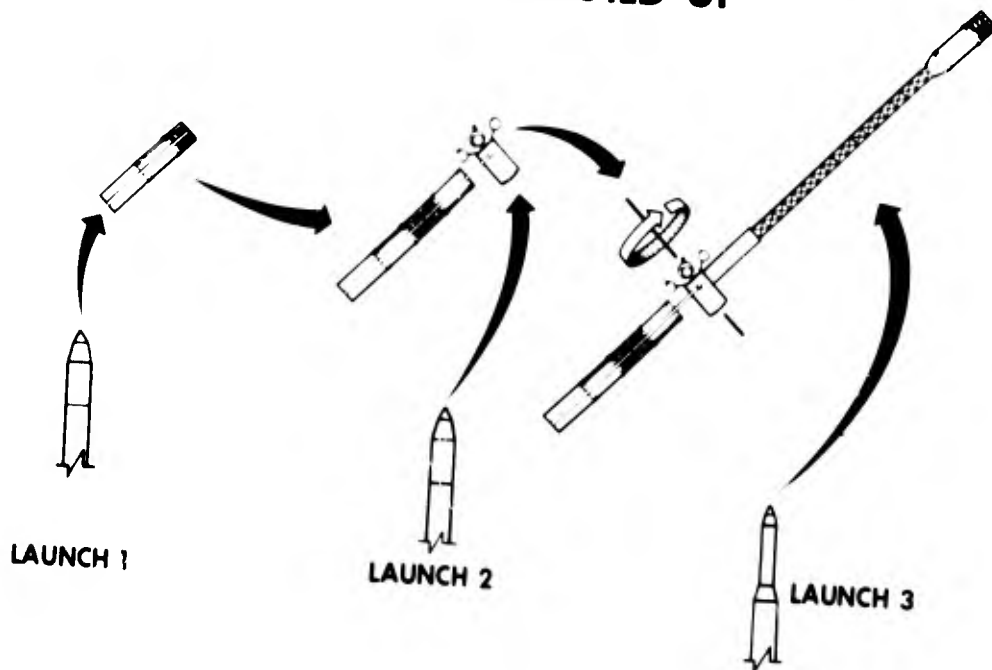


Figure 21

hub, while the majority of other on-board experiments would be located in the rotating g section. Included in that section would be complete machine shops and repair rooms, as well as would be the living quarters and command and data reduction section of the spacecraft.

The station would be launched in three separate parts and assembled in space. Figure 21 shows the manner of launch and assembly.

It is important that such a station have growth possibilities, and we have indicated in Figure 22 that, with an additional launch of the Saturn V, we could easily double the accommodations by docking the payload to the rotating part and balancing on the other end by the booster which brought it up. A similar operation would enable us to add capability to the zero-gravity hub. An even more

ADD-ON CAPABILITY

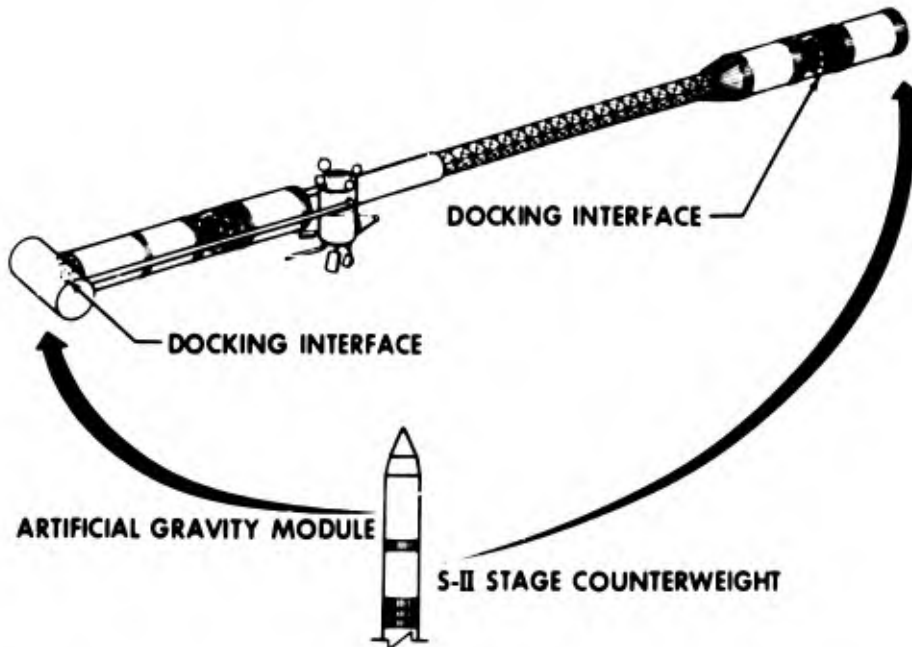


Figure 22

economical way to expand our living and working space is available because of the use of the S-II stage as part of the basic structure. The empty tanks of these stages contain over 36,000 cu ft of volume which can be entered, pressurized, and interior accommodations constructed with the same techniques we are developing with our Apollo Applications wet workshop.

CONCLUSION

I have tried to indicate the place of the space station in future space programs; the reasons why such stations will be important links with the future; the prototype steps we are taking in the Apollo Applications Program; and finally, a possible picture of the shape of things to come in terms of the conceptual design of a relatively large space station.

Such a station as described merges the space technology of the period with the elements of both pure science and practical science

into a single facility which can be logistically operated at a single place in space. Its purpose will be to reap an economical return from the use of space and to thrust basic research into a new and stimulating environment. Permanency and vastness will be the station's predominant assets, and it will provide a stately reservoir of energy and utilizable volume. A philosophy of continuous reuse and the capability to expand its resources will enhance its long-term economic return. The ten's of thousands of hours of operational experience, with men and equipment, in the space environment that it will give us will assure that it will be a true gateway into the exciting space programs of the more distant future.

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XI

Bioastronautics and Orbiting Space Stations

Gen. James Ferguson*

Thus far people have not been going into space for their health. Further, it's unlikely that in the future doctors will be recommending 6 months in space, as they now prescribe trips to San Antonio or Phoenix for some of their patients.

Nevertheless, as this Symposium demonstrates, we *are* professionally concerned about health and our national space program. We are concerned, first, about the well being of the program and its continuation as a viable force in our nation's development. We are concerned, secondly, about the physiological and psychological problems connected with the adaptation of man to the space environment.

My purpose today is to relate these subjects to each other and to the prospects for future orbiting space stations.

When we wonder about space today we find that the question marks have shifted, from "when and how" to "where and at what pace?"

The war in Southeast Asia and other pressing domestic and international needs have served to limit Federal appropriations for space.

There are other reasons for the apparent decline in public enthusiasm for the national space effort. To some extent the

*Commander, Air Force Systems Command, Washington, D. C.

excitement has worn off. We have become "conditioned" to space, accustomed to successes there, and no longer surprised by spectaculars. It is a characteristic of our day that novelty is short-lived, and space ventures seem to be no exception. No great public clamor for next-generation space programs is currently discernible in our society.

The crux of the matter, however, appears to lie in justifying, in tangible terms, the *costs* of future space programs—the large ones, at least. We must prove that space projects can pay their way—that our space program can earn its keep or bring something unique to our society.

This need for program justification in terms of meeting specific objectives is no great revelation to most of you here today. Those of you familiar with Defense Department policy know that military space programs must show distinct promise of directly enhancing national security. Further, those space programs must represent either the *only* way to get the job done or the most cost-effective way of doing it.

As an aside comment, I think it's worth noting here that the Moon program was intended from the outset as a departure point—a mind-stretching venture—an experience-building enterprise. Yet, perhaps, too many people have come to equate the lunar expedition with our total space program or to think of it as an end rather than as a beginning. We see evidence of this in inclinations to support the Moon program "because we're committed to it," but to defer other space activities.

This attitude is further enforced by the fiscal facts of life. As we've already noted, since President Kennedy opted for the Moon some of our national values have had to be reassigned, priorities have been shifted by world events, and we have encountered many other demands on our time and treasure and technology.

Thus, in the real world of today, it seems unlikely that a future bold and costly goal like the lunar landing will again be adopted *unless* the benefits to be accrued can be quantified in functional or economic *specifics*.

In this matter of "which comes first, the technology or the task," the most fruitful approach may be the best of both worlds—a technically challenging task which serves long-term interests. I think the manned orbiting space station represents this well-reasoned, constructive approach to *national space objectives*.

For example, the bulk of the basic technology is in hand for a first-generation, long-life, multi-manned vehicle. Such a station could be operational in the mid-70's.

On the other hand, the cost of such a station could run to several billion dollars, an amount that might be difficult to justify under present circumstances.

However, there are indications that such justification will come and that the combined national needs for a laboratory capitalizing on *all* the features of the space environment will be sufficient to win support for the program.

Now, why do I say this? The feeling is partly intuitive and partly based on the experience gained in the last 10 years. The applications for earth satellites already far exceed our earlier expectations, and more uses are being identified every day. Rapid progress in electronics and in the miniaturization of components has revolutionized our thinking in terms of functions. The ability to predict with remarkable accuracy the lifetimes of component parts has given us a new concept of reliability and made multiple-purpose satellites (among other things) economically attractive.

Accordingly, there are good reasons today to feel that the classic picture of space—one in which man plays a central role—need not be abandoned or even significantly slowed. Admittedly, we are not ready yet to boast about the "conquest" of space, for conquest connotes mastery, and we can't presume to that status until man is operationally secure in space. But neither are we ready to surrender the toe-hold we have or to rest on our laurels.

There has, perhaps, been more progress toward the design, development, and justification of manned orbiting space stations than appears on the surface. In fact, we have in hand the beginnings of a sound technological base for the realization of extended-life stations.

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But, as this audience knows well, there is much work yet to be done, especially in the area of bioastronautics. This is not an isolated area. The approach we take toward solving bioastronautic problems will affect the cost of the program. The data obtained will affect the prediction of performance and ultimately influence the basis for program justification. Furthermore, from both the Defense and NASA point of view, it's important to know what restraints bioastronautic considerations will impose upon mission performance.

We have, as I say, made progress. Since your 1964 symposium a number of significant technical accomplishments have been realized. These include:

- Rendezvous and docking
- Substantial improvements in equipment reliability
- Manned flight duration of 14 days
- And a total of nearly 2000 hours of manned "space time" for U.S. astronauts.

Some of the major crew-related events still to come include:

- Flight test of crew-task time-line concepts
- Effects of the space environment and work/rest schedules upon crew circadian rhythms
- Extravehicular performance
- More efficient design of crew compartments.

Both the S-IVB Workshop and the Manned Orbiting Laboratory (MOL) will contribute to better understanding and broader experience in these areas. A few of the contributions expected as a result of these programs include:

- Adaptability of man to the space environment during progressively longer periods of time
- Assessment of the crew compartment provisions
- Adequacy of the ground simulations and training devices
- Assessment of data management systems.

Mr. Gilruth, I'm sure, will describe the NASA programs in detail; therefore, let me discuss Air Force objectives, with the clear understanding that NASA and DOD aims are complementary, and our programs are fully compatible.

The Air Force Manned Orbiting Laboratory, now under development for flight in the early 1970's, will provide an operational test-bed for the development of equipment for use in both manned and unmanned military space projects; additionally, it will provide empirical "cost-effectiveness" and technical data on the ability of man to perform militarily useful tasks in space. As many of you know, the basic MOL is a two-man space station made up of a Gemini B, a Laboratory Module, and an Experiment Module. The system is designed typically for 30-day orbital missions and will be placed in orbit by the Titan IIIM launch vehicle.

The Gemini B spacecraft, of course, is a modified Gemini re-entry vehicle which will be manned during the ascent and descent.

The Laboratory Module consists of both an unpressurized and a pressurized compartment. The unpressurized compartment houses the electrical power subsystem, reaction control subsystem, storage for expendables, and the pressurized tunnel for crew transfer between Gemini B and the Laboratory.

I might point out that Extravehicular Activity (EVA) is not inherent in the MOL plan. Emergency return from the laboratory to the Gemini can be accomplished by EVA, if necessary, but none of the normal MOL operations require EVA.

The pressurized compartment contains the control station for the space station and experiments, flight crew quarters, and the laboratory subsystems. The total pressurized volume is approximately 1000 cu ft, which includes some 400 cu ft of free space for the crew. Within the pressurized compartment of the Lab, the atmosphere is nominally established at 5 PSIA total pressure, and is composed of 70% O₂ and 30% He. We plan to provide a secondary pure O₂ atmosphere for emergency use.

The Experiment Module is an unpressurized structure housing the experimental equipment.

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I'd like to emphasize that in addition to our hardware work, we have conducted an intensive human engineering program for the MOL program. A major element has been a sizable simulation program consisting of KC-135 zero-g flights and underwater testing.

Real time and stored data on crew performance will be constantly monitored at the Mission Control Center by specially trained flight surgeons and biomedical engineers. Sufficient data will be obtained to diagnose and measure individual performance in an operational environment.

I am convinced that as a result of the experience acquired in the MOL and Orbital Workshop programs, we should be able to move on to larger stations capable of longer periods of operation.

There obviously is a need for diligent and meticulous planning to insure that the maximum information is derived from each flight. Equally obvious is the need to further develop our resourcefulness in the use of ground-based facilities to broaden the data base. Wherever possible, flights should be used only to confirm or refine the data obtained during ground-based studies.

I mentioned earlier that I feel there is justification that the long duration multiman space station will be achieved in due time. In support of this thesis, I invite you to consider the variety of uses for Earth satellites now unfolding, ranging from point-to-point communications to navigation and traffic control.

As to military functions of satellites, I assure you that in such areas as communications, meteorology, and navigation, satellites are proving to be "important elements" in our worlds of defense and security.

Accordingly, I ask you to ponder the extent to which satellite services could be further augmented or improved by putting man "on the scene," joining his unique and far-reaching capabilities to those of the "unmanned" satellite.

The benefits could be considerable, in my judgment, sufficient to earn the justification needed for program support.

On the other hand, there is some speculation that over the next generation or so computers may match, simulate, or surpass some of man's peculiarly human abilities, including perhaps some of his creative capabilities. Considering the fantastic advances achieved in the computer field in recent years, we must be cautious about arbitrarily stating that man—at least for space missions—can't be replaced. Clearly the inherent limitations of computers is an open question today.

But as Herman Kahn points out in his book *The Year 2000*, "If it turns out that they cannot duplicate or exceed certain characteristically human capabilities, that will be one of the most important discoveries of the 20th century."

For our present purposes, however, I think we must assume that man is valuable, if not absolutely essential, and that the collective national needs for a manned laboratory optimizing the unique attributes of the space environment will be sufficient to warrant eventual support.

On this premise, what then are the principal bioastronautics problems to be solved? What impact do these problems have on station design, cost, and effectiveness?

Let's assume that the hypothetical space station system, for this discussion, will consist of an orbiting station and a logistics resupply vehicle system. The station may be injected into orbit in a single launch, or may be launched in segments and assembled in orbit. Either scheme is feasible for future stations, and the choice will depend upon many variables, not the least of which will be the payload capability of available launch vehicles.

Resupply and crew rotation capabilities will be required and these will be the tasks of the logistics resupply vehicle.

The bioastronautics problems and provisions can have serious impact upon the space station design, cost, and operations. Consider, for example, the impact of crew rotation interval. In one study of a long duration system, the savings accrued by doubling the intervals from 30 to 60 days were dramatic, ranging from about \$220 million per year to \$470 million per year, depending upon altitude. The savings from 60 to 90 days were on the order of another \$100 million per year.

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Next, observe the effect of crew size. Fortunately, for the same cost, a slightly longer rotation interval can support another pair of men. For example, in a low altitude case, a four-man crew with a 90-day rotation cycle costs the same as a six-man crew with a 100-day rotation cycle.

I think it's apparent that we must aim for crew rotation intervals on the order of months. If increasing crew size will help accomplish this end, we then need to determine the optimum crew size. If a future station can be expected to be useful over a period of many years and if its cost can be amortized accordingly, the operating cost will dominate, with the result that efforts expended to achieve long crew rotation intervals have a very large potential pay-off.

However, extended duration missions bring with them the increasing probability of crew exposure to radiation beyond the limits established by the Atomic Energy Commission for career workers. The prime natural sources of crew radiation are solar flares and the Van Allen Belts, and the risk to the crew must be assessed in terms of mission impact. Decisions regarding the need for conventional or electromagnetic shielding, early and reliable solar flare warning, and design of dosimetry equipment hinge upon a detailed assessment of the radiation risk to be expected in the mission.

Considerable attention has been devoted to the compartment volume required per crew member and its relationship to time in orbit. The data presently available are limited, particularly in terms of multiple manned crews, although good data exist on volumes required to avoid the impairment of small crews for periods up to 30 days or so.

From the MOL program and the Orbital Workshop, the validity of extrapolation of simulator data to space should be determined. Detailed questions as to whether environmental effects are additive or independent may then be answered to a more satisfactory degree.

From an engineering view, the designers for interplanetary travel place great importance upon minimum volume. Although the consensus to date indicates that a pressurized volume of 600 to 700 cu ft per man is adequate to permit efficient performance

for up to a year of operation, further studies must be done. Trade-offs on weight and volumes based on harder facts are clearly in order.

For reasons of economy, stations will require versatile astronauts as a means of minimizing crew size. For example, it may not be logical to place a highly specialized scientist aboard a space laboratory unless his addition could make a longer stay on station feasible.

On the subject of crew size and compatibility, which is still wide open, several questions come to mind. What, if any, effect does crew complement and makeup have on rotation interval? In addition to the peculiar skills, what criteria should be used to select minimum crew size for near-maximum crew rotation interval? Can cross-training compensate for a small crew size?

In order to utilize man's abilities effectively, routine functions generally should be performed by automated equipment to the maximum extent practical. This will allow the crewman to perform as the station manager, directing most of his attention to operational or scientific tasks. However, for routine station-keeping functions, crew members still will have to perform certain housekeeping chores, and replace or calibrate failed equipment.

There is a good deal of information available on human efficiency as related to the work/rest cycle and peak-working efficiency periods within the cycle. However, it is quite possible that future earth orbital systems may have to benefit from the very long term approach and therefore should plan an *expedition* which will be cut off from physical contact with the earth for many months. The equivalents of vacations or "R and R" need to be identified and evaluated. Some unanswered questions in this area are: What durations, conditions, and equipment are needed to satisfy this function? What are the benefits, if any, in terms of efficiency and tolerance for an extended duty tour?

The atmosphere for a space station should, ideally, have the same composition as the earth's atmosphere at sea level, since this would eliminate the unknowns of any long-term effects due to lower pressures and different atmospheric compositions.

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However, sea level atmospheric pressure may not be the best overall solution for a long duration spacecraft. Although much work has been completed in developing data for atmospheric selection, the data "book" on this subject is far from complete.

Continued studies of the various "inert" gases for use as diluents are needed.

The effects that pure oxygen has upon the cellular and metabolic processes in man need further definition.

The "book" on atmosphere needs to be developed in a way that selection of the atmosphere for any space vehicle can reflect all the factors influencing vehicle design, operational considerations, and crew limits.

Weightlessness has probably raised more questions than any other single factor. While much of the original pessimism has been erased by the flights to date, many questions related to changes in the body systems as a result of longer weightless exposure are still unanswered. These include changes in heart regulation, fluid and electrolyte balance, the energy costs of living and working in zero gravity, mineral and bone metabolism, hormonal shifts, cell development, and even the ability to sleep.

The data available are encouraging, but the detailed definition and limitations of man's adaptive process must be better understood.

Additionally, ground-based experiments, using bed rest and water immersion techniques, encourage us to believe that 30-60 day missions can be undertaken safely. However, for longer flight durations, there still are many uncertainties. For example, will man's adaptation to weightlessness have operational impact? What provisions or time must be dedicated to keeping the crew "fit"? Will man eventually need artificial gravity to permit him to go beyond certain limits of orbital stay? And if artificial gravity is required, when is the optimum time to introduce it? How much artificial gravity would be sufficient?

In conclusion, I suggest that there really is very little reason to doubt the assimilation of space as a part of man's environment.

How soon this happens depends largely on our attitude and aptitude. While technology is clearly a pacing factor, the acquisition or application of technology alone probably is not a sufficient rationale today for justifying enormous commitments of our nation's resources. Nevertheless, we must continue to be concerned about the health and vitality of our national space program. The technical community must provide the program managers with the facts, estimates, and alternatives they need to make the hard decisions relative to new undertakings.

The incentives for space progress have not been dimmed or diminished. Our national well-being provides one of those incentives.

Gen. John P. McConnell, Air Force Chief of Staff, has put it this way: "We do not know what the future holds in store for us, the free nations of the world. But it is safe to predict that whatever nation or alliance of nations achieves and maintains superiority in the third dimension of aerospace will be in an excellent position to achieve and maintain commensurate superiority in the other two dimensions—on the surface of the earth and under the sea."

In this context, man indeed occupies the central role with respect to space prospects. This will continue to be true regardless of the final verdict on the feasibility or effectiveness of large manned space stations. For the focal point of man in space centers in his ability to plan, design, develop, and to produce useful means of applying space techniques and technologies to the alleviation or resolution of his common problems.

The challenges of space are perhaps more severe today than they were 10 years ago, when we had no practical experience there. For now we know that space is accessible in man's purposes. We must ascertain more fully what these purposes are, cultivating those which can serve to our advantage while guarding against those which would compromise world peace and the security of our nation.

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XII

Orbital Flight Results

Charles A. Berry, M. D.*

The major challenge to the discipline of space medicine is the characterization of the nature and degree of all major changes in man's functional capabilities which result from prolonged exposure to the spaceflight environment. Two circumstances make the problem difficult to solve. First, knowledge is relatively limited on normal or reference functional capabilities of the human organism despite rapid advances in biomedical science during the present generation. Second, the specific consequences of certain environmental changes on the functional capabilities of man have not been defined, making this a rather primitive field of study where theories predominate and findings are often controversial. Faced with this situation, the first NASA programs were aimed at verifying theoretical predictions through a series of increasingly comprehensive flight observations. As new data were gained, attention turned to fundamental questions about the suitability of man as a long-duration inhabitant of the spaceflight environment.

PROJECT MERCURY AND THE GEMINI PROGRAM

It was conceded at the outset, and it must be constantly reiterated, that man is not inherently qualified for space missions. His function as a total human organism and the function of significant body systems must be evaluated in response to the stresses of spaceflight just as the engineer evaluates the spacecraft systems. In an attempt to provide a safe and biologically sound method of grossly qualifying man for the next step, a technique has been adopted of doubling the duration of exposure to the

*Director of Medical Research and Operations, NASA Manned Spacecraft Center, Houston, Texas.

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flight environment. This technique reached its zenith with the completion of the 4-, 8-, and 14-day missions in the Gemini Program. The overall performance of the crew and the detailed physiological findings which were available were reviewed after each step before man was exposed to the next longer increment in flight duration. The immediate objective of the Gemini Program was to qualify man for the lunar mission, and, thus, durations of 8 and 14 days were most significant. The objective of these missions was to observe system changes in relation to the duration of exposure of the two crewmen on each flight. The elucidation of mechanisms responsible for any observed changes was to become a part of more complex studies in future programs. More sophisticated physiological and behavioral studies are now required to qualify man for continued spaceflight.

A most significant point to remember in evaluating the progress to date concerns the stage at which the early flight evaluations have been conducted. All flight programs to date have been aimed

NASA-S-66-12064 **Table I. Mercury Manned Flights**

MERCURY MANNED FLIGHTS

TABLE I

FLIGHT	CREW	LAUNCH	HRS	MIN
MR-3	SHEPARD	5-5-61		15
MR-4	GRISSOM	7-21-61		15
MA-6	GLENN	2-20-62	4	56
MA-7	CARPENTER	5-24-62	4	56
MA-8	SCHIRRA	10-3-63	9	14
MA-9	COOPER	5-15-63	34	20

Table II. Gemini Manned Flights

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GEMINI MANNED FLIGHTS

FLIGHT	CREW	LAUNCH	DESCRIPTION	DURATION		
				DAYS	HRS	MIN
G-III	GRISSEM YOUNG	3-23-65	3RD REV MANNED TEST		4	52
G-IV	MC DIVITT WHITE	6-3-65	1ST EXT DURATION AND EVA	4		56
G-V	COOPER CONRAD	8-21-65	1ST MEDIUM DURATION FLT	7	22	56
G-VII	BORMAN LOVELL	12-4-65	1ST LONG DURATION FLT	13	18	35
G-VI	SCHIRRA STAFFORD	12-15-65	1ST RENDEZVOUS FLT	1	1	53
G-VIII	ARMSTRONG SCOTT	3-16-66	1ST RENDEZVOUS AND DOCKING FLT		10	41
G-IXA	STAFFORD CERNAN	6-3-66	2ND RENDEZVOUS AND DOCK- ING 1ST EXTENDED EVA	3	1	04
G-X	YOUNG COLLINS	7-18-66	3RD RENDEZVOUS AND DOCKING 2 EVA PERIODS; 1ST DOCKED AGENA-PROPELLED HIGH APOGEE MANEUVER	2	22	46
G-XI	CONRAD GORDON	9-12-66	1ST RENDEZVOUS AND DOCKING INITIAL ORBIT; 2 EVA PERIODS 2ND DOCKED AGENA-PROPELLED HIGH APOGEE MANEUVER; TETHER EXERCISE	2	23	17

at trying to develop a reliable capability to get man into the space environment and to provide the assurance that both the crew and the equipment sustaining them would function for the required flight duration. I'm reminded here of General Armstrong's remark during the first space symposium in 1952, "Aerospace medical research should be completed before the engineers sit down at the drawing board to design a spacecraft." I fully agree that this should be the case, but technology has forced us to the position in the flight program where many things must be done simultaneously. This has put great significance on the confirmation of ground-based research by flight observations. A summary of the Mercury and Gemini manned flights is shown in Tables I and II, respectively.

I would like to emphasize the significant role that man has in the conquest of space. There should be no doubt that I am an enthusiastic supporter of man's capability to perform in this environment. Recently, questions have again risen concerning

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man's limitations, and allusions have been made to the possibility that unmanned exploration would not be hampered by such human limitations. I think this is sheer folly, for if the space environment is ever to be used, man must be there, and I am confident he can do the required tasks if we life scientists do our jobs well. Man has become an increasingly important part of the total spacecraft systems since Project Mercury and has proved himself to be a good performer. The medical role requires not only that operational support and the experiments necessary to assist in qualifying man be provided but also that the medical team serve as engineering design advisors. This requires close and constant liaison at all stages of design, manufacture, test, checkout, and flight, in order that reliable advice concerning the duration of the next longer mission can be provided.

Significant features of the spaceflight environment include the null-gravity state, an altered ionizing radiation flux from that encountered within the Earth's atmosphere, and an altered exposure to sunlight and darkness. Other features are provided by the spacecraft designers, such as: the breathing atmosphere, the volume available for living and working, noise and vibration levels, and a multitude of others which, when combined, make spaceflight truly unique in the history of human experience.

Through the years, a number of dire predictions have been made concerning man's response to spaceflight. These predictions have involved both the environment and the reaction of man's physiology to it. The flight program to date has begun to give some insight into the validity of ground-based predictions concerning man's responses. It is important to realize the harm done by both the dire predictions of disaster which are unwarranted and the overly optimistic projections of man's responses. Man's proven capability, or his lack of it, must continue to be documented at every spaceflight opportunity.

The scientific questions to be answered, and those questions which are appropriate to manned spaceflight research, are as diverse and inexhaustible as those common to Earth-bound laboratories. There is no foreseeable end point for space-related biomedical studies. However, there is a series of what can be characterized as major plateaus of knowledge to be achieved sequentially in order to proceed rationally with increasingly complex

flights and with justifiable expectation of success. The program of ground-based laboratory studies combined with the knowledge gained from observations made during the Mercury and Gemini programs has formed us to at least two such plateaus to date.

The First Plateau

The null-gravity state cannot be produced for any appreciable length of time short of actual orbital spaceflight. Therefore, the first orbital flights of animals by the United States and Russia were literally necessary to refute untested, but plausible, theories which predicted catastrophic failures of various vital functions in an organism suddenly thrust into an environment without gravitational force. Our first plateau, then, was achieved when knowledge gained in the Mercury program demonstrated that man could expect to remain alive and operationally effective for brief excursions into space. The Mercury flights were cautiously extended in duration to terminate with the 1½-day flight of Mercury-Atlas 9 (Table I). However, by the end of Project Mercury, positive evidence was available to indicate that significant physiological changes were appearing which were similar to those observed in man during prolonged bed rest or water immersion.

The Second Plateau

At the Third International Symposium on Bioastronautics and the Exploration of Space, just a short 4 years ago, I discussed our medical plans for Project Gemini prior to launching the first flight. Much has indeed happened during the ensuing period. The studies conducted during the Gemini Program were directed toward evaluating the magnitude of flight-related changes first noticed late in Project Mercury. In addition, the validity of conflicting reports of possible central nervous system and cardiac disturbances were evaluated. These reports arose, in part, from isolated interpretations of scattered and incomplete data from Russian manned spaceflights. It was also necessary to identify and characterize the importance of other physiological changes that might occur in manned flights lasting up to 2 weeks in duration. Since the principal changes observed in Mercury were concerned with alteration of cardiovascular reflexes that regulate the flow of blood against hydrostatic pressure in the gravity field, heavy emphasis was placed on evaluating the cardiovascular system during the Gemini Program. The preflight and postflight measurements, and

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the inflight evaluations which were accomplished during the Gemini Program, were largely qualitative and primarily intended to detect gross alterations in the functional status of the major human systems as flight durations lengthened. The manned missions flown are shown in Table II.

The results of the Gemini studies have been reported in detail in a number of publications (Refs. 1 to 8). The negative as well as the positive findings are certainly of interest. It was demonstrated that some of the major human physiological systems exhibit consistent and predictable changes after exposure to spaceflight, and these observed changes in flights lasting up to 2 weeks are completely reversible and probably will not degrade human performance or crew safety during missions required to achieve the goals of the Apollo Program. The status of studies involving the response of human functional systems to spaceflight is shown in Figure 1. Note that only one system, the cardiovascular system,

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STATUS OF HUMAN FUNCTIONAL SYSTEM
STUDIES ESSENTIAL FOR SUPPORT OF
MANNED SPACE FLIGHT

MAY, 1967

<u>SYSTEM OR FUNCTION</u>	<u>FLIGHT-RELATED CHANGES DETECTED</u>	<u>DEPTH OF INVESTIGATION</u>
NEUROLOGICAL	NO	MINIMAL
BEHAVIORAL	NO	MINIMAL
CARDIOVASCULAR	YES	EXTENSIVE
PULMONARY	NO	MINIMAL
BODY FLUIDS	YES	MODERATE
MUSCULOSKELETAL	YES	MODERATE
METABOLIC EFFICIENCY	NO	MINIMAL
GASTROINTESTINAL	NO	MINIMAL
GENITOURINARY	NO	MINIMAL
ENDOCRINE	YES	MINIMAL
IMMUNOCELLULAR DEFENSES	YES	MINIMAL

Figure 1. Status of human functional system studies essential for support of manned spaceflights.

has been investigated extensively. Two other systems, the body fluids and the musculoskeletal, have been moderately investigated. It is no coincidence that these systems have shown flight-related changes. Changes were detected in the cardiovascular system, in the musculoskeletal system, in the composition and quantity of body fluids including the circulating blood, in hormone levels, and in the white cells of the blood, which afford defense against stressful environmental factors and invasion by harmful microorganisms. The fact that changes were not detected in other systems observed merely means that, if changes occurred, they were not of sufficient magnitude to be detected by the methods employed.

Figures 2 and 3 are presented to describe what little is currently known of the time course of observed physiological changes in six parameters of interest in the Gemini Program. These parameters are also indicative of the most significant positive physiological findings obtained during the Gemini Program. The loss of bone density in the os calcis (heel) peaked at 14% in the 8-day

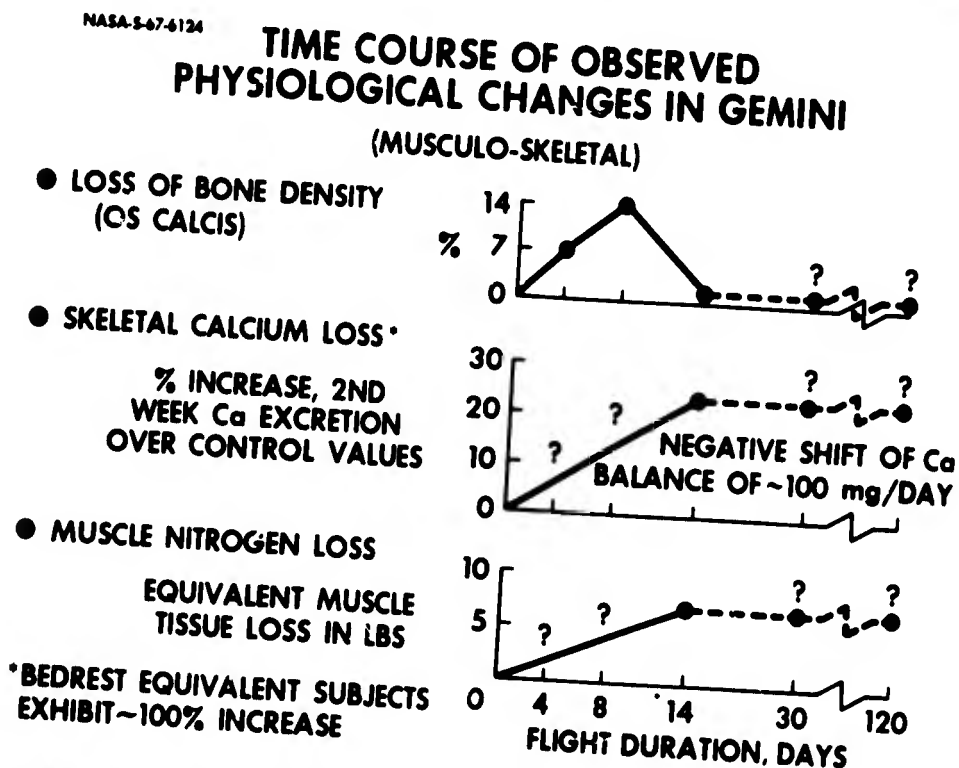


Figure 2. Time course of observed physiological changes in Gemini (Musculo-Skeletal).

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TIME COURSE OF OBSERVED PHYSIOLOGICAL CHANGES IN GEMINI

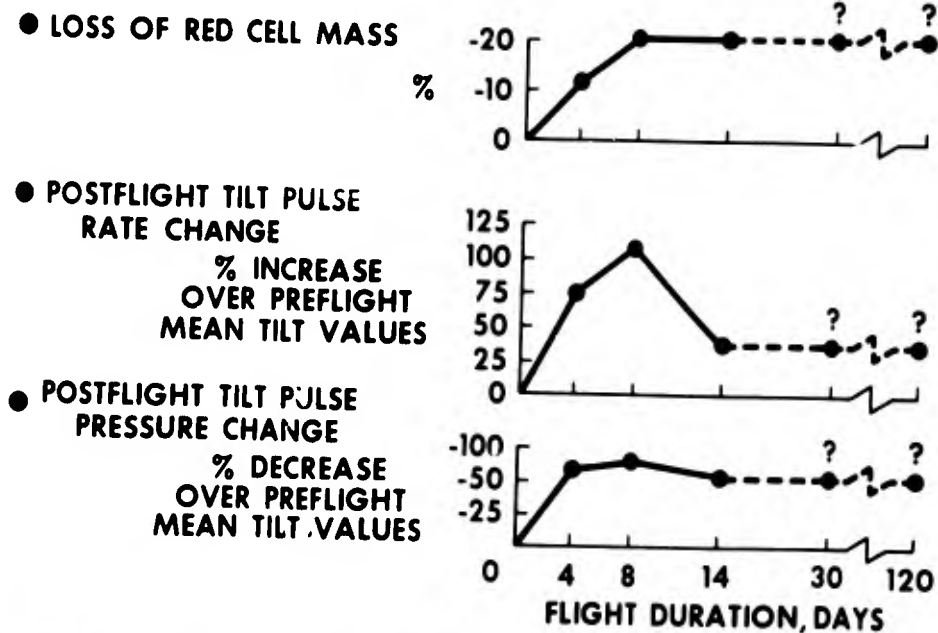


Figure 3. Time course of observed physiological changes in Gemini.

flight and returned to a 1% loss in the 14-day mission. The measurements indicating loss of bone density in the os calcis are remarkable for their inconsistency. Following the 4- and 8-day flights, there was sufficient reason to believe that progressive loss of calcium from bones would continue as the exposure to weightlessness was lengthened. The surprisingly small amount of demineralization which the Gemini VII crew experienced after 14 days in space raised questions regarding the efficacy of exercise, adequate water and calcium intake, dietary factors, and rest as probable causative agents in determining the amount and rate of calcium loss from bones. Another interesting observation concerning the loss of calcium relates to the small finger, which was planned as a control, but whose loss of calcium or density follows that of the os calcis. This entire area bears further investigation.

The 14-day flight produced data indicating a small, but significant, loss of muscle tissue, the time course of which is unknown because measurements of this parameter were not available on the 4- and 8-day flights. As was the case with loss of bone density,

the changes that might be expected on flights of longer duration are entirely unknown.

The tendency for the loss of the red-cell mass to subside, and perhaps to level off as time progresses, is impressive. The 20% loss in the 8-day flight was duplicated by that in the 14-day flight. This is entirely conjectural, however, and there are no data to support the hypothesis that the loss of red-cell mass is a self-limiting phenomenon.

The last two parameters relate to cardiovascular deconditioning. The postflight tilt pulse rate changes and the tilt blood pressure changes are essentially inconclusive because there were rather remarkable differences in the 8- and 14-day flights with respect to food and water intake, exercise and thermal comfort. The crew of Gemini VII was also permitted to doff their space suits for a considerable portion of the flight. The reduction in sweating and the overall increase in thermal comfort may account in part for the apparent improvement in the physiological status relative to flight duration. I seriously doubt that 14 days of spaceflight are necessarily better for one than are 8 days.

Five astronauts have completed 12 hours 25 minutes of extravehicular activity (EVA) during the more than 2,000 man-hours of spaceflight exposure (Figure 4). It was generally thought that, although EVA would be a new experience for the crewmen and would require cautious familiarization and emotional adjustment, it would prove to be no more difficult than accomplishing the same task in an altitude chamber on the ground. The tasks which had been outlined were attempted in the altitude chamber and then in the zero-g aircraft where all of the activity and the environment could be simulated. Weightlessness of course was produced for less than 1 minute. The first experience with EVA in Gemini IV (Figure 5) required the astronaut to evaluate EVA by means of slow and deliberate movements, a short period of propulsion with a hand-held maneuvering unit, and his capability to move about by pulling on a tether. Films of this activity revealed that he handled the tasks very well, moved about deliberately, and rolled or tumbled at will. He had no sensation of disorientation. The heart rate of 170 beats per minute did cause some concern about the real-time monitoring of future extravehicular activities. It should be emphasized that there was little requirement for actual physical

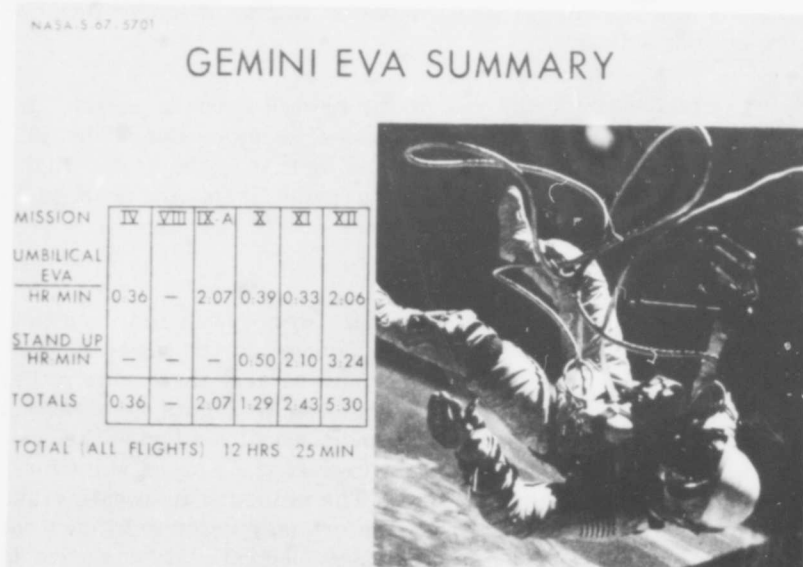


Figure 4. Gemini EVA Summary.

work during this initial extravehicular excursion; that is, there was no requirement for the astronaut to remain at a fixed location to do a particular task.

The first EVA mission was followed by three missions which increased the demands on the extravehicular crewmen. One of these experiences produced only moderate increases in heart rate and what was estimated to be workloads, whereas, two were aborted owing to heavy exertion producing heat and sweat which could not be handled by the suit environmental system and, also, owing to crewman fatigue. The best example of the latter occurred on Gemini XI where the EVA crewman's heart rate was from 170 to 180 and his respiration rate was 40 at the time of peak activity.

Only one lead of electrocardiogram and respiration has been available for real-time monitoring of the extravehicular crewman. There has been no way to determine the actual in-flight metabolic cost of the activity in which he has been engaged. In an attempt to estimate this, the capacity workload of the crewmen has been

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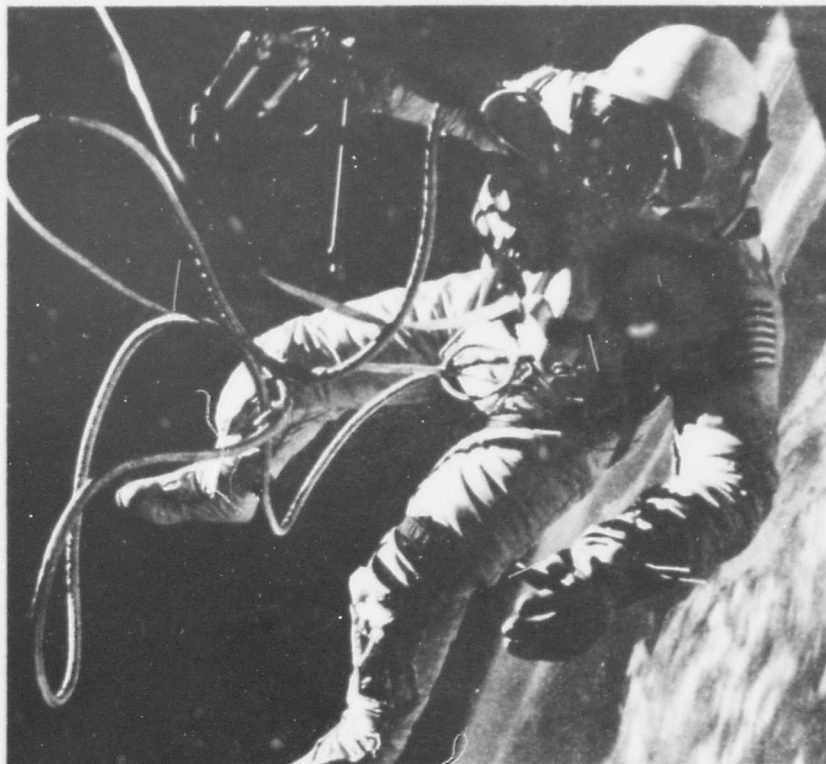
GEMINI IV
EXTRAVEHICULAR ACTIVITY

Figure 5. Gemini IV extravehicular activity.

measured in preflight testing using a bicycle ergometer. This has allowed the medical team to plot heart rate versus work output in a laboratory situation. While it is realized that there are many unknowns in trying to compare these data with the actual in-flight situation on a real-time basis, the laboratory data have given a general idea of the work involved when used in the context of the actual situation as determined by voice, heart rate, respiration, and known activity.

Prior to the Gemini XII mission, it was obvious that the basic laws of physics producing action, reaction, and the need to stop an action, the difficulty in trying to maintain a fixed position to

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do a task, the problems of mobility in a 3.5-psi suit, and some amount of in-suit heat load and carbon dioxide level in the helmet all combined to produce the undue fatigue noted on the Gemini XI mission. Some emotional response was certainly involved but probably played a small role in this myriad of factors. In an effort to assess more accurately the nature of the metabolic costs, detailed monitoring of the Gemini XII pilot was accomplished in the pre-flight simulations in the hard suit at 1 g, in simulated zero-g underwater and in zero-g aircraft flights (Figure 6). Exercise



Figure 6. Gemini XII underwater training.

ergometry was obtained, and, in addition, exercise tests which could be used in flight and compared with the preflight observations were done to give us a very rough idea of the significance of the factors (other than strict physical work) involved in producing our heart rate changes. Responses to this exercise in flight were amazingly identical to those of the preflight baselines. In addition, the heart rates observed during extravehicular activity on the Gemini XII mission were all at acceptable levels and remarkably similar to those observed during the underwater simulations. The Gemini XII (Figure 7) mission has given us much confidence in man's capability to perform extravehicular work if he is properly tethered so as to allow him to utilize his efforts strictly at the task, if he has propulsion capability or a method of reaching the task by handhold, and, finally, if the tasks are programed with proper rest periods. Much is still to be learned about the metabolic cost of EVA in a hard suit.

The translation of physiological requirements into engineering reality has proven to be a continuing problem for such biosupport



Figure 7. Gemini XII extravehicular activities.

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URINE COLLECTION DEVICE

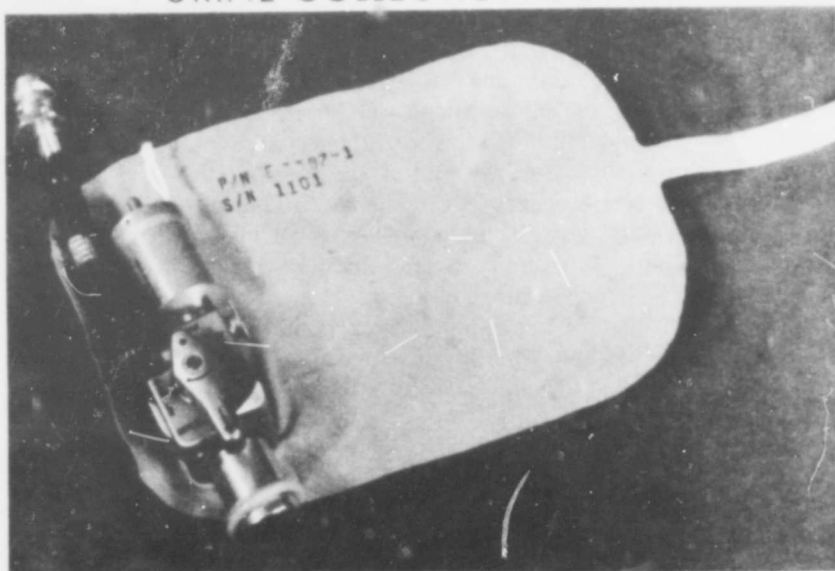


Figure 8. Urine collection device.

items as environmental control systems; food, water, and waste management systems; and bioinstrumentation. The normal requirements of living which we take so easily for granted here on Earth become difficult problems for the physician and engineer. A typical example is the waste management problems which were first encountered in the longer duration flights in the Gemini Program. The systems used for handling liquid and solid wastes are shown in Figures 8 and 9. The Apollo waste management system is shown in Figure 10. The urine system was made excessively complicated in an attempt to obtain urine volume data and an adequate sample, and to provide an overboard dump capability. This created operational problems in its use. The fecal disposal system was decidedly simple, but left much to be desired from an aesthetic point of view. It could, indeed, be called primitive by modern housing standards. While development to meet stated requirements was attempted for the Apollo Program, it appears that we will use the Gemini waste management systems. A great deal of engineering ingenuity is required if we are to

FECAL BAG

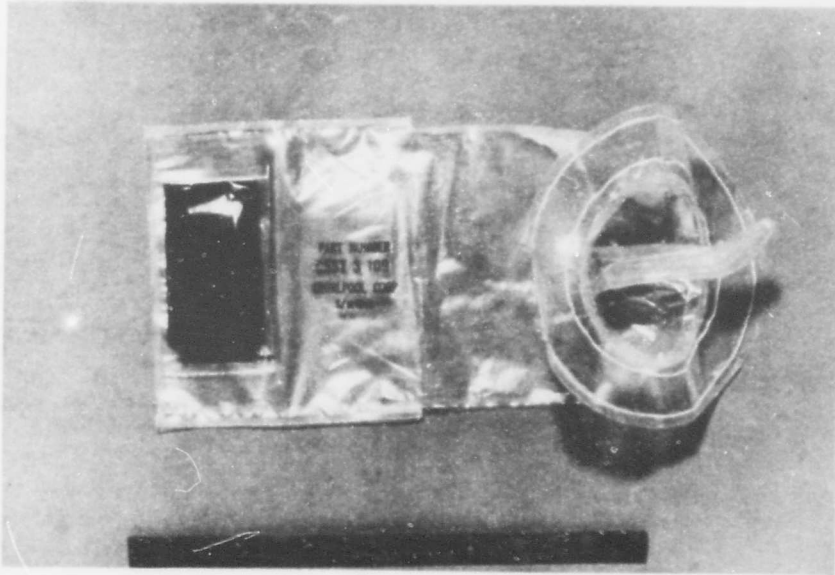


Figure 9. Fecal bag.

provide the necessary habitability to enable man to perform at a peak level in long-duration spaceflight. The time has come to not build an airplane cockpit but to build a house in order to sustain man for the long periods necessary. This will indeed call forth all the ingenuity of both the engineer and the life scientist.

THE APOLLO PROGRAM

The spacecraft volume and the operational and technological complexities which must be mastered during the Apollo Program have made it necessary to defer attempts to conduct more elaborate and meaningful in-flight biomedical studies until after the lunar landing goal has been achieved. It is planned to confirm the Gemini data with adequate preflight and postflight observations on every possible flight. These will involve blood volume and red-cell mass studies, lower body negative pressure, X-ray densitometry, biochemical studies, and exercise response. Documentation of these data will only place us on a firmer footing on the



Figure 10. Apollo waste management equipment.

second plateau. We have not, and still will not, obtain any data on real-time changes prior to the follow-on programs to the Apollo Program. A new requirement has resulted from the quarantine requirement on lunar return. The crew and spacecraft microbial flora will be documented, preflight and postflight.

APOLLO APPLICATIONS PROGRAM (AAP) — THIRD PLATEAU

Two flights are currently programed for the 1970-71 period, one to be of 28 days' duration and one to be of 56 days' duration. The workshop will consist of the Apollo command module, a multiple docking adaptor, an airlock, and a spent hydrogen stage (SIVB) that will be converted into living quarters and a laboratory (Figure 11). One of the prime objectives of the AAP is the qualification of man for a longer duration flight. Certain critical in-flight biomedical measurements are required to insure success

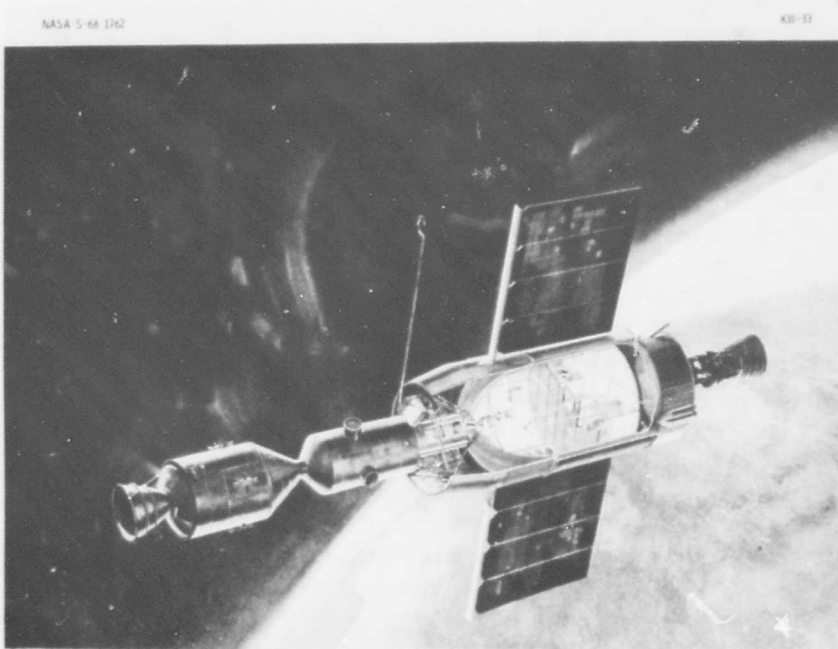


Figure 11. SIVB workshop.

in manned missions lasting 2 months or longer. Physiological changes have consistently been observed which could reduce the overall capability of man to cope effectively with the stresses of reentry and landing, and with in-flight emergencies. It is impossible with present knowledge to describe the rate of onset of deleterious physiological changes or to determine the relative importance of weightlessness as the primary causative factor. Furthermore, very little is known of the influence of such man-made environmental features as the physical confinement, the oxygen-rich atmosphere, or the acceleration profiles of reentry. If the changes observed should be continuous as a function of mission duration, difficulty would be likely upon landing after a 2-month mission. The capacity of the human organism to accommodate to environmental stresses must be appreciated as well as his ability to acclimatize and perhaps even adapt to continuing major alterations in the external environment.

It is encouraging to observe the general similarities in the postflight condition of the astronauts in the 8- and 14-day missions.

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It is vitally important to confirm whether or not the natural processes of acclimatization are being observed rather than just the gradual and progressive deterioration of the body. The in-flight medical experiments proposed for the initial manned mission in the AAP will provide the first new knowledge required to explain the nature and the extent of human acclimatization to the spaceflight environment in Earth orbit. Attaining this goal will represent our desired third plateau of knowledge. Instead of identifying only what happens, a determination will begin of why, and of how, it happens.

Flight data, thus far, indicate that physiological change occurs during the early hours of exposure to the spaceflight environment. All data have been concentrated in 3- and 4-day missions with the exception of the single 8- and 14-day flights. Evidence of readaptation to a 1-g environment is being obtained in our postflight measurements, and information must be obtained concerning the in-flight adjustments that occur at an early date. Preparations must be made to obtain critical data on the proposed experiments from the first day of flight onward. Preparations to do this by placing the medical experiment equipment in the multiple docking adaptor are currently being made. This will allow its use even before the SIVB workshop is activated.

Various medical studies have been proposed to verify man's capability for extended space activities which have been deemed critical. A summary of the necessary experiments is shown in Figure 12. A set of medical investigative procedures has been developed which are believed to be feasible and within the scope of current plans for AAP missions. All procedures are addressed to the areas of greatest medical interest in establishing the qualification of man for long-duration spaceflight. However, they all depend also upon the provision of hardware which will meet the physiological specifications. Initially there were four major areas of interest:

- (1) Cardiovascular function, including hematology
- (2) Respiratory metabolism and energy expenditure during measured workloads
- (3) Musculoskeletal function in nutritional balance
- (4) Neurophysiology of the vestibular system, and sleep.

**PROPOSED
MEDICAL
EXPERIMENTS**

- ENERGY COST OF INFLIGHT TASKS—
1 g VERSUS 0 g O₂, CO₂, EKG,
BODY TEMPERATURE, ERGOMETRY
- CARDIOVASCULAR FUNCTION DURING
PROLONGED SPACE FLIGHT
0 g TILT ANALOG, EKG, BLOOD
VOLUME STUDIES
- MINERAL METABOLISM DURING EXTENDED
SPACE FLIGHT
 - BONE AND MUSCLE BREAKDOWN
 - SALT (ELECTROLYTE) LOSS
- NEUROLOGICAL EFFECTS OF EXTENDED
SPACE FLIGHT
 - VESTIBULAR
 - SLEEP ANALYSIS
 - COORDINATION (CLINICAL
NEUROLOGICAL TESTS)

Figure 12. Proposed medical experiments.

Each of these governing protocols has a number of specific measurements, or tests, which give a clearer picture of the function of that particular body system. The cardiovascular study, for example, involves the use of lower body negative pressure: pre-flight, inflight, and postflight (Figure 13). This instrument tests the cardiovascular system reflexes which normally function in regulating regional perfusion pressure in the distribution of blood throughout the body as postural changes occur in the Earth's gravitation field. This is a vitally important measurement of cardiovascular system response. The in-flight measurement will allow the medical team, for the first time, to establish the onset, the rate of progression, and the severity of adverse functional changes in the protective reflex responses. This procedure requires a medically trained observer and would not be conducted without a physician astronaut on the crew. The cardiovascular investigation also includes obtaining a vectorcardiogram during given workloads on a bicycle ergometer. The use of an antideconditioning garment will also be investigated.



Figure 13. Lower body negative pressure device.

The conduct of the metabolic experiment will require that the habitability hardware, food, water, waste management, personal hygiene, and sleep stations be configured in the best state-of-the-art knowledge, and that they be available for the early portion of the flight. The workshop itself could be utilized to test advanced concepts in habitability and to try various experimental concepts.

CONCLUSIONS

Then what is necessary to qualify man for still longer duration spaceflight? Data must be obtained from an adequate sample (preferably six crewmen) for flight durations of 6 months in order to give adequate prognostic capability for flights in excess of this duration. A 6-month period would give us reasonable assurance that all the body's systems have had ample time to show evidence of change and, if possible, acclimatization.

The efforts must not be limited to orbital flights, however. Man must be used to explore the universe, to go to the planets,

to build in space, and to use this new frontier for developments—many of which are probably not even dreams now.

Man must capitalize on his tremendous investment in the future and on the scientific and technological base he has built. The benefits to man on Earth—from our further exploration of space—will continue to grow and continue to be realized by all.

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XIII

Geologic Orbital Photography: Experience from the Gemini Program

Dr. Paul D. Lowman, Jr.*

INTRODUCTION

The potential geologic value of photography of the Earth from space has been recognized since high-altitude pictures from sounding rockets became available after World War II (Merifield, 1963; Lowman, 1964; Garcia, 1966). Project Mercury Astronauts W. Schirra and L. G. Cooper performed the first orbital photography specifically for geological purposes in 1962 and 1963 (O'Keefe, et al., 1963). Study of these and other hyperaltitude photographs led to the proposal for a Synoptic Terrain Photography Experiment for the Gemini Program. The experiment was carried out by astronauts on most of the Gemini flights with remarkable success (Gill and Foster, 1968), and, in fact, all but the aborted (though successful) Gemini VIII flight produced some geologically useful photographs.

Study of these pictures, of which there are nearly 1100, has produced considerable information of inherent value. From a broader viewpoint, the Gemini terrain photography is of great value as the first major attempt at systematic geologic studies of the Earth conducted from orbiting spacecraft. The purpose of this paper is, first, to describe the objectives and results of the

*Planetology Branch, NASA Goddard Space Flight Center, Greenbelt, Maryland.

terrain photography experiment and, second, to summarize the major conclusions which can be drawn from it as to applications, advantages, disadvantages, and planning of orbital photography for geologic purposes.

THE SYNOPTIC TERRAIN PHOTOGRAPHY EXPERIMENT

The objective of the Synoptic Terrain Photography (S-5) Experiment (Lowman, 1966) was originally to obtain high-quality small-scale color photographs of selected parts of the Earth's surface for geologic study. However, the striking quality and coverage of the pictures obtained during the Gemini III, IV, and V flights demonstrated the usefulness of such photography in other fields. Accordingly, the scope of the experiment was expanded from Gemini VII on to include areas of geographic and oceanographic interest as well. Meteorological photography was covered by the Synoptic Weather Photography (S-6) Experiment, which used the same cameras and films; principal investigators for this experiment were K. M. Nagler and S. D. Soules of the Environmental Science Services Administration. It should be pointed out here that the S-5 and S-6 experiments were only two of fifty-two total experiments carried out on the various Gemini flights (Foster and Smistad, 1968). Furthermore, these were strictly subsidiary to the main objectives of the Gemini Program, which were essentially to develop the capability for long, complex space missions (Mueller, 1968).

EQUIPMENT, CREW TRAINING, AND METHODS

The three 70-mm hand-held cameras used during the ten manned flights for operational, weather, and terrain photography (Thompson, 1967; Underwood, 1968) were as follows:

- (1) Hasselblad 500-C: This camera, modified for space use (by Cine Mechanics, Inc.) and equipped with a 65-frame capacity magazine built by Cine Mechanics, Inc., was the basic camera for most terrain photography. The lens used for most pictures was the standard 80-mm Zeiss Planar; a number of pictures were taken on Gemini VII with the 250-mm Zeiss Sonnar telephoto lens.
- (2) Maurer Space Camera: This camera was developed especially for astronaut use and could accommodate a wide variety of

components. Terrain photography with the Maurer was done with the 80-mm Schneider Lens.

(3) Hasselblad, Super Wide Angle: The 90° field of view of the Zeiss Biogon lens made this camera useful for general purpose photography, but a large number of good terrain photographs were also taken with it despite the short (38-mm) focal length. It was used with the same magazine as the Hasselblad 500-C.

The Hasselblad cameras, when used with color film, were fitted with haze filters (Haze 50 or 63) cutting off light below 3400 Å. When used with Ektachrome Infrared, they were fitted with infrared filters cutting off light below 5000 Å. No filters were used for terrain photography with the Maurer 70-mm camera.

During the Gemini V flight, the Surface Photography Experiment (D-6) was carried out. Equipment used included a Zeiss Contarex camera and a 200-mm Nikkor and 1270-mm Questar lenses. The objective of the experiment (to acquire, track, and photograph objects on the ground) was accomplished (Ballentyne, 1968) with a number of high-resolution pictures being returned. Although not related to the terrain photography experiment, the D-6 results are of interest because they demonstrate the feasibility of obtaining relatively large-scale photographs from orbit.

The majority of terrain pictures was taken with Ektachrome S.O. 217 or S.O. 368. One magazine of Anscochrome D-50 was used on Gemini V. Ektachrome Infrared, Type 8443, was used on Gemini VII. The equipment, films, and other pertinent data are summarized in Table I.

Because of the various types of photography required of the astronauts during the Gemini Program, they were intensively trained by the Photographic Technology Laboratory. For terrain photography, the crews were given one or two briefings covering the following subjects:

(1) Experiment objectives: These were as stated previously. In briefings for later flights, some time was given to summarizing progress to date, with examples of good and bad photography from previous missions.

(2) Areas to be covered: With the aid of flight-path maps (Fig. 1), the areas desired were discussed in order of priority, with

Table 1. S-5 Photography on Gemini Flights

Flight	Camera	Film	No. Usable Pictures	Land Areas Covered
3	Hasselblad 500C	Ektachrome	7	NW Sonora, Rio Grande Valley, Bernauda
4	Hasselblad 500C	Ektachrome	100	NW Mexico, SW United States, N. Africa, Bahama Islands, Arabian Peninsula
5	Hasselblad 500C	Ektachrome Super Anseochrome	175	SW U.S.A., Bahama Islands, SW Africa, Tibet, India, SW Asia, China, Australia
6	Hasselblad 500C	Ektachrome	60	NW, Central and Eastern Africa, Australia, Canary Islands
7	Hasselblad 500C	Ektachrome Ektachrome IR	250	N Africa, Arabian Peninsula, India, Caribbean Sea and adjacent land areas, Brazil, Mexico; Infrared film: Gulf Coast, United States; Northeast Brazil
9	Hasselblad 500C Hasselblad SWC	Ektachrome	160	N Africa, N South America, Caribbean Sea, Mexico
10	Maurer Space Camera Hasselblad SWC	Ektachrome	75	N Africa, China, Taiwan, NE South America
11	Maurer Space Camera Hasselblad SWC	Ektachrome	102	N Africa, Arabian Peninsula, S India, NW South America, Gulf Coast of United States
12	Maurer Space Camera Hasselblad SWC	Ektachrome	160	S United States, N Mexico, N Africa, SW Asia, Arabian Peninsula

NOTE: Spacecraft altitudes in Gemini flights ranged from about 100 to 200 statute miles. On the Gemini II flight, however, the orbit was changed for two revolutions from about 174 statute miles (circular) to 174 (perigee) and 850 (apogee) statute miles. Most of the pictures taken on Gemini II were from the two high revolutions, at altitudes of about 400 to 850 miles. On Gemini X, an altitude of over 450 statute miles was achieved on some revolutions.

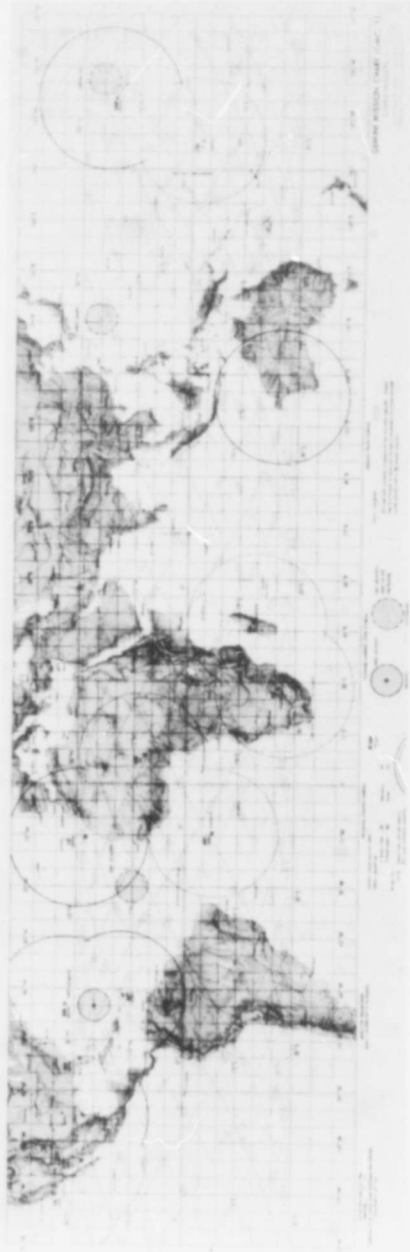


Figure 1. Typical Gemini flight-path map, showing areas covered during a 24-hr period. Note latitude restrictions and separation of adjacent flight-path segments.

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as much time as possible spent on the geologic reasons for studying each region. For example, considerable weight was put on the African Rift Valley because of its geologic importance, size, and possible relation to continental drift. In all briefings, it was stressed that good pictures of *any* land area would be of value; if planned areas could not be covered because of clouds or other reasons.

(3) Techniques: The crews were requested to take vertical pictures at 5-second intervals to obtain 25-mile separation between photographs and roughly 60% overlap at normal altitudes (generally between 100 and 200 statute miles). Recommended time for photography was local noon plus or minus 3 hours, to avoid having to change camera settings which were generally f 11 at 1/250 sec for Ektachrome. Measures to avoid stray reflections and scattering from the windows were also discussed.

The crews followed the planned procedures as much as possible; their skill and perseverance in this is demonstrated by the quality and quantity of the pictures returned. Three main problems were encountered: First, fuel or electrical power restrictions (preventing use of the inertial platform) frequently prevented the crew from pointing the spacecraft straight down; because of this, many of the terrain pictures are high obliques. Second, cloud cover, especially on the shorter missions, frequently obscured the primary areas. Third, window obscuration by deposits from boost-phase ablation, rocket exhaust during staging, and window gasket degassing degraded some pictures. This problem was especially severe on Gemini VII.

RESULTS OF THE TERRAIN PHOTOGRAPHY EXPERIMENT

The terrain photography experiment was highly successful, thanks to the skill and perseverance of the astronauts and supporting personnel. Nearly 1100 pictures usable for geologic, geographic, or oceanographic study were obtained. Some pictures of all the major areas requested were obtained; some of the areas, such as the North end of the Red Sea, were repeatedly photographed. Others were photographed at high-tilt angles. Some of the smaller areas, such as certain oceanic islands, were not covered. A condensed summary of the results is presented in Table I.

Dissemination of the pictures has been a difficult problem, especially in view of the high cost of color prints. Most of the usable pictures from Gemini III, IV, and V have been published in *Earth Photographs from Gemini III, IV, and V*, NASA Special Publication 129, available from the Government Printing Office, Washington, D.C. A second volume containing selections from the remaining flights is in preparation. A collection of sixty-eight Gemini photographs was published by Lowman, 1968. Dissemination of color transparencies and black-and-white prints to scientific organizations is the responsibility of the National Space Science Data Center, Code 601, Goddard Space Flight Center, Greenbelt, Maryland 20771.

A discussion of all the usable terrain pictures would obviously be beyond the scope of this paper; in addition, interpretation will take several years of work. Therefore, a few selected pictures will be presented and their geologic content summarized in some detail.

GEOLOGIC APPLICATIONS

The photograph of Figure 2 was the first in a spectacular series of thirty-nine overlapping pictures taken on the Gemini IV mission by J. A. McDivitt and E. H. White, which is at this time the longest continuous strip taken from manned spacecraft. It shows several thousand square miles of northern Baja California, Mexico, in which a number of major geologic features are visible. This picture and the three succeeding ones have been used to prepare a geologic map with a 1:250,000 scale by F. Garcia, Consejo de Recursos Naturales Non-Renovables, Mexico.

An aspect of special interest in this picture is the synoptic view it provides of the regional geologic structure. The pronounced lineament at the lower left is the Agua Blanca fault, discovered as recently as 1956 by Allen, Silver, and Stehli, 1960, although it is one of the most prominent tectonic features in Baja California. The Gemini picture reveals that the Agua Blanca fault is one of a series of at least three (1 cm) and probably more—faults with similar trend. Furthermore, it appears that, although Allen, et al., described the Agua Blanca fault as a right lateral wrench fault, its companion to the north has little, if any, noticeable

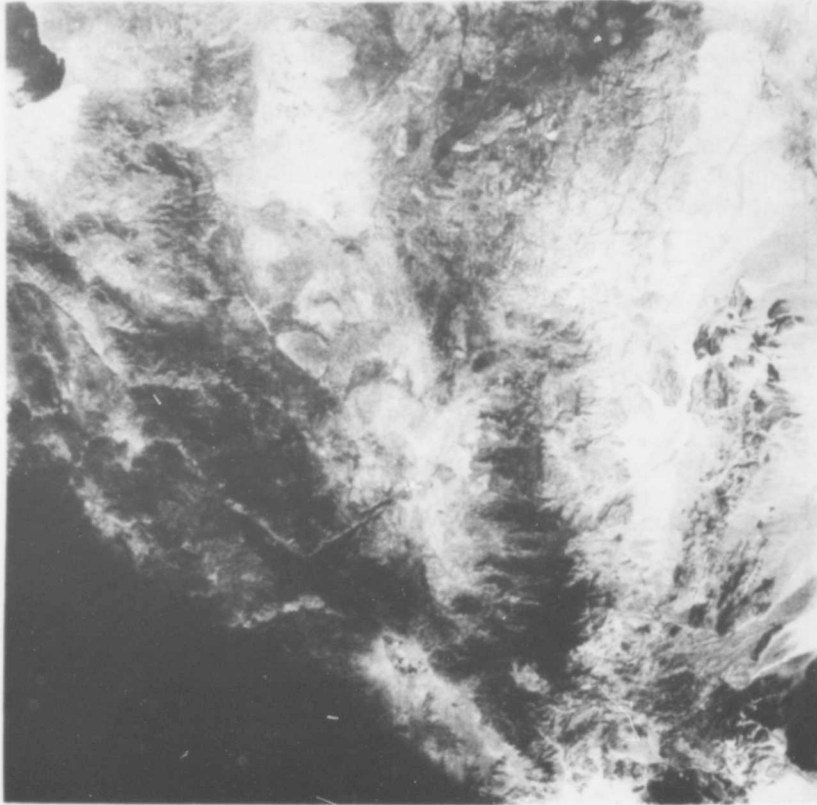


Figure 2. Northern Baja California, Mexico, showing an area about 70 miles wide (North at top). Agua Blanca fault zone at lower left, parallel to spacecraft window. Note semicircular pluton north of Agua Blanca fault at center. Dark areas are generally mountains; light areas, valleys or coastal desert near Gulf of California. Gemini IV photo; original in color.

lateral displacement. Evidence for this conclusion lies in the circular feature, underlain partly by a granite pluton and partly by cretaceous sedimentary rock. This outcrop pattern is consistent with vertical displacement, but the circular structure is apparently not offset laterally.

The usefulness of orbital photographs in revising geologic maps and in studying regional structure is demonstrated by Figure 3



Figure 3. Northern Chihuahua, Mexico, and Southwestern New Mexico, showing an area about 70 miles wide at the top of the picture (North at top). Palomas volcanic field at center; West Potrillo Mountains volcanic field at upper right. Note gradation of structure from folded mountains at lower right to block-faulted mountains at upper left, trending about $N60^{\circ} W$. Tres Hermanas Mountains are just north of the Palomas volcanic field; the Florida Mountains are just north of them, at top center; both are surrounded by conspicuous pediments. Gemini IV photo.

(Palomas), a later picture in the overlapping series by McDivitt and White (Lowman, McDivitt, and White, 1967). This photograph shows part of Southern New Mexico and Northern Chihuahua, Mexico. One of the most conspicuous geologic features on it is the large volcanic field in the center, which will be referred to as the Palomas volcanic field, although some maps show it as the

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Sierra Carizarilla. This feature is not shown on the most recent (1965) geologic map of North America, although it is about 15 miles in diameter and similar in size to other Quaternary volcanic fields which are shown. There is no mention of it in a pertinent reference (Griswold, 1961) covering the geology of Luna County, New Mexico, although some of the volcanics just over the American border are clearly related to the Palomas field. In a sense, then, this prominent feature can be said to have been discovered by orbital photography. Field and aerial reconnaissance by this writer and H. A. Tiedemann have confirmed the volcanic nature of the Sierra Carizarilla; preliminary petrographic study indicates the rocks to be a uniform olivine basalt.

This picture also provides considerable insight into the regional structure. Perhaps the most striking tectonic characteristic of the area is the continuous gradation from folds (lower right) in the extension of the Sierra Madre Oriental to the faults (upper left) of the Basin and Range Province in the various ranges of New Mexico. This implies considerable control of the faulting by pre-existing fold axes in the latter area, as proposed by Jones (1961). In addition to the concordance of fold and fault trends, however, a comparison of this picture with geologic maps of the area shows that the folds are largely confined to the folded Mesozoic sedimentary rocks and the faults combined to areas of Tertiary volcanics. This tends to support Mackin's (1960) hypothesis that the block faulting of the Basin ranges is the result of crustal subsidence following the immense ignimbrite eruptions of the Tertiary.

Still another aspect of the tectonic pattern revealed by the Gemini photograph related to the Texas lineament (Moody and Hill, 1956), a major fault system believed to extend in a N60° W direction from West Texas through El Paso into California. Study of this and adjoining photographs in the Gemini IV series reveals no definite evidence of a single lineament west of the Quitman Mountains, some 75 miles southeast of El Paso. For example, the West Potrillo Mountain volcanoes show no evidence of a N60° W alignment; they appear, instead, to be at least partly controlled by fold axes (Merifield, 1964). Furthermore, there is no evidence to support Griswold's (1961) suggestion that the Texas lineament passes between the Florida and Tres Hermanas Mountains. There is, however, a dominant fault trend of N60° W in these and other nearby ranges which is the "Texas Direction" suggested by Moody

and Hill (1956), although the influence of fold axes on this direction, shown on the Gemini photographs, implies that North-South compressional stresses alone are not the only cause of this direction.

Finally, it should be pointed out that this photograph provides an excellent synoptic view of pediments in this area and should be valuable in studying the relation of pediment formation to structure, rock type, and other geologic factors.

Because of the generally good weather over North Africa, as well as the geometry of the flight paths, this area was extensively photographed during various Gemini flights. Figures 4 and 5, though not photogrammetrically the best of these pictures, are of considerable geologic interest. Figure 4, taken on the Gemini 4 mission, attracted immediate attention because of the striking linear pattern shown southeast of the Tibesti Mountains. Later pictures, such as Figure 5, clarified the nature of this pattern whose true extent and shape is not shown on even recent topographic maps such as the Largeau 1:1,000,000 sheet of the Institut Geographique National (Paris, 1961). It appears to be a composite feature, consisting primarily of fractures enlarged by prevailing winds which have also produced linear sand dunes in some places. Grove (1960) illustrates features northwest of the Tibesti Mountains which appear similar in air photos. The regional extent of the fracture pattern surrounding the Tibestis appears to have been unsuspected. In accordance with the findings of Lattman and Nickelson (1958) and Wobber (1967), the fractures are interpreted as joints, probably formed by tension during the uplift of the Tibesti massif. It is interesting to speculate on the possible connection between this uplift and the generation of magmas which formed the extensive Quaternary volcanic fields; one is reminded of Rich's "magma blister" hypothesis, Von Haarman's "geotumor," or King's "cymatogeny" (1967).

Another interesting structure revealed in Figure 4 is the circular structure east of the Tibesti Mountains. Although shown on the Largeau sheet as a series of concentric sandstone ridges about 9 miles in diameter, there is no mention of it in geological literature, such as Gerard's 1958 report on the geology of Chad. Since undiscovered impact structures have been one of the objectives of the terrain photography experiment, this feature was immediately suspected. An igneous origin (e.g., a laccolith or stock)

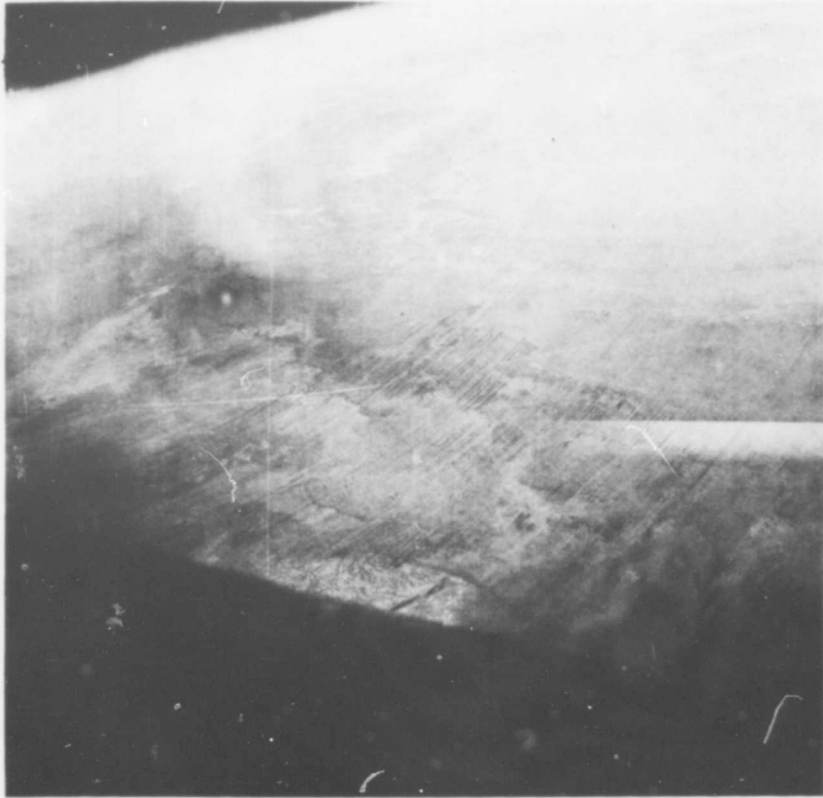


Figure 4. North-Central Africa, looking northwest over Libya, Chad, and Egypt. Tibesti Mountains, with Emi Koussi, are at left. Concentric pattern in foreground believed to be combined erosion and dune features. Circular feature at center is the unknown structure discussed in text. Gemini IV photo.

seems more likely, in view of its proximity to the vast Tibesti volcanic field; a salt or sedimentary diapir may also be responsible. However, an impact origin should also be considered, and, in particular, evidence of shock metamorphism should be searched for in rock from the center of the disturbance.

Pictures taken in the vicinity of the Arabian Sea on Gemini IV, XI, and XII were used by Lowman in 1967 to study the possibility of continental drift in this area. Carey proposed (1958) that the Arabian Sea (Fig. 6) is a "sphenochasm," or wedge-shaped rift,

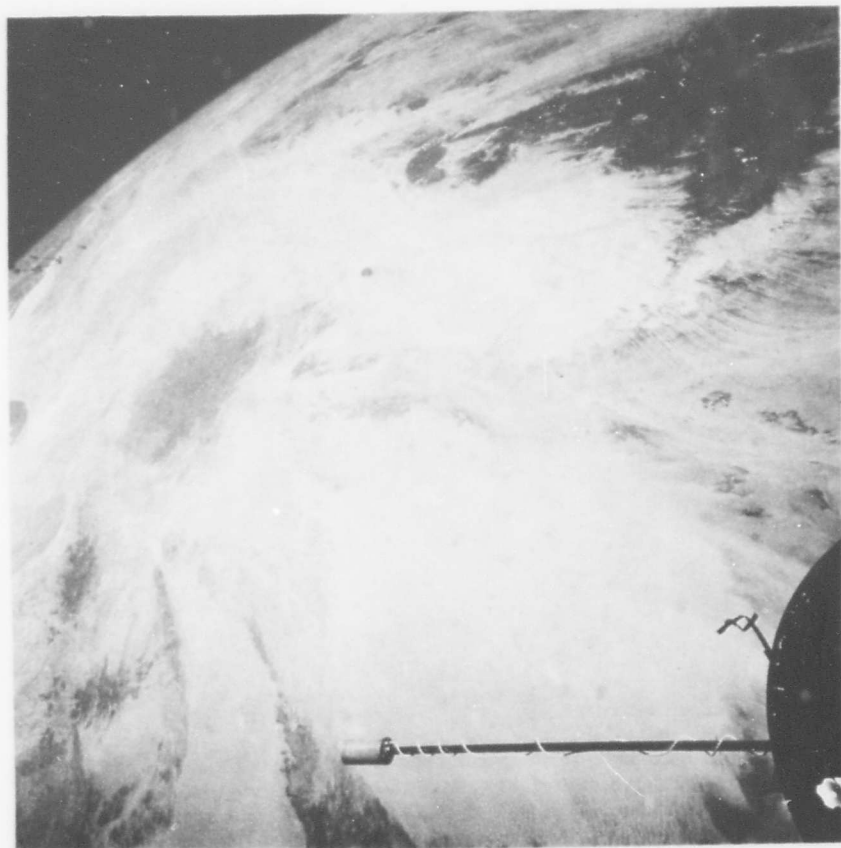


Figure 5. North-Central Africa, looking toward the northeast, over Libya, Chad, and Egypt. Mediterranean Sea is at upper left. Marzuq Sand Sea is at lower right; Haruj al Aswad (recent volcanic field) is at left center. Tibesti Mountains are at upper right, note concentric ridge and dune features. Gemini XI photo.

produced by rotation of the Indian subcontinent away from the Arabian Peninsula and Africa. This theory is based partially on the belief that the Oman Range and the Kirthar and other ranges in West Pakistan are the disrupted ends of a formerly continuous structure. The Gemini photographs contradict this theory in three ways: First, they show (Fig. 7) that the Oman Range turns south at the East end of the Arabian Peninsula, rather than east, as formerly supposed. Secondly, they demonstrate the strong dissimilarity in physiography between the ranges of the two areas.



Figure 6. Eastern half of the Arabian peninsula, looking northeast toward Iran and the Persian Gulf (right), Pakistan (top center), India and Arabian Sea (right). The Oman Range is just above Agena transponder antenna, at center. Photograph was taken from about 260 nautical miles during the high revolutions of the Gemini XI flight.

Third, they demonstrate an equally strong dissimilarity in lithology; the ranges of Sind (Fig. 8) are primarily sedimentary rock of great thickness, and the Oman Range is primarily a geanticline of igneous rock mantled by relatively thin sedimentary rock.

Arguments that these differences are to be expected in view of the considerable distance between the two areas can be answered by still another orbital photograph (Fig. 9) showing the prevailing continuity for great distances along strike characteristic of the Makran Ranges. It appears, in summary, that there is no close relationship between the Oman Range and the supposed corresponding ranges in West Pakistan; to the extent that continental



Figure 7. Eastern end of Arabian Peninsula and the Ras al Hadd; Oman Range is at upper left. Wahibah Sands are at lower left (North at top). Note the pronounced southward trend of the structure at center. Gemini IV photo.

drift in this area is based on such a relationship, the Gemini photographs tend to disprove its reality.

ADVANTAGES OF ORBITAL PHOTOGRAPHY

In comparison with aerial photography, orbital photography for geologic purposes appears to have the following advantages.



Figure 8. Kirthar Range, West Pakistan, and Indus River (right) (North at upper right). City of Karachi is the small dark spot on the coast, just above the spacecraft's nose. Note discordance of Kirthar Range with coast. Gemini XII photo.

Large Area Per Picture

This is of course the most striking difference between photos taken from aircraft and those taken from spacecraft. Standard vertical airphotos generally cover an area measuring roughly 3 to 9 miles on a side, whereas vertical orbital photos, such as those shown here, typically measure at least 70 miles on a side. The importance of this for geological studies is that it becomes possible to see large features on one picture, such as the volcanic field south of Palomas, and to see regional structure covering immense areas.

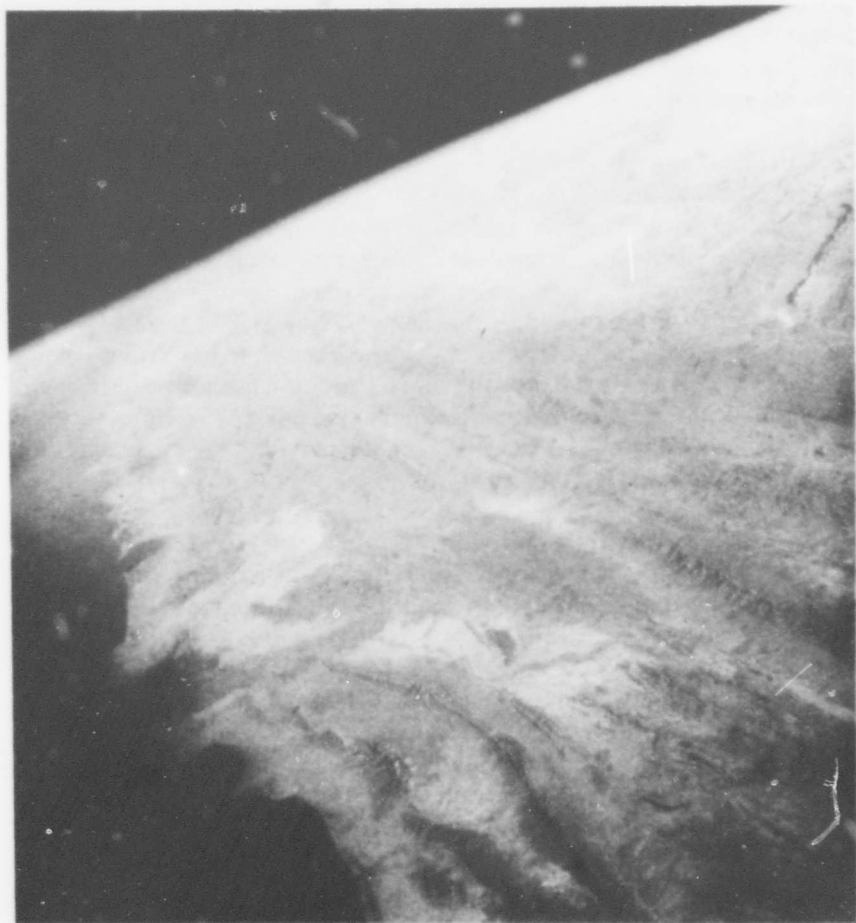


Figure 9. View of the west over the Central Makran Range, West Pakistan, and Iran. Note prevailing continuity of structure along strike. MA-9 photo.

The question naturally arises as to whether this coverage can be duplicated with mosaics (Lowman, 1967). The answer appears to be that even if a mosaic of a given area can be prepared (and this is not possible for many remote or restricted areas or because of the expense), the dodging necessary to remove tone differences between adjoining pictures necessarily removes considerable tonal or color information of geologic importance. Furthermore, the mosaic does not provide stereoscopic coverage of

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large areas as can orbital photograph pairs. Obviously, mosaics will continue to be used where possible, but it seems clear that there is no real substitute for hyperaltitude photography if large area coverage is needed.

Global Coverage

Peculiar to geology is the need to see over the next hill—or the next ocean. Many geologic problems insoluble in one area may yield quickly to studies in another area where critical relationships are exposed. Werner's belief, that basalt was a sedimentary rock, arose partly from the fact that his travels were confined to the Freiberg region where the hill-capping basalts could reasonably be interpreted as sedimentary strata. Had Werner been able to visit the Auvergne, his erroneous theory might not have been formed.

Orbital photography provides a global view of the Earth's geology and will clearly prove invaluable in studies of regional tectonics, orogenesis, and continental drift, because it becomes possible to ignore natural and artificial boundaries. In the study of continental drift around the Arabian Sea just cited, the geologically crucial areas lie in several different countries, some of which are separated by major topographic, oceanic, or political barriers. Furthermore, there is no one organization charged with investigating such regional problems: for example, the Hunting Survey Corporation, whose Colombo Plan report (1961) on the geology of West Pakistan was a major advance, could give only peripheral attention to the Oman-Pakistan problem. Orbital photography can contribute to the solution of such region geologic questions: first, by bringing them to the attention of a large segment of the geological community; and, second, by providing a synoptic view of large or widely separated areas.

Unlimited Dissemination

Most of the world's land area has been photographed at one time or another by civil, commercial, or military organizations, but much of this photography is not easily available, or not available at all, for geologic studies. Oil companies, for example, commission considerable aerial photography, but once having paid for it they are naturally not inclined to give it away. Military secrecy

also prevents dissemination of much geologically valuable photography.

The situation in regard to orbital photography obtained by the National Aeronautics and Space Administration is quite different. NASA is required by the National Aeronautics and Space Act of 1958 (P.L. 85-568) to "... provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." One result of this requirement is that the 70-mm photographs taken on the Mercury and Gemini flights have been made available to qualified investigators from all over the world. This will clearly lead in a few years to a much better acquaintance with the geology of remote areas and will help avoid provincialism in geologic education and research.

Availability of Color Coverage

It is generally realized that color aerial photography is inherently more valuable than black-and-white photography because of its greater information content. A major disadvantage of color photography, however, is its higher cost. Orbital photography may make color coverage of a large part of the world practical, for at least two reasons: First, the addition of color film to the photographic payload adds a negligible amount to the overall mission expense. Second, the greater coverage area per picture obviously reduces drastically the number of prints or transparencies necessary for a given area. This is probably a major advantage of orbital photography, since most of the added expense of color aerial photography is that of reproduction.

This discussion applies to multispectral coverage as well, which may be geologically valuable in areas where vegetation distribution provides clues to structure and lithology.

Range of Scales

Orbital photography has a one-way advantage over aerial photography in that it is easy, from altitudes of 100 miles or more, to obtain coverage with scale numbers of several million. From aircraft, by contrast, the highest scale numbers of geologically useful photography are probably on the order of 250,000, although balloon

photographs with scale numbers of 700,000 have been taken (Katz, 1960). One advantage of satellite-borne cameras is that they can go down to much smaller scale numbers by the use of long focal lengths. This was demonstrated by the D-6 Experiment on Gemini V, which produced usable pictures with scale numbers between 50,000 and 100,000 using a 56-inch focal length (McKee, 1966). In principle, then, although scale and resolution are not perfectly reciprocal (Katz, 1960), orbital photography can duplicate aerial photography to a considerable degree, while the reverse is true only to a very limited extent.

This conclusion should not, of course, be considered a recommendation that spacecraft replace airplanes for photography; it does, however, indicate the inherently greater versatility of orbital methods.

DISADVANTAGES OF ORBITAL PHOTOGRAPHY

It is unfortunately easy to fall into the habit of unconsciously thinking of spacecraft as remarkably fast, high-flying airplanes. Such thinking tends to obscure certain real limitations of orbiting spacecraft as camera platforms, such as the following.

Orbital Characteristics

For photography, the major difference between spacecraft and aircraft is that spacecraft flight direction (relative to the Earth) is primarily determined, after injection into orbit, by the laws of celestial mechanics, whereas an aircraft can fly in any direction and can change this direction as often as is necessary. This point cannot be overemphasized, since, as Harman, et al., 1966, pointed out, proper choice of flight direction is vital to efficient photography. Slight changes in spacecraft direction (orbital plane changes) can be made, but are extremely expensive in terms of fuel; for example to make a 2° plane change from a 100-mile altitude requires a velocity change of about 1000 ft per sec. Altitude changes, on the other hand, are relatively less expensive if accomplished by coplanar orbital transfer.

Among the orbital parameters affecting photography of the Earth are the apogee and perigee heights and the ellipticity. The

effects of altitude on scale need no elaboration here. However, it may be pointed out that, because of atmospheric drag, the lowest practical Earth satellite altitude is about 100 miles. Below this, the satellite will re-enter within a few hours at most.

Probably the most important orbital characteristic of concern here is the inclination of the orbital plane to the equator. This is equal to the latitude coverage; e.g., an orbit with 32° inclination will cover a latitude band between 32° north and south of the equator. Low inclinations of this order were typical of the Mercury and Gemini flights and are the reason for the relatively restricted geographic coverage of their photography. High inclinations are clearly desirable for efficient photography, but are not easy to attain for several reasons: First, a launch in any direction but due East loses some of the potential extra velocity added by the Earth's rotation (about 1500 ft per sec at the equator). Second, range safety requirements for some sites restrict launch azimuths; rockets launched from Cape Kennedy, for example, must use a corridor between azimuths of 45° and 108° . As pointed out previously, moreover, plane changes can be very expensive in terms of fuel requirements. To give a pertinent case: to increase the latitude coverage of a spacecraft launched into a 30° inclination orbit 5° , by a plane change from a 100-mile circular parking orbit, would require energy equivalent to a velocity increase of about 2000 ft per sec. Gaining the additional 5° by launching more nearly north, on the other hand, would require only a few hundred feet per second equivalent velocity change (from loss of the increment from the Earth's rotation), but range safety requirements set limits to this approach from some sites. The USAF Western Test Range at Point Arguello, California, permits launches due South and, for this reason, is used for polar and retrograde orbits.

The implication of the foregoing discussion for orbital photography of the Earth is that latitude requirements must be factored into mission planning from the very beginning, since they will strongly affect major decisions such as the choice of launch site and of vehicle type.

Another photographic problem arising from the characteristics of satellite orbits is that of obtaining sidelap. The difficulty arises from the fact that the minimum orbital period of a photographic

satellite is around 90 minutes, during which time the Earth will rotate eastward some 22° ; for low-inclination orbits, nodal regression caused by the equatorial bulge will increase this westward movement of the flightpath. As may be seen from Figure 1, the resulting separation of adjoining flightlines was between 800 and 900 miles for Gemini orbits, and for swath widths of about 80 miles, typical of the 70-mm photography on these flights, precluded sidelap over most of the latitude band covered. There are compensating factors, such as the convergence of flightlines at higher latitudes, and the intersection of flightlines near the top of the latitude band and other points (Fig. 1). Furthermore, the use of wide-angle systems will increase the swath width, although, as will be discussed under "Camera Orientation," the value of oblique photography from orbital altitudes is questionable. A useful example of the allowance that must be made for sidelap in mission planning is presented by Bock and Lane (1967). A technique for obtaining low-altitude sidelap is to design the spacecraft orbit so that it does not complete an integral number of revolutions in 24 hours and hence does not follow precisely the same path (John Thole, personal communication).

Spacecraft Orientation

Unlike airplanes, orbiting satellites have relatively little inherent tendency to maintain a particular orientation; they can roll, pitch, and yaw rather freely if no measures are taken to prevent this. The problem of spacecraft orientation for photography was a severe one on Gemini flights because of restrictions on thruster fuel or power for the inertial platform, and many of the photographs were taken during drifting flight. The importance of orientation for systematic photography requires some discussion of the topic: for a general description of satellite attitude control, see Corliss (1967). The Gemini systems are described by Carley, et al. (1966).

A wide variety of attitude control systems are available—using gas jets, momentum storage, the gravity gradient, magnetic field torques, and spin stabilization. Gas jets and momentum storage devices such as flywheels appear to be the most promising for photographic missions—providing fast, accurate spacecraft orientation. Nimbus I, for example, was stabilized to within 1° in all three axes. However, both have limited lifetimes because of the

gas supply (most momentum storage devices use an auxiliary pneumatic system) which must be allowed for in mission planning.

A more general orientation problem is the conflict among attitude requirements. A large spacecraft, for example, may have to keep solar panels turned toward the Sun and may carry other experiments with individual pointing needs which will not necessarily coincide with the photographic requirements. This particular problem is a strong argument for unmanned, single-purpose photographic satellites, such as the Tiros series.

Cloud Cover

Orbital photography shares the problem of weather with aerial photography, in particular, that of cloud cover. The Earth has proven to be dismayingly cloudy when seen from orbit; it is estimated that about 50% of the Earth's surface is covered by clouds at any one time. The percentage is greater, moreover, at high latitudes. Obviously, this average is meaningless when applied to any one area, but, since orbital photography is global by definition, it is clear that world cloud cover is a severe problem. As early as 1962, orbital photography of South America was prevented by clouds (Lowman, 1964).

The problem can be approached in several ways. The conventional measure of staying on the ground when the weather is too bad for photography is hardly practical for orbital photography. Another technique is to plan the mission with the aid of cloud cover statistics, as suggested by Bock and Lane (1967), and to include extra film to allow for unusable pictures. More generally, weather statistics could be used to adjust launch schedules for the best photography of large areas.

A method used on the Gemini IX-A mission shows considerable promise for future photographic missions. During the IX-A flight, cloud cover charts were prepared by the Environmental Science Services Administration from weather satellites about every 6 hours as an aid to recovery operations and the S-6 Synoptic Weather Photography Experiment. Personnel of the Flight Crew Support Division (MSC) noticed on these charts that South America at one time was remarkably cloud-free. Knowing that photography of this area was an objective of the S-5 Experiment, they notified

the flightcrew that an opportunity existed. Accordingly, Astronauts Stafford and Cernan took a remarkably useful photographic series of a previously uncovered area. Since meteorological satellites are now in routine operational use, this technique should be usable for other photographic satellites, including unmanned ones if delayed ground command or real-time satellite-to-satellite-ground relay is feasible for areas outside the direct range of ground stations.

Daylight Restrictions

The global nature of orbital photography makes it necessary to take the availability of daylight into account; on some 4-day Gemini flights, for example, it was not possible to photograph areas south of about 10° S latitude because they were dark during possible photographic passes. For long missions, this difficulty is minimized, but allowance must be made for it and, more specifically, for the suitability of Sun angles. A computer program, ERSOS, has been prepared by IIT Research Institute (Bock, 1967) that takes into account not only solar illumination but also orbital elements, instrument performance, and other specifications to produce a schedule for photography during a given Earth-orbital mission.

Window Obscuration and Similar Problems

Slight window obscuration was noticed on terrain photographs taken by W. Schirra during the MA-8 flight; this turned out to be the first encounter with what proved to be a troublesome condition during the Gemini flights. McDivitt and White noticed during the Gemini IV flight, that a substantial coating was left on the left-hand window when White's boot accidentally scraped part of it off during EVA. Although it caused little loss in picture quality, a similar coating during Gemini VII (Lowman, 1966) greatly reduced the value of the pictures (Fig. 10). Postflight investigations show that the deposit was a combination of residues from the rocket exhaust during staging, ablation from the front of the spacecraft during the boost phase, and degassing of window gaskets.

Although various measures can be taken to protect spacecraft windows or to clean them after injection into orbit, it appears that

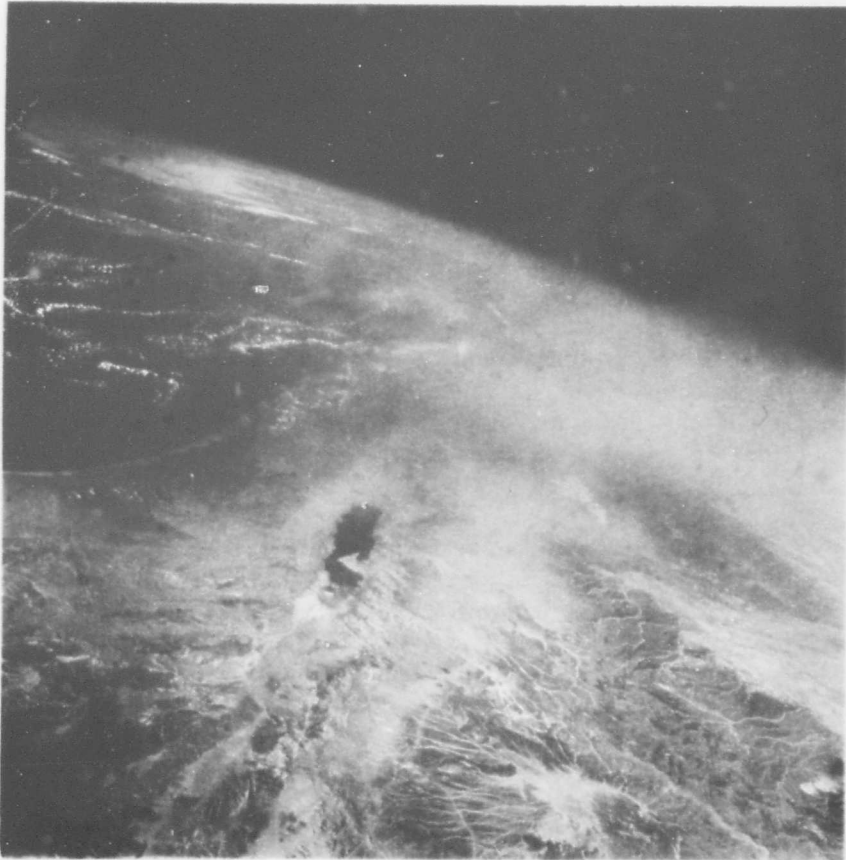


Figure 10. Gemini VII view to the North over the Dead Sea; the Mediterranean Sea is at left. Prevailing haziness of photograph in center is the result of deposit on spacecraft's window.

the best technique in the long run will be to have the cameras completely outside the spacecraft, or at least exposed directly to space, during photography. This would also eliminate the problem of restricted spectral transmission: windows on the Apollo command module, for example, do not transmit much radiation beyond about 8000 Å.

A related situation that could affect orbital photography is the existence of what amounts to a transient atmosphere around a spacecraft. First noticed during the MA-6 flight (Glenn, 1962),

when the pilot sighted "fireflies" [later found by Carpenter (1962), to be ice sticking to the spacecraft], various solids, liquids, and gases given off by life-support systems and thrusters may stay around the spacecraft for some time. Although this has so far caused no problem during terrain photography, it obviously should be considered in spacecraft design and mission planning.

Resolution Limits

The ground resolution obtainable from orbital altitudes must obviously be relatively low compared to that of aerial photographs taken with comparable equipment, a fact which had led to skepticism about the geologic value of orbital photography. It must therefore be asked if in fact resolution limits will be a serious handicap in this respect.

First, let us examine the performance of the camera/film combination used in the S-5 Experiment. According to an unpublished report by the Data Corporation, edge analysis of a Gemini IV picture taken with the Hasselblad 500-C (80-mm lens) and Ektachrome S.O. 217 film indicated a resolution of 30 lines/mm for a medium contrast target, a coastline on the Arabian Sea (preflight laboratory tests had achieved 50 lines/mm). The ground resolution can be calculated, using this value at a typical scale number of 2,250,000, to be about 245 feet. However, many linear features with medium to high contrast (such as roads, railroads, and airport runways) and as narrow as 40 feet can easily be seen on the Gemini pictures, confirming previous experience (Katz, 1960), indicating that calculated resolution alone is not a reliable guide to the amount of detail visible in a hyper-altitude photograph.

Next, consider the geometric nature of geologic targets. Among the most important of these are edges representing contacts between major geologic units. If the units are large in area, low resolutions can be tolerated because the contact can be consistently delineated, although located with relatively low precision. A second important type of target includes lineaments (used here solely as a geometric term) which may be drainage features, dikes, or dipping strata. Here, the fact that long lines are more easily detected than small objects (Katz, 1960) comes to our aid, and it is apparent from experience gained with Gemini photos that

lineaments, even small ones, are easy to map from orbital photographs. In general, the type of targets important in geological mapping are the large ones (Table 2), compared to those of interest in other fields, such as individual buildings, vehicles, or aircraft.

It is clear that resolution limits will not be a serious handicap in most geologic applications of orbital photography. However, every effort must be made to obtain the highest resolution possible without sacrificing the unique value of orbital photographs, their extensive coverage per picture. Larger format sizes, 9 × 9 inches or larger, are especially needed, coupled with focal lengths of 6 to 12 inches. The remarkably high resolution of the Gemini photos, taken on 70-mm film chiefly with 80-mm focal length lenses, emphasizes the quality of the pictures to be expected with photogrammetrically adequate equipment.

Target Acquisition

Although the amount of ground detail visible from an orbital altitude to the unaided eye turned out to be surprisingly great,

Table 2. (Modified from Merifield, 1964) Resolution Necessary for Identification of Geologic Features (10 lines/mm image resolution assumed)

Feature	Resolution (meters) Minimum Ground	Equivalent Scale No. on an 8 × 10-in. Print
Relief	450	3,000,000
Major Drainage (e.g., Rio Grande)	450	3,000,000
Tributary Drainage (e.g., arroyos, streams)	150	1,000,000
Erosion and Deposition Surfaces (e.g., Terraces, Bajadas, Pediments)	200	1,350,000
Playas	1,000	6,500,000
Large Faults (e.g., San Andreas)	450	3,000,000
Smaller Faults and Fractures	100-150	800,000

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it was found that acquiring specific points on the ground can be difficult or impossible. During the Visual Acuity Experiment (Duntley, et al., 1966) on Gemini V and VI, for example, the crews had relatively little trouble seeing the ground targets, but they found it hard to locate them at first. The pilots recommended that coastlines and major rivers be used as landmarks.

A technique for finding specific objects with known positions was developed by engineers at the Manned Spacecraft Center (R. D. Mercer, personal communication). A series of curves were computed for time of closest approach of the spacecraft to any point on Earth, in space, or on the celestial sphere, from which the necessary pitch and yaw angles for aiming the spacecraft could be derived. This method can be used on future photographic missions. However, the great value of vertical photography implies that the most effective target acquisition method will simply be the orientation of the cameras straight down at a predetermined time so that it will be unnecessary for the astronaut to locate points on the ground.

Film Degradation

Conditions tending to degrade film in orbital flight are generally similar to those encountered in high-altitude aerial photography, such as low temperature, low humidity, and static electricity discharges. The near-vacuum of space tends to accelerate drying and cracking of film on long exposure to space, but this too is essentially enhancement of an effect already encountered. The major new degrading factor in orbital photography is radiation. This subject is obviously too broad for more than a brief outline here: a review of the effects of radiation on film is given by Harvey (1965); and a bibliography of particles and fields research is given by Hess and Mead (1966).

There are three potentially serious sources of film-damaging radiation in orbital flight: the Van Allen belts, solar flare radiation, and radiation from sources on the spacecraft.

Radiation in the Van Allen belts is chiefly electrons and protons, trapped by the geomagnetic field, of both natural and artificial origin (the latter from high-altitude nuclear explosions). It increases sharply at altitudes of 300 to 500 miles and slightly

with increasing latitude at low altitudes. A prominent feature of the trapped radiation is the South Atlantic anomaly; partly because the Earth's magnetic axis does not coincide with its rotational axis, the radiation belt over the South Atlantic Ocean is abnormally low, and dose rates may be several hundred times those outside the anomaly at a given altitude. The most obvious way of avoiding film damage from the Van Allen radiation is to keep the satellite orbit below 300 miles for missions of more than a few days and, perhaps, to avoid extravehicular camera exposure while going through the South Atlantic anomaly.

Protons produced by solar flares are a sporadic but potentially serious radiation hazard. Flares occur chiefly during the maximum of the 11-year solar cycle; most are relatively mild in terms of corpuscular radiation. Because protons with energies characteristic of flare events are strongly deflected by the Earth's magnetic field (i.e., have low rigidities), they are strongly latitude-dependent: for major events, the proton flux received by a polar-orbiting spacecraft would be several thousand times that received in a 30° inclination orbit. Beyond the protection of the Earth's magnetic field (i.e., above several thousand miles altitude), the flux also is much greater. Because of the rarity of major flares, they should not be a serious detriment to Earth-orbiting photographic missions if precautions are taken. One precaution that seems indicated for future flights is the use of the flare-warning system developed for the Apollo Program to detect major events; since protons take several hours to reach the Earth, while the flare is seen (in H α light) some 8 minutes after it occurs, it should be possible to abort the mission if necessary to avoid film damage.

A third source of damaging radiation is the spacecraft itself (such as thorium-containing alloys) or part of its payload (such as radioisotope power sources). This problem can obviously be controlled, but again it emphasizes the fact that, for best results, a photographic orbital mission should be planned as such from the very beginning.

The main questions remaining to be answered are just what sort of doses are necessary to damage film and whether Earth-orbiting spacecraft will encounter this much radiation. Although much more information is needed on the sensitivity of film to X-rays, gamma rays, and particulate radiation, there seems to be

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general agreement that 1 rad (roughly the absorbed dose of any ionizing radiation liberating 100 ergs per gm of absorbing material) is the threshold at which effects such as loss of resolution and contrast become detectable for black-and-white film. For color film (generally slower), the threshold is about 2 rads. Significant effects begin at about 5 to 10 rads for most films.

There is, of course, an immense amount of information on space radiation from the many satellites flown for this purpose. However, the crew dosimeter results from the Gemini flights (Higgins, et al., 1968) are sufficient to give one a rough idea of how much radiation might be encountered by a reasonably well-protected film in Earth orbit. The dose to the left chest of the command pilots, for flights longer than 1 day, ranged from 0.015 to 0.770 rad, the highest figure being that received on the Gemini X flight, which made several passes through the South Atlantic anomaly at about 400 nautical miles altitude. The Gemini VII mission—a 2-week flight at about 160 nautical miles—recorded a total dose of 0.192 rad. If we assume this to be typical of low altitude, low inclination flights, we see that it would correspond to a dose of about 5 rads for a 1-year flight. This is obviously a very rough approximation, but indicates that normal radiation should not be a serious detriment to orbital missions under these conditions, especially since the film alone could be shielded much more than were the pilots on the Gemini flights.

Atmospheric Scattering

Since orbital photography must be taken through the entire optical thickness of the atmosphere, scattering effects become important. An excellent summary of the problem is given by Harvey and Myskowski (1965); experience gained during the Gemini program is useful in determining the effects of scattering on color photography.

These appear to be more or less what might have been expected from experience with aerial photography. First, the loss of color in the blue-green region of the spectrum is considerable, even with the filters mentioned. This is largely due to scattering by moisture in the atmosphere, and, since the heavily vegetated parts of the world are usually humid, there were relatively few good color pictures obtained of the major tropical forests. Color infrared was

used successfully on Gemini VII, however, despite window obscuration (Lowman, 1966). Second, there was considerable loss of contrast and resolution in humid areas due to scattering.

Scattering effects do not appear to be an insurmountable difficulty to geological orbital photography, despite the Gemini experience, for several reasons: First, the colors of greatest geological importance are the reds, yellows, and browns—the longer wavelengths which are not very strongly affected by scattering. Second, the best areas for any sort of geological photography are the deserts, which are characterized by dry air. Finally, the use of color infrared film, color film with enhanced red response, or multispectral cameras (Badgely, et al., 1968) promises to overcome the problem of getting good color photography in humid, heavily vegetated areas and hence to make geologic photography practical to the extent that vegetation reflects structure and lithology.

Camera Orientation

As mentioned earlier, many of the Gemini terrain photographs were taken during drifting flight, and most are obliques with various degrees of tilt. They thus provide valuable experience in the limitations of oblique orbital photography; the main advantage of obliques, their areal coverage, is of course accentuated by the great altitudes of satellites.

Study of the Gemini pictures indicates that obliques lose a considerable amount of detail near the apparent horizon. The geometry of the situation reveals the reason for this; the slant range is inversely proportional to the cosine of the tilt; and the cosine increases very rapidly for angles over 75° . The scale numbers increase proportionately (even neglecting curvature) to values of several million, at which only very large features are distinguishable. However, with this decrease in resolution go two other nonlinear effects. The thickness of atmosphere increases with the slant range, causing rapid loss of color and additional resolution loss. Also, the foreshortening becomes extreme, making it difficult to get true impressions of geometric relations, which is extremely important in geologic studies. At the present time, it appears that pictures with tilt angles much greater than about 50° are of little use geologically (except in special cases, as in

searching for lineaments parallel to the line of sight) because of these effects. Rectification of Gemini obliques has been done successfully by the Autometric Corporation under a U. S. Geological Survey contract; however, this obviously restores only the geometry, not the resolution and color, lost in the original photographs.

This situation has important implications for orbital photography: First, it suggests that panoramic cameras will have limited value unless very large formats, long focal lengths, and infrared film are used. Second, it accentuates the importance of planning orbits so that sidelap is obtained without excessive slant ranges.

SUMMARY AND CONCLUSIONS

It is clear that, as a result of the Gemini Program, we now have a firm grip on the "problems and prospects," to use Katz's phrase, of orbital photography of the Earth's surface. The major conclusion to be drawn from this report is that orbital photography for geological purposes is clearly feasible and uniquely valuable. Beyond this, several specific areas of geologic application can be delineated.

Regional geologic mapping, at scale numbers of 250,000 and larger, can be done from orbital photographs with a reasonable amount of ground truth from supplementary low-altitude photography and field work (Lowman and Tiedemann, 1967). This includes, of course, revision of older geologic maps. Tectonic problems, such as the study of major wrench fault systems, are especially susceptible to attack with orbital photography. Geologic education can be freed from such problems as provincialism with the global coverage possible from satellites. Studies of currently active geologic processes, such as near-shore deposition (Wobber, 1967), can benefit from simultaneous photography of extremely large areas.

Orbital photography should also be valuable in planning geological and geophysical fieldwork, making it possible to single out the most potentially interesting areas in advance. The results of regional geophysical surveys may be more easily interpreted when correlated with the regional photographic coverage possible from orbit.

It seems safe to say that, in these and in other fields, orbital photographs will rapidly become as nearly indispensable as aerial photographs are today.

ACKNOWLEDGEMENTS

The successful accomplishment of the photographic experiments carried out by the Gemini spacecraft was the work of many people. The astronauts who took the pictures are to be commended for their perseverance and skill in carrying out exacting scientific tasks under difficult conditions; it should be made clear that these men were acting as cooperating scientists as well as acting as test pilots. In addition, thanks are due the many personnel of the Manned Spacecraft Center who supported the S-5 Experiment, particularly the Experiment monitors, R. D. Mercer and R. W. Underwood, and the members of the Flight Crew Support Division. Finally, I wish to thank my colleague, H. A. Tiedemann, for his valuable assistance on the later Gemini flights.

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XIV

Conditions on the Planet Venus

Dr. John D. Strong*

In the time available, and considering other limitations, it is impossible to give here more than a reporter's résumé of the present status of our knowledge of Venus. In recent months, there have been other preceding résumés; each one tempered by its author's bias. Here we present another, tempered by this author's intuitions and judgments in instances where a consensus of opinion has not yet evolved.

Since early telescopic views revealed Venus as a featureless crescent, copying the phases of the moon—and continuing after observation of the extensions of the horns of her crescent indicated a structured atmosphere, until the most recent *drop-sonde* and fly-by results—each new or confirmed fact relating to conditions on the planet Venus induces elaborate inference to explain unexpected mystifications.

Some of the study of Venus has been unproductive—for example, the polarization of the reflected sunlight and the absence of “rainbow enhancements” have not led to incisive conclusions. And the light, lemon-yellow color of the Cytherian clouds remains unexplained. The overall albedo has only recently become reliable.¹

Dunham and Adams were able to discover strong carbon dioxide absorption in the Venus spectrum because, as we now know, the Venus atmosphere is more than 90% CO₂, with a base pressure of almost 20 atm. But they were not able to detect

*Professor, Department of Physics and Astronomy, Hasbrouck Laboratory, University of Massachusetts, Amherst, Mass.

water absorption in the 1930's. In 1955, Mentzel and Whipple showed that this failure was to be expected.² As for the CO₂, the reflected radiation that they observed had penetrated two orders of magnitude more CO₂ on Venus than in coming down through the Earth's atmosphere to their ground-based telescope. In the case of water vapor, this situation was inverted. However, at an altitude of 90,000 feet, the supernatant telluric vapor lying above a balloon-borne telescope is two orders of magnitude less than that penetrated in the Venus atmosphere; and it was under this condition that water vapor was discovered on the Moore-Ross balloon flight of 1959.³ In 1964, this result was confirmed and refined by observations made from an unmanned flight.⁴ The 1964 flight showed 0.0140 gram of water vapor per sq cm above a postulated reflecting cloud deck, at a pressure of 200 mB. Mentzel and Whipple's ingenious calculation—*loc. cit.*—predicted 0.0130 g per sq cm for ice clouds. The 1964 result is particularly reliable because the water absorption was observed to be shifted $0.49 \pm 0.05 \text{ \AA}$; with a Doppler shift of 0.495 \AA computed from the line of sight velocities. Two ground-based telescope results have confirmed the 1964 result. The USSR *drop-sonde*⁵ gave 0.1% to 0.7% as the water vapor content of the Venus atmosphere. Considering the planet's dense atmosphere, the USSR result indicates 20 grams of water per sq cm above the planet's surface.

The Venus IV result, concerning oxygen in the Venus atmosphere, was 0.4% to 0.8%, amounting to a partial pressure of about one-third that of the Earth's atmosphere. The gases CO, HCl, and HF are found present in trace amounts.

Many cloud compositions have been suggested by astronomers—but, in deference to the negative water result of Dunham and Adams, all these clouds are anhydrous. There are even interpretations that deny the ice cloud conclusion indicated by the similarity between the infrared spectrum of laboratory ice clouds and the 1964 observed Venus spectrum.⁶ (see Figure 1). Rea and O'Leary deny that this similarity indicates that the clouds on Venus are ice particles, mainly because Kuiper did not observe any 1.5μ depression beyond that which could be accounted for by atmospheric absorption. They contend that Kuiper's ground-based telescope result leaves no room for a 1.5μ ice cloud feature, such as Zander observed in the laboratory. Our balloon cloud spectrum of Venus, unfortunately, began at 1.8μ and extended to 3.4μ —thus

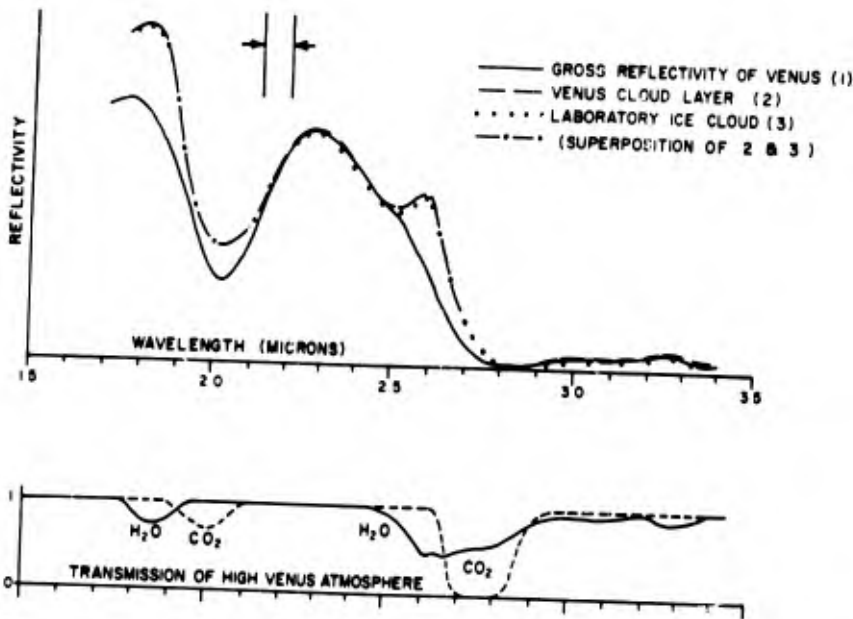


Figure 1. Reflection spectrum of Venus clouds showing correction for upper Venus atmosphere.

we missed observation of Venus at 1.5μ . Rea and O'Leary contend further that the 2μ absorption feature, also, is not strong enough in our Venus spectrum. They contend that the ice crystals must be approximately submicron in size; and that such ice particles—necessary for fitting the observed 1.5μ and 2μ features—fail to provide a low spectral albedo such as was observed at 3.2μ and beyond. Hansen and Cheyney⁷ have considered these criticisms; and, in a paper in press, they report new theoretical calculations that satisfactorily conform to Zander's laboratory spectra, with his ice particles;⁸ and then, considering the Venus spectrum, they arrive at a contrasting conclusion: "We do not maintain that we have presented positive evidence for ice clouds on Venus. It seems clear, however, that the Rea and O'Leary arguments against ice clouds are not as strong as they believed them to be."

Both Mariner V observations and the results of the Venus IV *drop-sonde* indicate an isothermal region in the Venus atmosphere:⁹ And this freedom from thermal gradient above the cloud level explains the failure of the spectrum observed by Strong and Sinton¹⁰ to show the 9.4μ and 10.4μ absorption bands of CO₂.

Nicholson and Pettit,¹¹ and all subsequent observers who have made radiometric studies of the distribution of the 8 to 14 μ brightness temperatures of Venus, have reported that the dark hemisphere of Venus is not as cold as one might first expect—rather, it lies within 5° C or so of the temperature of the sunlit side. This lack of a larger difference in temperature can be explained¹² as the result of latent heat liberated by the water vapor that is carried around to the dark side of the planet to condense there as ice crystals. Such a condensation should bring temperatures up to -39° C, the Schaefer point.¹³ This point coincides with the predicted albedo temperature, 234° K, as well as the observed brightness temperature.

Murray and collaborators¹⁴ have obtained corresponding brightness temperatures that are almost 10% lower. Either Strong and Sinton or Murray *et al.* have made insecure extrapolations, correcting for telluric absorption. Assuming an overall thermal equilibrium for the planet, a deficiency of emission at one wavelength band must be compensated by an excess of emission at other wavelength bands in the Venus spectrum. In particular, the excessive emission at a brightness temperature of 600° K at wavelengths greater than $\lambda = 40\mu$ compensates an inferior emission at $\lambda < 40\mu$ and would explain a brightness temperature 20° C under the albedo temperature. However, Prof. de Vaucouleurs tells me that he is of the opinion that the albedo does not provide a temperature as secure as this discussion implies. In 1966, we attempted balloon-borne observations of planet emission, made throughout the infrared spectrum, to resolve these questions concerned with the heat budget, but the balloon flight was a failure and a subsequent attempt has not followed.

Temperatures inferred for the lithosphere surface from microwave observations are about 150° C higher than the Venus IV thermometer, surface temperature. These circumstances make "former strictures against life at the very poles slightly relaxed." In fact, Prof. Libby has proposed¹⁵ polar ice caps to explain the mystery of lost Cytherian water over equatorial regions. A similar proposal has been made,¹² based on a postulated non-polarized and presumably nonthermal component of the microwave emission; but it has been ruled out by Mariner I results, as interpreted by Pollock and Sagan.¹⁶

The revolution of the planet could produce a variation in observable water vapor if glaciers and rivers extended down unsymmetrically in longitude. Such a circumstance might explain why some observers have seen less water vapor than others. A remarkable and mysterious coincidence makes the resolution of this possibility easy: the planet's period of rotation is just one-fifth of its synodic period.¹⁷ Thus one can easily assign longitudes to the times of successful and unsuccessful spectroscopic observation of water in the planet's atmosphere. This comparison, however, did not yield any significant correlation.

The ultraviolet photographs of Venus by Ross,¹⁸ and by others subsequently, show dark markings. Although these are usually evanescent, sometimes they are stable enough to serve as motion indicators of presumed upper-air movement. But these motions of the Venus atmosphere have not yielded any incisive result about the planetary circulation—which, being almost free of coriolis force, will be significant for theoretical meteorology when it is observed.

Hunten⁹ says of a possible anhydrous cloud component: "It is tempting to suggest sodium chloride . . . in view of the established presence of . . . small amounts of HCl." If, as Libby proposes, Venus once had oceans like Earth, they could have left a thick layer of sodium chloride of 100-ft average depth over the planet's entire surface, such as the Earth would leave if it should evaporate its own oceans. Forchhammer, long ago, found HCl to be liberated when he evaporated seawater to dryness. Our partisan position on the clouds is that the spectrum that we have observed indicates a top layer of ice particles, but, if there is a lower dust layer, we would expect the dust to be mainly composed of almost white NaCl crystals.

As for the future, aside from the wonderful radar work that is now being done (but not reported here), one would like to see a determination of the heat budget of Venus by measurement of the entire infrared emission spectrum with a balloon telescope. Also, one would like to get further information about atmospheric composition obtained by rocket-ultraviolet observation, and by balloon-borne spectroscopic study in the infrared, of high resolving power. But, above all, we look forward to the scientific fullness and definiteness of a United States *drop-sonde* landed near her pole.

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XV

The Sun

John W. Evans*

Superficially, the Sun is a rather simple body. It is a gaseous sphere 1.4×10^6 km in diameter, with a nuclear power plant at its core producing energy at a rate of 4×10^{33} ergs/sec. This converts about 4 million tons of the solar mass into energy each second. The energy leaks out from the core to the surface by radiative and convective transfer and finally escapes into space in the form of electromagnetic radiation and particles. The white visible surface of the sun is the top of a layer of light-scattering cloud at a temperature of about 5800° . It, and the minute layer of transparent material overlying it, are the only portions of the sun accessible to direct observation.

For the everyday interests of the inhabitants of planet Earth, this description of the sun tells all. We have a globe 1.4×10^4 km in diameter radiating at a temperature of 5800° . Most of the radiation is in the visible spectrum (where, by a strange coincidence, our eyes function best) and is sufficient to maintain the earth at a temperature that fluctuates conveniently around the freezing temperature of our most prevalent liquid, water.

However, man's insatiable curiosity has led us into activities that are profoundly influenced by the relatively insignificant tails of the energy distribution curves of solar electromagnetic and particle radiation. The quantity of energy involved is negligible, but we are finding that it is quality that counts. Its origin is largely in the small deviations of the Sun from our picture of a quiet static radiating globe.

*Director, Sacramento Peak Observatory, Air Force Cambridge Research Laboratories, Office of Aerospace Research, Sunspot, New Mexico.

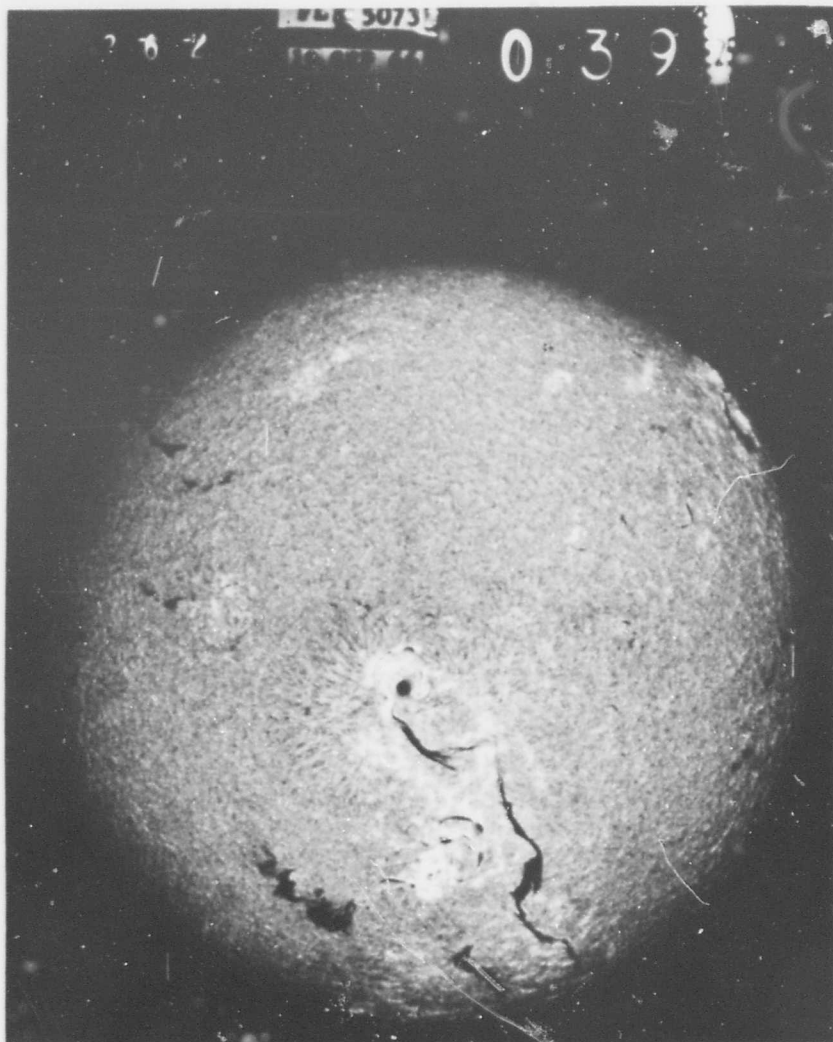


Figure 1. The Sun photographed in the light of the H α line of hydrogen. Note the active center near the center and a second one below it. A third one is visible at the 2 o'clock limb. The ordered fibrous structure in a large circle around the upper center is typical. The irregular dark objects are prominences high above the surface.

When we examine the observable solar atmosphere in detail, we find that it is not simple at all. Like the atmosphere of the Earth, it is full of local instabilities and continual changes, none of which we understand very well. There is no space here to describe the fascinating array of solar features the observer sees, a few of which appear in Figure 1. However, one class of them, which I term collectively *solar activity*, excites disturbances in space that are a serious concern to space experimenters and explorers.

Most solar activity occurs in limited areas a couple of hundred thousand km in diameter called *active centers*, usually surrounding sunspot groups. The two bright areas below the center in Figure 1, with surrounding disturbances, are typical samples. The basic ingredient of an active center is a powerful magnetic field with peak field strengths of 1000 to 4000 gauss. All the observable phenomena, sunspots and flares in particular, are manifestations of the magnetic field and its changes. The mere presence of a strong field generates a spot (Figure 2) by cooling and darkening the solar gas. This is the result of two actions: (1) the addition of a large magnetic pressure to the gas pressure, and (2) the partial suppression of the convection which normally transports energy from the interior to the solar surface. For our purposes, however, the solar flares are the most relevant features of solar activity. We know what they look like (Figure 3), what changes they make in the solar spectrum, their characteristic light variations, some of the particles and electromagnetic radiations they emit, and so on; but we do not really know the physical causes of all these. The effort to learn this is the major item on the research agenda of the Sacramento Peak Observatory. The best I can do now is to relate some of the observed characteristics and the observed effects on the regions of space that have been probed.

Flares typically occur in the more spectacular sunspot groups (Figure 4) where complex structures mirror complex magnetic fields. Unlike the large sunspots, which develop and decay over periods of days or weeks, the flares are rapidly changing features that rarely last as long as 8 hours. In a telescope equipped with a sharp-band filter tuned to the frequency of the red $H\alpha$ line of hydrogen, a flare first appears as an irregular patch of bright material somewhere near a sunspot. It brightens rapidly and may

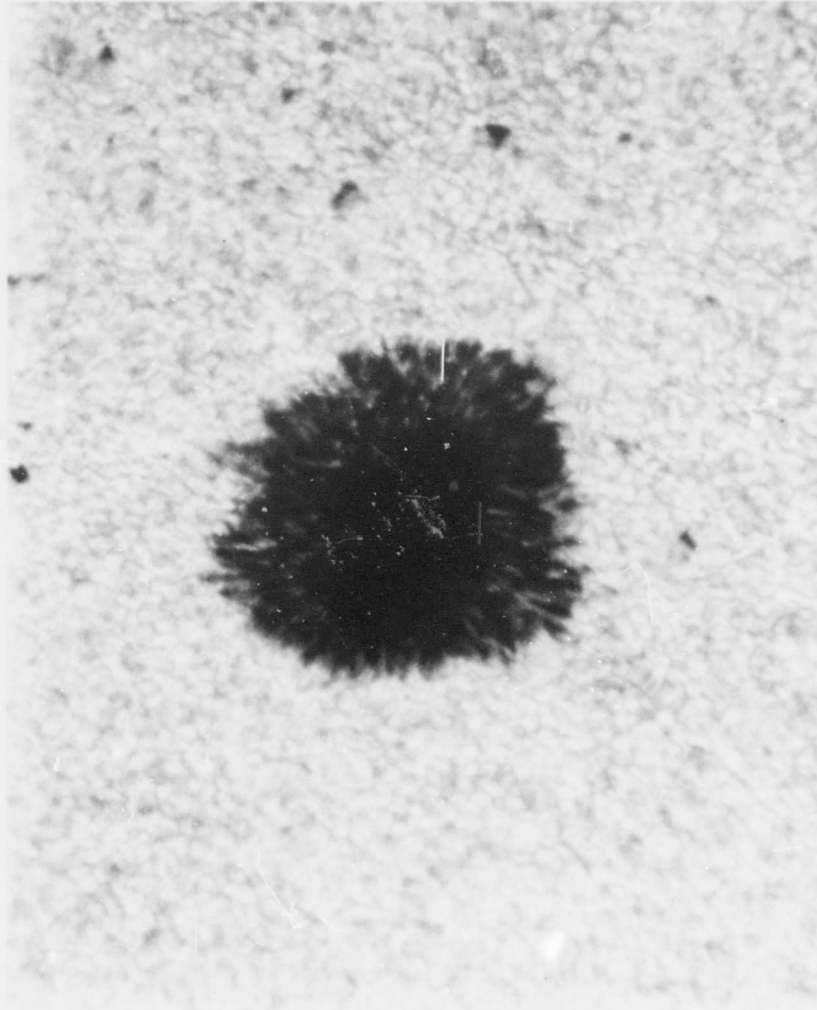


Figure 2. A small sunspot of the simplest type in white light. Note the convective granular structure of the surrounding solar surface.

become five to twenty times as brilliant as its surroundings in 5 to 20 minutes. It then fades slowly, dropping back to background intensity in 10 to 150 minutes. Flares vary in size from 1000 to 150,000 km in diameter, and, as a general rule, the larger ones



Figure 3. Details of a medium flare in a sunspot group.

change less rapidly than the little ones. Along with these conspicuous visible changes, the flare has a number of invisible features, some of which we have become aware of over the years by quite different methods of detection. The first detector used was the atmosphere of the Earth. The fluctuations in atmospheric

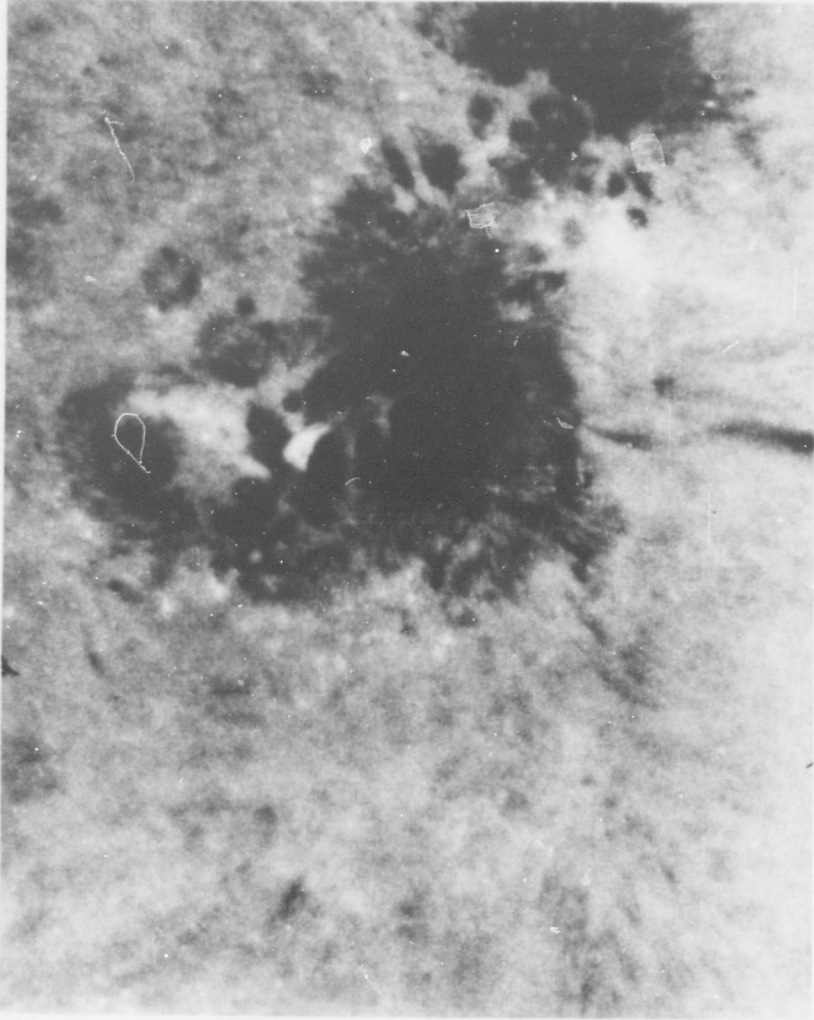


Figure 4. A large sunspot group of the type likely to produce flares.

ionization, measured by radio sounders, are a pretty rough indication of what is going on, but they have the enormous advantages of being free and being always on active watch for flare effects. Now that we can send highly sophisticated packages into orbit, however, we are learning a great deal more about flare radiations than could ever be deduced from atmospheric responses.

The observed flare-associated emissions are XUV radiation of wavelengths from about 1200 Å down to some undetermined limit less than 1 Å, and electrons and protons ejected over a broad energy spectrum from a few Kev to a few Bev. All of these radiations have perceptible effects on the Earth's atmosphere and the space environment, some of them harmless and some of them troublesome. The one we are presently most concerned about is the high-energy proton shower.

Probably, every flare ejects some electrons and protons into space by some accelerating mechanism which we do not presently understand. The vast majority of the particles have energies of the order of hundreds of Kev, with the numbers falling off very sharply toward higher energies. The major flares, which in numbers constitute 2% or 3% of all flares, produce streams of particles so numerous that the high-energy tail of the spectrum contains fluxes of tens of thousands of protons per sq cm/second with energies greater than 100 Mev. The particle streams appear to be highly directional, and only about one in ten hits the neighborhood of the Earth-Moon system. These high-energy proton showers are, of course, similar to the radiations from nuclear piles and such devices. They penetrate thin metal skins and become a serious hazard to men in space. I am no radio biologist and cannot judge the extent of the danger. The discussions I have heard do not give a very definite answer, but I gain the impression that no one thinks the hazard is negligible, and most authorities believe that a major proton shower is quite sufficient to kill an unprotected man. We know from experience that it can do serious damage to some kinds of delicate solid-state equipment in space.

Some of the reactions with the upper fringe of the atmosphere are also potentially troublesome. The high-energy particles cause density variations at the 80- to 250-mile levels that affect the slight aerodynamic drag on orbiting space vehicles. The result is an unpredictable change in the orbit. Massive showers of lower energy particles occasionally produce ionized clouds which may be difficult to distinguish on a radar screen from a rapidly moving vehicle. They also excite the aurora and accompanying magnetic storms. The well-known radio blackouts that sometimes occur with large flares are the result of bursts of X-rays rather than the slower particles.

Clearly, it behooves us to learn as much as we can about the proton showers and to take whatever precautions we can to avoid their damaging effects. Fortunately there is a good deal that we can do. We at Sacramento Peak Observatory have been concerned with efforts to forecast the proton showers since 1961. If the space experimenter expects a proton shower, he can delay a launch or take other evasive action.

We started the work in response to pained cries from space experimenters who had the misfortune to be in operation during some really vigorous proton showers, particularly those of November 1959. The task of spreading the word to a host of interested users became very burdensome, and in 1965 we were much relieved when the Air Weather Service set up the Solar Forecasting Center (SFC). They took over the responsibility for collecting data from all over the world and making periodic forecasts of flares and other solar phenomena that are relevant to space operations and the use of various radio devices from the ground. Best of all, the SFC relieved us of the problem of disseminating forecasts, which was rapidly getting out of hand. Sacramento Peak, along with many other stations, now transmits its observational data to SFC on a regular schedule, with special reports when sudden solar catastrophes occur. SFC does a fine job, and we are free to do our proper work, trying to devise better prediction methods for them to use. Toward this end, we have continued our own independent predictions, with results as described below.

The proton showers are always associated with major solar flares. After a flare occurs, the time required for the protons to reach the Earth varies from $\frac{1}{2}$ hour to about 8 hours. Hence, if a flare is observed, we can hoist the "red flag" for this interval. If a man in space can protect himself by entering a lead coffin or (perhaps some time in the future) by performing an evasive maneuver, a warning of $\frac{1}{2}$ hour could be quite useful. However, what the astronomer really hopes to do is to give forecasts much farther into the future. For this, he needs to predict the actual occurrence of a proton shower with some indication of its intensity as far ahead as possible. This is a goal toward which we are now taking a few first steps in trying to predict big flares (which may or may not produce proton showers) 1 or 2 days in advance.

As you know, sunspots, and the flare-producing active regions around them, wax and wane in an 11-year cycle. The numbers of

flares and of proton showers share this cycle. In a year of minimum activity (like 1964), there will ordinarily be one or two big flares and probably no proton showers. In contrast, 1967, near the peak of activity, had 107 major flares and about ten or fifteen proton events (depending on the threshold level adopted). So in the worst years, we have to worry about 100 flares and perhaps a tenth as many proton showers.

Now how does one approach this problem of forecasting big flares? One can do it right by learning the physics of the flares and the ejection of particles. Then one can presumably pick observable activities that indicate the preliminary cocking of the flare mechanism. This is the approach that consumes most of the research effort at Sacramento Peak, but, unhappily, it is not the operational method we use for predicting flares. Instead, we resort to a lowly empirical approach of zero scientific merit, but, apparently, of some utility. This is a stop gap that will have to do until we learn more about the flare process.

I am going to describe the procedure we use and its effectiveness. Then I shall discuss briefly (1) the problems that stand in the way of the rational approach, and (2) its current status.

Our empirical method is more art than science. It grew out of the fact that our observers seemed to anticipate most major flares and were sitting at the telescope with cameras cocked and ready to go when they appeared. As nearly as I can describe it, the conscious part of the art goes something like this: We know from experience that only a small fraction of the sunspot groups that appear on the solar disk are flare producers. Those that spawn flares do so generally at a certain age. Our first task, then, is recognition of the dangerous sunspot groups. This turns out to be not altogether easy. Signs of potential flare activity are: a highly complex sunspot structure (like that of Figure 4), a multiplicity of positive and negative poles in the magnetic field, rapid changes of any observable structures, frequent occurrence of minor flares in the region, evidences of high-atomic excitation such as the occurrence of highly ordered loop prominences (like that of Figure 5), with hot spots in the overlying corona, and so on. Of course, most active centers show some of these signs and others do not, and the predictor's task is to weigh what he sees and to crawl out on the limb. However, there seems to be more to it than identifying

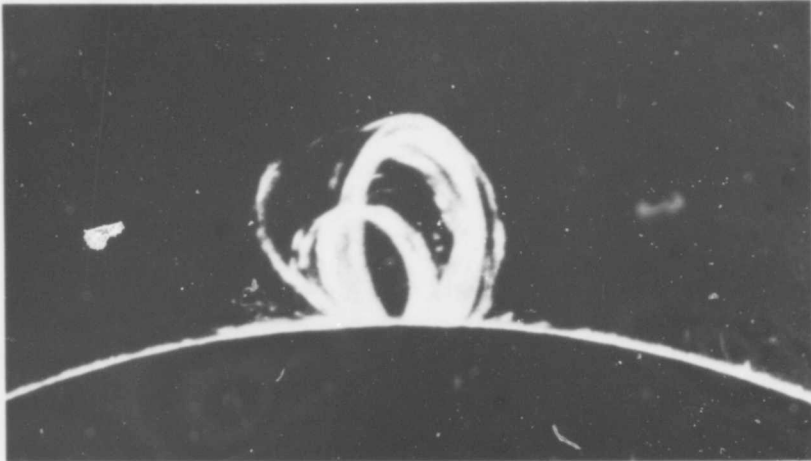


Figure 5. A sample of the relatively rare loop prominences standing above the solar limb. The disk of the Sun has been artificially eclipsed in the telescope.

these signals. The structure which is visible around a sunspot group through an $H\alpha$ filter is always beautifully complex, with thousands of little, dark, fibrous markings and all imaginable configurations. Occasionally, in active groups, the markings are arranged in a highly ordered fashion, in the form of a rosette or of a vortex around a large spot. You can see this in the region around the big spot in Figure 1. Possibly, the observers, after some years of looking at solar active centers, are unconsciously sensitive to less obvious degrees of order, and they develop from this the premonitory sense they seem to have. Whatever it is, the statistics show that the observers' premonitions are not entirely idle.

It is not altogether simple to estimate the success of a prediction program of this sort. For one thing, the user of predictions and the solar physicist will have different definitions of success. The former will consider the program successful if the time intervals that are predicted safe turn out to have fewer flares than a random selection of equal time intervals. The solar physicist, on the other hand, is dissatisfied unless the program leads on to new insights about the Sun, whether the predictions are accurate or not. As matters stand, he is very much dissatisfied.

Because figures can be so easily misinterpreted, I usually try to avoid numerical assessments of the predicting program in public. However, if I can define their meaning clearly enough, I think a quantitative estimate is worthwhile here. We will look at the program from the point of view of the space experimenter who wants to avoid operation during a solar flare. He evaluates the program in terms of the risk of encountering a flare, R , that he must accept in order to operate a given fraction of the time, T . The aim of the forecaster is to minimize R and to maximize T , and there is an obvious tradeoff between the two. One can always lower the risk by being more conservative in declaring a day "safe," but there will inevitably be fewer such days. So we avoid an onerous responsibility by letting the experimenter decide on the balance between the two that he considers most favorable for his purpose.

At Sacramento Peak Observatory the observer looks at the Sun first thing in the morning. After some thought (to avoid any unseemly appearance of haste), he gives his estimate of the probability, p , that a flare will occur during that day or next day. In other words, he makes a prediction for the following 48 hours, once every 24 hours. Of course, any agreement between estimated probability and true probability would be surprising, but our purpose is served if the two are reasonably well correlated.

We can then define safety in terms of a critical estimated probability, p_c . Safe days are those for which $p < p_c$, and dangerous days are those for which $p > p_c$. We can now look at the occurrence of flares in relation to the distribution of safe and dangerous days, and calculate the risks and the percentage of days that are called safe as functions of p_c .

I am going to analyze the performance of the Sacramento Peak 48-hour predictions during the year 1967. I confine this analysis to the flares actually observed at Sacramento Peak because an examination of the worldwide records shows that the definition of a major flare of importance, two or greater, seems to vary enormously from one observatory to another. I have more confidence in the homogeneity of the Sacramento Peak data simply because I know how much care is lavished on these measures of flare importance.

Because Sacramento Peak can observe only during 35% of the time (being inactive at night and during cloudy intervals), the

observed numbers of days with flares have to be converted to inferred numbers for 24-hour days by dividing by 0.35. This is not strict statistical cricket, but the error is negligible in our case.

The aim of the analysis is to compute curves showing R and T as functions of p_c . Our procedure is to adopt a series of p_c and determine for each the R and T : a very simple matter which is probably suspect because it does not require a CDC 6600 computer.

We count the safe intervals, s , when $p < p_c$ and the dangerous intervals, d , when $p > p_c$. Then, we find out how many safe intervals and dangerous intervals had flares, F_s and F_d , respectively. Then, $R = F_s/s$, and $T = s/365$. After calculating R and T for a series of p_c , we can construct the desired curves. We know the end points of the curves in advance. For $p_c = 0$, $R = 0$, and $T = 0$. This says that if $p_c = 0$ all days are regarded as dangerous, and our experimenter would incur no risk because he would not operate at all. At the other extreme, he could operate all days with $T = 1.0$, which is equivalent to setting $p_c = 1$. Then, his risk is simply the fraction of days that had flares.

Figure 6 shows observed R and T as functions of p_c for the interval 24 to 36 hours after the forecasts were made (the observing day following the forecasting day) during 1967. The light curves above and below the central curves represent plus and minus one standard deviation: calculated on the assumption that the standard deviations of the counted numbers of actually observed flares are the square roots of the numbers. Note that at $p_c = 1$, $T = 0.91$ instead of 1.0. This reflects the fact that the observations included only 333 of the 365 days (due to cloudy weather).

The curves indicate that the predictions 24 to 36 hours in advance are apparently of some use when $p_c < 0.4$. If our experimenter ignores the predictions ($p_c = 1$) he takes a risk of $R = 0.33 \pm 0.04$ each day and wastes no time on silly false alarms. He can cut the risk to $R \approx 0.05$ by adopting $p_c = 0.125$ and still operate on 26% of the days ($T = 0.26$). This is certainly not a spectacular gain, but it does indicate that our forecasters are not just fanning the air.

In a way, this result is a surprise to me. In 1962 to 1964 when the solar cycle was at its minimum, the situation was always simple because there was rarely more than one active center that was

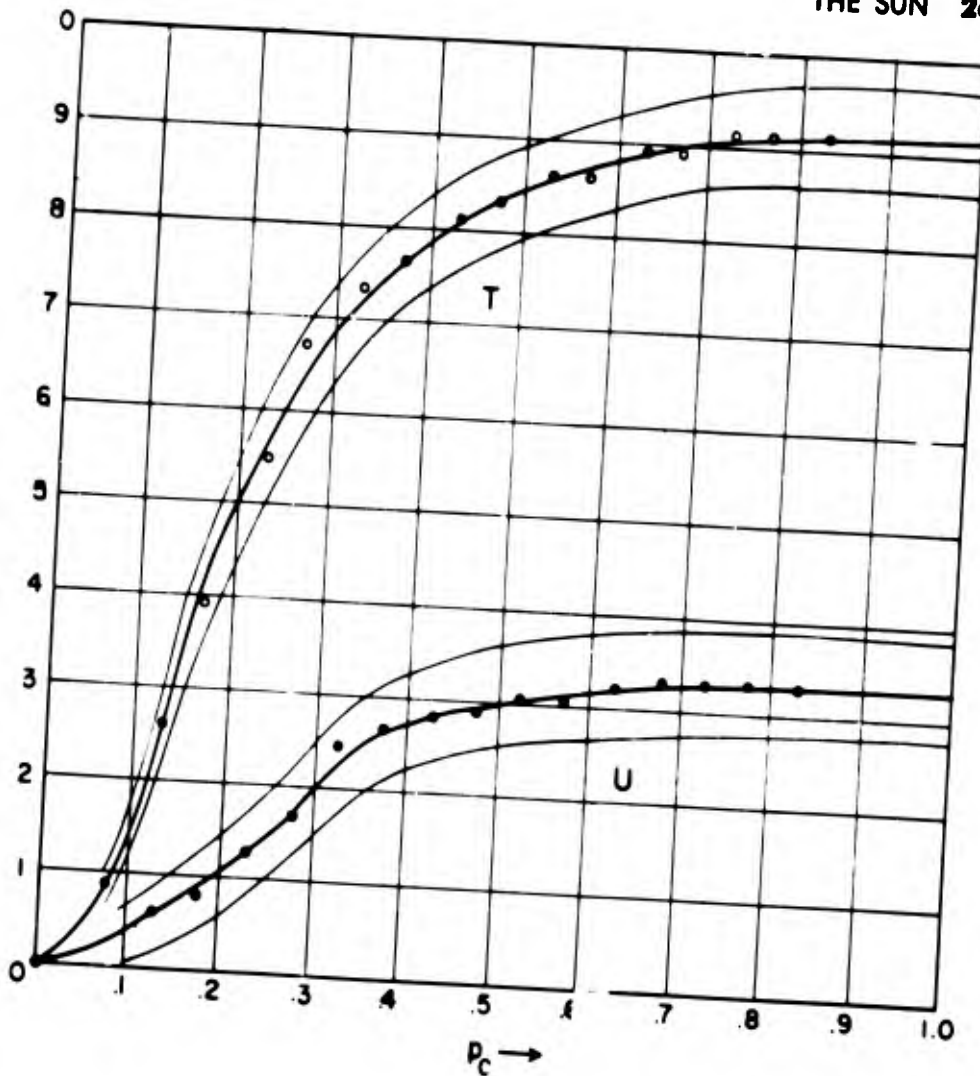


Figure 6. Risk, R , and the fraction of days that are "safe" ($p < p_c$), T , as functions of p_c .

visible on the Sun at any one time. The forecasters were not doing as well then as they are now. I predicted that, in 1967 to 1969, at solar maximum, they would always find the signs of danger and all days would be called dangerous. The predictions would then be nearly useless. I was wrong. The 1967 analysis shows an improvement over the old days. Apparently the benefits of abundant exercise outweigh the difficulties of increased complexity in the state of the Sun.

All this is concerned with the prediction of flares. Of themselves, they are a hazard only to the few experiments that could be damaged by X-rays. Predictions of flares are only a first step toward what we really need, predictions of high-energy proton showers. Dangerous proton showers always follow big flares, but only one flare in ten produces a proton shower near the Earth. When we see a flare, we can often decide whether it is likely to eject protons, but so far nothing in the prediction techniques gives any indication of this likelihood.

Although I hope the predictions are useful, they are unsatisfactory in several respects. They are subjective, and they are based on empirically determined associations of flares with various other features of active centers, rather than on causes and their effects. As a scientist, I believe that we will not have sound predictions until we can base them on the physics of active centers and flares. Before we can do this, we have a great deal to learn.

Although the things we do not know about flare physics outweigh what we do know, the situation is certainly not hopeless right now. The theoretical studies of the last 5 years have fairly well defined the conditions under which magnetic energy can be converted into heat or mechanical energy at rates corresponding to the growth of a flare. Tensions build up in the magnetic fields like those in a wound clock spring. The windup finally reaches a point of instability, and the field collapses locally like a broken spring, releasing the energy we see as a flare. This mechanism has been assumed for a long time, but now we have some quantitative idea of the field configurations that signify mounting tension and those that have reached the level of instability. This gives us something to work on, provided we can obtain sufficiently detailed observations of the magnetic field in an active center. The observations turn out to be rather difficult, primarily because they are not very useful unless they result in a magnetic map in a matter of a few minutes. The quantity of data that has to be recorded and processed per second is large, but well within the modern data techniques.

We now have at Sacramento Peak Observatory a 16-inch telescope with a magnetic analyser dedicated solely to this task. The solar magnetic fields split sensitive lines in the spectrum into two or more components, the wavelength separation of which is proportional to the field strength. In principle, we merely have to

measure the separation in a spectrograph and multiply by a constant to determine the field strength. In fact, that is exactly what we do; but, to map the field in an active center, we must do it for some thousands of points in the active center, one at a time. The Sacramento Peak magnetograph automatically scans an active center, recording the line separation digitally on magnetic tape. A detailed scan takes about 4 minutes. A computer then looks at the tape and draws a contour diagram of the magnetic field in the active center. This is the present state-of-the-art, but we still have further steps to take. The computer will calculate the three-dimensional magnetic field (with the aid of a few questionable assumptions) and compare successive scans to detect changes. When the field configuration and the trend of the changes fit the theoretical pattern of a windup toward instability, the machine will advise us that a flare is imminent within so many hours at a certain point on the sun.

If theory is correct, prediction should be correct. I fully expect that the first period of observations will uncover weaknesses in the theory rather than in the inevitable occurrence of flares. With luck, our theoretical friends will be able to repair the theory for a second approximation containing fewer dubious assumptions. I am confident that, in the end, this is the approach that will work. The most exciting prospect is the likelihood that we will find peculiarities that reveal the mechanism of proton ejection and the possibility of predicting proton showers directly. Whatever the immediate outcome will be, we are going to learn more about the physics of solar activity, and this is clear gain.

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XVI

Empirical Arguments Concerning Dirac's Gravitational Hypothesis

Pascual Jordan

INTRODUCTION

Arguments based on cosmology and the theory of elementary particles led Dirac, more than 30 years ago, to the idea that the gravitational constant, G , might be in reality a variable, diminishing extremely slowly in the course of the development of the universe. As in the literature of General Relativity, we prefer here to use the notation

$$\kappa = \frac{8\pi}{c^2} G. \quad (1)$$

Dirac assumes that we have today

$$-\frac{\dot{\kappa}}{\kappa} = 10^{-10} \text{ or } 10^{-9} \text{ per year.} \quad (2)$$

Although this revolutionary hypothesis won little attention for many years from the majority of physicists and astronomers, more discussion has arisen in the recent years, especially since R. Dicke came to similar conclusions; several authors have indicated possibilities of still undetected changes in the fundamental constants of physics, during time intervals in the order of magnitude of the age of the universe. Especially, Gamow⁵ discussed the idea that the elementary unit, of charge e , could be variable in time.

With our cosmological concept being deeply influenced by the Friedmann cosmological models, we easily can assume that any

variability of fundamental constants, if existing, making a so-called constant a *Scalar field variable*, will take the form that this scalar may in the first approximation, or in most cases, be constant in space but slowly variable as a function of the time coordinate in the Friedmann cosmos. (Naturally, processes of a quasar type may make κ essentially variable in space as well as in time.) Though recent discussions consider also the value of e (Gamow) or of c (Treder²) as perhaps cosmologically variable, the author of this note showed³ that in the most simple description of the physical universe only *two* values, being ordinarily thought of as constants of Nature, might be variable indeed: The gravitational constant, being the object of Dirac's hypothesis, and possibly also the Fermi constant of beta decay.

This result of the author won strong additional support recently by Dyson⁴ who from further empirical facts concluded that the relation of Coulomb forces to nuclear binding forces cannot have varied considerably during the history of Earth.

Taking κ as a field variable, we have to think about a suitable generalisation of Einstein's relativistic field equations. About 15 years ago, the author believed that the generalised field equation would arise from the variational principle

$$\delta \int \kappa \left(R - \zeta g_{kl} \frac{\kappa_{;l} \kappa_{;k}}{\kappa^2} + \kappa L \right) \sqrt{-g} d^4x = 0 \quad (3)$$

with $L =$ Lagrangean of matter and Maxwell field. The dimensionless constant ζ may have any value of the order of magnitude 1.

For several years I have preferred (at first reluctantly) another form of these field equations, giving room to some criticism put forward against (3) by Pauli and by Fierz. Recently, Hönl and Dehnen^{5, 6} showed that indeed only the "new" field equations, and not (3), are in accord with what we now know empirically concerning the isotropic electromagnetic radiation of temperature 3° K. These modified field equations arise not from (3) but from

$$\delta \int \left(\frac{R}{\kappa} - \zeta g_{kl} \frac{\kappa_{;l} \kappa_{;k}}{\kappa^3} + L \right) \sqrt{-g} d^4x = 0. \quad (4)$$

Their mathematical consequences form a chapter which we shall exclude here from full inspection.

Schwarzschild and Pochoda¹, and in a similar manner Gamow⁷, made a very valuable contribution to the discussion of Dirac's hypothesis by proving the following fact: Assuming that Dirac's hypothesis is correct and that κ is not only a monotonously decreasing function in the course of time, but also *that* function (not to be discussed here in detail) which Dirac thought to be probable, and, if this was already the case at the time of the formation of planets, then according to the theory of *star development*, the Sun must in former times have given away so huge amounts of radiation energy that by now it would already have developed to a red giant. The mentioned authors see in this result a severe argument *against* Dirac's hypothesis.

For, theoretically, the luminosity of the Sun must be strongly influenced by any variation of κ ; Teller has shown already several years ago, that in a rough approximation this luminosity would be proportional to κ^7 . Markedly greater values of κ during the first chapter of the history of our planetary system therefore would have made the Sun radiate with exceedingly huge luminosity.

The author of this article thinks that this meaningful result does not force us to discard Dirac's hypothesis, but it leads us to a better understanding of the consequences of Dirac's idea. As already indicated, it cannot be postulated how κ would develop as a function in time and space; the appropriate manner to treat the cosmological and astrophysical consequences of the hypothesis must be based on the relativistic field equations in their new form, including not only the tensor field, $g_{\mu\nu}$, but also the scalar field κ .

Now it is a general law—allowing no exception—that in any theory formulated in Lagrangean equations (as in our case, Ref. 6), strong physical action of any agency, A, upon another agency, B, must be coupled with a corresponding action from B upon A. (It may even be called the strongest indication of insufficiency of the old classical mechanics that, according to it, the metric of space and time is binding for the motions of masses but is not influenced [as in Einstein's theory] by these masses themselves.) Now, if high values of κ cause locally, in a special system such as a star, extremely strong luminosity effects, these effects must react on the field variable κ and cause a very sharp *local* decrease of κ . This is qualitatively an unavoidable consequence of field equations of the Lagrangean type. To make quantitative theoretical statements, we still know too little about time dependent solutions of the

field equations with a scalar variable κ (in the case of spherical symmetry). But there cannot be any doubt that the consequences of (4) must include that, in the early stages of development of the Sun, the field variable κ must have become, in the *interior* of the Sun, significantly smaller than in interstellar space or in the Friedmann universe as a whole. Only in later stages, this local diminution of κ could have been met by the general decrease of κ in the Friedmann universe.

Already Teller, when proving the mentioned rough proportionality of the luminosity of the Sun with κ^7 , saw a difficulty of Dirac's hypothesis in the consequence that the Sun would have been too hot in Paleozoic or even precambrian times. We shall discuss this point later, but the result of a refined recent application of the theory of astrophysical development made by Dicke should here be mentioned. If really κ were *exactly constant* then we would now have a slow *increase* of the Sun's luminosity, great enough to cause the surface of the Earth in precambrian times to have been always at temperatures below 0°C . Thus, origin and development of organic life would have been impossible.

POSSIBILITIES OF TESTING THE HYPOTHESIS BY DIRECT PRECISION MEASUREMENTS

Certainly the best way to secure the reality of Dirac's supposed variability of κ would be—if feasible—to prove it by direct measurement. In order to look for such possibilities, one primarily has to clarify theoretically what consequence the hypothesis, if true, would have for celestial mechanics. In my mentioned book, I found, by a very simple mathematical analysis, that the change in a Newtonian n-body problem caused by an extremely slow change of G would be the following: The system would, apart from its calculable movements according to the laws of Newtonian mechanics and the rules of perturbations, undergo an additional expansion in analogy to the Hubble expansion of the great system of all galaxies, and also a slow uniform decrease of its velocities, expressible by a *varied time scale*. The measure of expansion in the course of time would be of the same order of magnitude as that of the Hubble expansion, but today there do not exist theoretical foundations for any decision whether the measure ϵ of this new type of expansion must exactly equal the Hubble constant α or agree with it only in the order of magnitude.

To express in a formula what I tried to explain here at first in words, let \vec{r}_k and t be the spatial and time coordinates of the mass points of an n -body system in an exact *inertial* coordinate system. The Newtonian equations may be solved by giving

$$\vec{r}_k = \vec{f}_k(t)$$

as functions of the time. Then the modified equations of motion and their results can be described in such a manner that we use modified coordinates, \vec{R}_k , and a modified time scale, T : The new coordinates (in an approximation neglecting $\epsilon^2 \cong 0$) are then *the same functions* of T as the old ones were of the time t ; but we have the relations

$$\begin{aligned} \vec{R}_k &= (1 - \epsilon t) \vec{r}_k \\ T &= (1 - \epsilon t)t \end{aligned} \tag{5}$$

The meaning of these relations obviously can be translated into the statement that the *real* space-time coordinates (as defined in an exact inertial system) take the new, modified form:

$$\vec{r}_k(t) = (1 + \epsilon t) \vec{f}_k(t - \epsilon t^2) \tag{6}$$

Here the factor $1 + \epsilon t$ shows the slow expansion of the system, and the factor $1 - \epsilon t$ determines the uniform slowing down of the motions. We can also write

$$\vec{r}_k(t) = \vec{f}_k(t) + \epsilon t \cdot (\vec{f}_k - t \cdot \vec{f}_k') \tag{7}$$

Measurement of these new effects appears to be possible. In regard to the *first* line of (5), showing the *expansion*, the fact that the precision of the measurement of planetary distances has been improved by at least two decimals since the introduction of the radar echo method does not yet give much hope for detection of this effect. But laser echo measurements from mirrors put on the Moon by rockets—an idea already discussed in detail by American scientists—will certainly help to clarify the situation.

The other point: nonlinear deviation of *Ephemeris time* T from *inertial time* t (defined by *atomic clocks*) is already being investigated now from registrations in operation for about 10 years. These registrations have been made by Nicholson and Sadler⁸; they have been discussed by Becker and Fischer⁹, using the author's theoretical formula¹⁰. Results of still preliminary character seem to show an ϵ of the order of $2 \cdot 10^{-10}$ /years.

The *expansion* of the Earth, caused by decreasing κ , must cause a perhaps measurable decrease of the rotation of the Earth, Iwanenko and Sagittov¹¹ indicated that perhaps the astronomically known slow decrease of the rotation of the Earth might be explained in this manner.

Taking the relative radial growth, \dot{R}/R , of the Earth as an approximate measure for the decrease of its rotational momentum, one finds (Jordan, 1966) that the decrease of the rotational frequency—measured not in inertial time t but in ephemeris time T —is determined not simply by \dot{R}/R , but by

$$\frac{\dot{R}}{R} + \frac{\dot{\kappa}}{\kappa} \quad (8)$$

This would be in sufficient accord with what we shall later discuss as probable empirical information about the rate \dot{R}/R of Earth expansion—if it would be permissible to neglect the influence of tidal friction, assumed generally to diminish the rotational momentum of the Earth.

Concerning this tidal friction—for which, as one knows, Jeffreys tried a quantitative interpretation in what may be called one of the most famous theories in geophysics—a peculiar scientific development occurred in recent years. Modern oceanic results showed that *oceanic* tidal friction in the Bering Sea is in reality much smaller than that which Jeffreys supposed. Instead of oceanic tidal friction, now friction in the Earth body is assumed by several authors to have exactly that value which Jeffreys supposed as the value of oceanic friction.

But it is necessary to keep in mind that the thesis of an astronomically significant role of tidal friction is based on the opinion, put forward by Adams (1858), that Laplace made an essential

error in his calculation of the secular acceleration of the Moon, which according to Adams would have only about one-half of Laplace's value if calculated by application of celestial mechanics: This was the opinion giving rise to the idea that still another additional cause for secular acceleration must be in operation—and, since Jeffreys, specialists believe that tidal friction must be this cause.

Looking into Adams' famous article, the author of this contribution came to the conviction that Adams' recalculation of the secular acceleration has been mathematically in error. I dare not yet say whether the result of Laplace can be defended as the definitive one; but that the result of Adams cannot be maintained appears to me a certainty. I hope to discuss this matter more fully elsewhere. Perhaps, at present, any astronomical effect of tidal friction must be denied; though it seems to have operated (according to the evidence given by Devonian corals) in former geological ages, when probably the areas of *shelves* were considerably greater than today.

EVIDENCE FROM THE MOON

According to Dirac's hypothesis, also, the Moon should show a certain amount of expansion by elastic response to the decrease of κ . Dicke, a number of years ago, mentioned this expansion as a possible explanation of the numerous rifts and rills found on the Moon.

Kuiper emphasized that, in the maria, many cases of radial or concentric rills encourage the interpretation as resulting from the shrinkage of the lava masses. Although this may be correct for a part of the great number of these rifts, it seems to me more probable that the majority of these rills—many of the smaller ones being discovered only by rocket observations—and the distinct details of them (discussed partly in my previously mentioned book) leaves scarcely any doubt that expansion must be acknowledged as the chief factor governing their formation. An especially interesting case is the famous *Alpine Valley*, which has been interpreted hitherto by almost all authors as the effect of a great meteoritic body having "scratched" the surface of the Moon in a practically tangential direction. In my book, I protested against this interpretation, and claimed this valley to be one of the examples of especially *great* rifts on the Moon, comparable to a series

of other well-known cases. This unorthodox interpretation found a brilliant confirmation by photographic results from *Lunar Orbiter IV*. The picture has been reproduced in the journal "New Scientist." It shows a typical rill running along the middle of the valley, and the journal comments:

"What is immediately obvious, apart from the accurately centered position of the median crack, is the very flat floor of the valley, and the fact that the profile of one wall of the valley in some place closely resembles that of the facing wall.

These characteristics seem to add up to a coherent story. Either tension or shrinkage initially started a crack in the Moon's surface which then widened; the process was halted while the floor of the valley filled up with fresh material; and finally the cracking movement recommenced along the older line of weakness. Such resumption of activity in predetermined places is typical of many terrestrial processes such as geological faulting."

Concerning the Moon, now the object of beginning exploration by the new methods of rockets and spaceflight, there are still many further points connected with the questions arising if we take Dirac's hypothesis seriously. But one cannot talk about the meaning of features of the Moon's surface without becoming entangled with the famous problems which have been the object of serious differences of opinion between specialists for many decades. Let me mention, for instance, the old question of whether the *great* craters of the Moon are of volcanic nature or are the result of impacts. Even today this question is not definitively settled in such a manner that really *all* specialists have the same opinion about it. There are still specialists—though only very few—who maintain that the *great* craters are volcanoes, in spite of all the impressive discussions and results of Baldwin, Urey, Kuiper and other prominent researchers who in the last decades cleared so many problems of the enigmatic structures of the Moon. Urey¹² once analyzed as the main cause of the deplorable lack of agreement in scientific opinion about the Moon the fact that specialists partially are appallingly uninterested to learn from the results of other specialists in this field and to revise their own hypotheses according to the whole mass of existing empirical information.

When I tried to study existing literature about the Moon—in order to see what could perhaps be concluded from the Moon about Dirac's hypothesis—I came to see how justified this comment of Urey's was and to what an appalling degree scientific assertions

about the Moon within great parts of the literature are influenced by theoretical or speculative hypotheses instead of being drawn solely from empirical facts. My attempt to learn what really must be acknowledged as proven *facts*, without intermingling with theoretical prejudices, gave me an opportunity to win an empirical mosaic-picture, clearly separated from dubious theories. I thought such an endeavour to be useful just now when we are at the beginning of Moon research with manned rockets and expeditions—surely it is a necessity to clear *now* all those questions which can already be cleared on the basis of terrestrial observations, so that direct lunar research can be concentrated on those problems which really necessitate fieldwork on the Moon itself. Seeing that geologists *still* have diverging opinions about the question of whether the famous Nördlinger Ries in Germany is a result of volcanic activity or the result of an huge meteoritic impact, I cannot consent that it must be a task of lunar expeditions to solve the problems of the great Moon craters—this problem must be solved from terrestrial inspection and analysis of the *totality* of Moon craters. Indeed, this problem is already a solved one—among the leading specialists, there exists today full agreement in the fact that the *great* craters are the results of impact—as surely are also many recently discussed similar examples on the Earth (and on Mars).

Also, several of the *maria* of the Moon have been shown in a convincing manner by recent discussion (especially that given by Urey) to be interpreted as analogous to the great craters caused by impacts by especially huge bodies. But serious doubts are put forward concerning other examples of *maria*. Some of the most prominent researchers are inclined to believe that during a certain period in the Moon's history great masses of lava flowed out from the interior of the Moon and formed the greatest *maria*. (I think it to be sure that the bottom of the *maria* really shows us lava, though attempts of other interpretations have also found, occasionally, the interest of very prominent researchers.)

But, could there have been in the past such a tendency in the Moon's interior to give out such huge lava flows, forming great *maria*? I think that today we are able to decide this question from *empirical* arguments only. These arguments are founded on the first results of lunar research with the help of rockets—and I think this to be among the most valuable data now offered by the beginning new era of lunar research. We know now that the back side of the Moon has only very few *maria* as compared with

the number on the visible side: this proves that the phenomenon of the maria cannot be caused by internal conditions which may have existed in the Moon at any time—they would have been unable to cause such a look of *symmetry* on the two sides of the Moon. Only the unpredictable statistical chances of impact of very huge bodies can have caused such a drastic violation of symmetry.

Let me mention here that Baldwin as well as Kuiper prefer to accept that interpretation of the greatest maria, which I believe to be in disagreement with the new facts revealed by the rockets which explored the back side of the Moon. Naturally, I (whose endeavour to learn about the Moon has been confined to studying the modern literature) am a little timid to deviate from the interpretations of so highly qualified specialists. But the mentioned empirical evidence seems to me to be overwhelmingly convincing.

Inclined to believe in the reality of great lava outflows from the interior of the Moon, Kuiper seems to be guided essentially by the well-known phenomenon of the frequent "domes" in the areas of the maria, which he interprets as volcanic. But there also exists another interpretation, given by Gold: The established existence of a layer of *permafrost* under the surface of the Moon makes it possible to think that these domes may be accumulations of ice, from water set free in deeper layers by dehydration of stony material. *This* seems to me to be an example of a problem solvable *only* by fieldwork on the Moon itself. The resolution of this question could also be of great practical importance in all future human activity on the Moon.

My study of the existing literature about the Moon also gave me the conviction that, perhaps apart from the topic of the domes, there does not yet exist any clear indication, or even real proof, of volcanic activity on the Moon *with real lava outflows*. All we really know is that there exists a lively activity in *gaseous eruptions* from very numerous *small* lunar craters. Naturally, what I say here may be overruled tomorrow by new observations; but just now I do not see any proof of the contrary. Technical progress in observational methods not using rockets leads to possibilities of testing the surface of the Moon *locally* for points of elevated temperature. The results so far are not numerous and are partly uncertain, partly negative. More must be learned about this special field of investigation.

The connection of the problem of lava outflows on the Moon to the topic of Dirac's hypothesis is the following. My late coworker, Binge, sketched an idea about *terrestrial* volcanism which seems to me very interesting and quite attractive. According to Binge, terrestrial volcanism belongs in the frame of *Earth expansion*, being one of the consequences and one of the indications of this expansion. If that were correct, it would make us inclined to be quite sceptical about attempts to interpret lunar structures as being caused by processes similar to terrestrial volcanism. Concerning this point, I am awaiting the results of future Moon research with great curiosity.

EVIDENCE FROM THE EARTH

Modern scientific development to a large degree rehabilitated the audacious geophysical ideas of Alfred Wegener, which were formerly criticised and refuted so strongly. We know now, for certain, that Africa and South America in the geological past were really sections of one continent—their separation began with the formation of a great "Grabenbruch," similar to what one can still see today in the great fissures in East Africa, or (more fully developed) in the Red Sea. Along the famous Atlantic ridge there still lies a long rift, part of the worldwide system of oceanic rifts which were discovered by Ewing, Heezen, and Tharp several years ago; the Atlantic part of this rift still shows the line of the beginning of the separation of the two continents, which today have the southern Atlantic linking them. Carey proved definitively that the similarity of the coastal lines of Africa and South America is *not* a meaningless result of chance—as has been proclaimed in the criticisms against Wegener. One has to consider the fact that the real boundaries of the continents are shown not by the coastal lines but by the *continental slope* which delimits the continents (to which also the *shelves*, areas of shallow sea, belong) against the deep sea.

The continents are "lumps" of a less dense material "swimming" on the denser material underneath; and the facts connected with *isostasy*—and, additionally, a great bulk of seismological results—show that the *thickness* of these lumps shows an astonishing degree of worldwide constancy, limited only by those effects which are caused by mountain formation. High mountains exist only on a small fraction of all continental areas. They do not

abolish the clear fact that primarily the continental lumps are of *spatially constant thickness*.

The interpretation of the great oceanic rifts (not to be confused with those other deep rifts belonging to the famous island arcs), put forward especially by Heezen, as lines along which a *spreading* of the ocean floors is going on, has been made a certainty by what may be called one of the most beautiful recent achievements in oceanography and geophysics. One knows now quite accurately (according to Cox, Dalrymple, Doell¹³) the timetable—for the last millions of years—of the repeated permutations of the two magnetic poles of the Earth; evidently the process of breaks-down and restitution of the magnetic field of the Earth (often with permutation of the magnetic poles) can occur during a time interval negligible in comparison to geological eras.

Now one finds, according to Vine¹⁴, parallel stripes at the bottom of the oceans along the rifts showing (by the methods of paleo-magnetic research) alternating formation during periods of normal and reversed situation of the magnetic poles; and this picture is symmetric to the rift as its center line. Obviously, the bottom spread here in such a manner that both sides of the ocean floor along the rift were moved apart, new masses from below continuously filling out the widening rift. Measurement gave as the order of magnitude for the widening of the rift a value of a few centimeters per year. Although, according to Ewing and Ewing¹⁵, along the Atlantic rift the spreading seems to have occurred in this manner only during the last ten million years—after a longer time interval of rest—we may believe that this recent process is a model of what has been going on (with interruptions or interludes) since the beginning of the separation of Africa and South America.

Several authors like to invent and discuss highly speculative theories claiming that this factual spreading of the ocean floors (going on also in the other oceans) is continuously compensated by other processes of some enigmatic kind, so that the total oceanic area remains constant through geological times. I prefer to take the empirically given spreading at its face value, believing that we are seeing here an *expansion process of the Earth*.

What seems to me as proof of the necessity of such an interpretation is the already mentioned fact of the worldwide constancy

(in first approximation) of the thickness of the continental lumps. This constancy indeed is *contained* in the information given in so many modern books about our Earth; but the fact is mostly indicated only dimly, and one does not find attempts to *explain* this very striking fact. Nowhere in the whole literature is there an earnest attempt of explanation put forth—and this encourages me to think that the following explanation, based on the idea of Earth expansion, is the *only* one which can be found by human imagination.

The explanation is: The layer of continental matter had been formed before the surface of the Earth solidified. It surrounded, in that early state of affairs, the whole sphere of the Earth, naturally symmetrical and in uniform thickness. After solidification, this outer layer was unable to participate in the process of expansion of the Earth taking place in the course of several billions of years. It has been torn apart, and the present continental lumps are shreds of that primeval skin which surrounded at the time of its formation the smaller Earth-sphere of that time.

Instead of going into detail, I prefer to mention only two points. This concept obviously necessitates that the continental lumps have been forced to undergo a steady decrease of their *curvature*. Making use of an idea indicated by Matschinski, I am inclined to believe that this might be the primary cause of mountain folding—thought in former times to be a proof for shrinkage instead of expansion of the Earth. Being far from understanding the great science of orogenetic processes myself, I mentioned this point only briefly in my book. But a young geologist, H. Glashoff¹⁶, made this chapter of geology, or geomorphology, the object of special studies which I think are highly interesting.

As mentioned above, J. Binge also promoted the idea that volcanism finds its final explanation only in the frame of the theory of Earth expansion. According to his concept, decreasing κ and growing radius of the Earth cause a steady development, bringing materials which are not too far under the surface of the Earth into conditions of decreased pressure, under which the high-pressure phases of this material cease to be thermodynamically stable. This must give rise to *explosive phase transformations* into low-density phases.

Taking Earth expansion now as a probable empirical fact (though the sketchy representation here allowed only indications), we have to ask for a physical explanation. Surely, Dirac's hypothesis is *needed* if we believe Earth expansion to be a fact. At first sight, there arise doubts as to whether Dirac's hypothesis can explain such a supposed fact quantitatively. What we know today about the spreading of the ocean floors makes it probable that van Hilten¹⁷ as well as Khramov and Komissarova¹⁸ were not far from reality when they put forward calculations which seemed to show (from paleomagnetism) that in the Carboniferous Age the radius of the Earth may have been only 80% of that of today. The method of calculation of van Hilten has been criticised; *but* this need not mean that his result is really considerably in error. Now one can calculate, from our seismologically founded knowledge about the interior of the Earth, the extent of the *elastic response* of the Earth to a decrease of κ . This calculation has been performed by coworkers of Dicke; and certainly this would give a *too slow* expansion to explain what I am inclined to believe to be empirically probable.

This situation lead me to an attempt to make use of an idea of Ramsey's who thought that the (outer) core of the Earth would not contain another chemical composition but only another *phase* denser than the mantle material. However, in discussions with Teller and Elsasser, I saw myself forced to acknowledge, at first reluctantly, that Ramsey's hypothesis is *surely* wrong. I am now preparing a translated edition of my book in which I shall replace that part of the text which made use of Ramsey's hypothesis by a new formulation of my theory of Earth expansion, according to which the excess of expansion, as compared with elastic response to $\kappa < 0$, is caused by transition of material from the outer core to the mantle, but *not* in the manner suggested by Ramsey's hypothesis. Most recent progress in the research concerning the chemical composition in the deeper layers of the mantle¹⁹ is favorable to this new concept, about which I delivered a contribution to a congress at Newcastle upon Tyne, 1967.

Although many details of the concept of Earth expansion still remain controversial—other theories being in competition with what I believe to be nearer to the truth—I have the impression that the great bulk of empirical knowledge about the history of Earth is *favourable* to Dirac's hypothesis.

This statement also includes the topic of the difficulties which Teller thought to see in the idea of a quite strong luminosity of the sun during Paleozoic and precambrian times. Long ago ter Haar indicated a possibility to eliminate those difficulties: In the case of a considerably stronger luminosity of the Sun, the chief consequence would be the development of a closed layer of clouds around the Earth; and, under these, cloud conditions which favored the early development of organic life.

Studying books and articles of paleobotanists, I found with astonishment that the picture traced by these specialists concerning climatic conditions, especially during carboniferous times, gives a convincing confirmation of ter Haar's idea of a closed layer of clouds although in contrast with opinions of other paleoclimatic specialists, visibly not so acquainted with paleobotany. Meteorological doubts against the theoretical possibility of a closed cloud layer (which seems to exist today at Venus) can be overcome.²⁰

This study also gave a quite new conception³ about the old huge glaciations in the remote past: Probably, they are not comparable with the glaciations in the course of the diluvium (made possible, probably by the continuous decrease of the Sun's luminosity, according to $\kappa < 0$), but showed fundamentally different features. That they were probably *not* concentrated in polar regions allows us to discard the well-known idea of *polar migrations*. But due to the popularity of this idea of polar migrations, my inclination to deny them aroused much indignation.

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The valuable opportunity to study the Moon's features directly from G. P. Kuipers wonderful *Photographic Lunar Atlas* has been given to this author by the kindness of the firm, *Bölkow-Entwicklungen*, Munich.

XVII

A Strategic Approach to Interplanetary Flight

Dr. Krafft A. Ehricke*

INTRODUCTION

Strategy designates the skillful management in attaining an objective; the art of planning, integrating and applying the means needed to accomplish the individual goals so that the overall objective is met in the most efficient manner. Most importantly, strategy establishes broad, basic objectives which serve higher order needs and requirements. A strategic approach to interplanetary flight incorporates science, technology, and exploration as important components of the total effort, but it aims at a more fundamental overall objective, through which alone one will be able to understand the general concept of interplanetary flight.

This overall objective may be defined as the stepwise acquisition of the solar system for mankind through the agency of those nations which are leaders in space. It consists of three consecutive overlapping phases (Fig. 1).

Each of the many worlds of our solar system will sooner or later constitute a specific goal. These goals must be compatible with the overall objective. The operational capabilities must be compatible with the goals; hence, they are also tied to the overall objectives. Operational capabilities are based on technological groundwork. Technology can advance only in finite steps whose

*Assistant Director, Astrionics Division, Autonetics, a division of North American Rockwell Corporation, Anaheim, California.

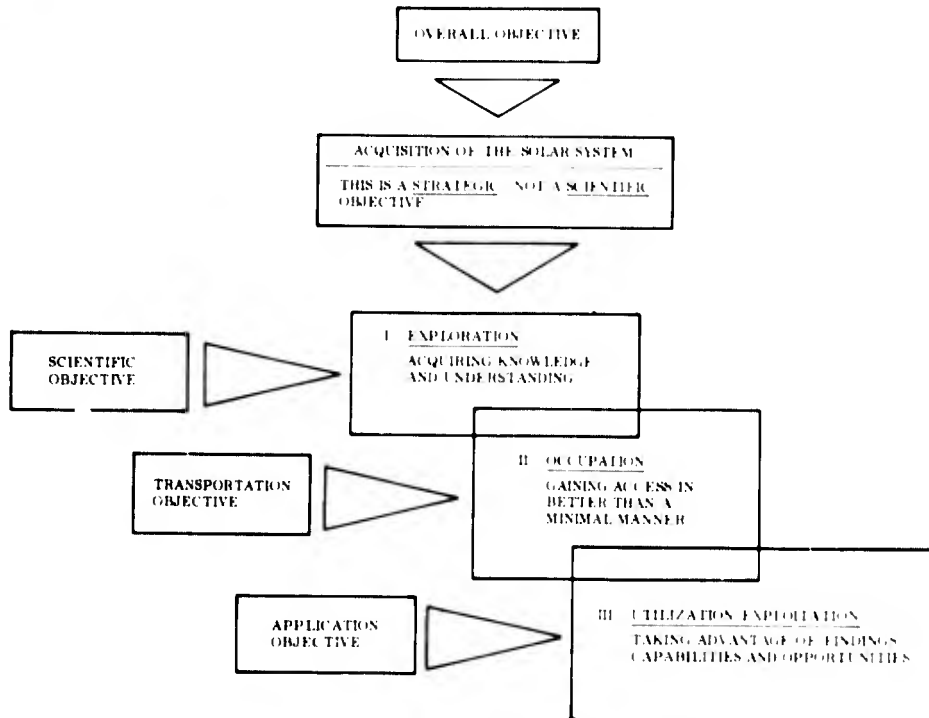


Figure 1. Overall objective by phases.

time constant is determined by limitations in scientific knowledge, in supporting technological capabilities, and by the degree of urgency assigned to the program. Present knowledge does not support the expectation that a practically foreseeable technology plateau some 20 years hence will provide a nonmarginal manned flight capability to more than half the number of planets in the solar system; nonmarginal is taken here to mean adequate propulsion for fast (hyperbolic) heliocentric transfer at the appropriate design margin for high crew survival and mission success probability.

On the other hand, no adequate foundation has as yet been laid for restricting the planning of manned interplanetary flights to one planet: Mars, only. Mercury is in a more difficult, but technologically by no means insurmountable, solar environment in terms of thermal and radiation conditions; but the planet's surface is quite easily accessible. The conditions on Venus will defy attempts at manned landings for some time to come. The surfaces of asteroids and of many moons of Jupiter are quite well

accessible, at least gravitationally.* They are located in a more restrained solar environment; but their meteoritic environment is suspected to be more severe than inside the orbit of Earth; Mars being in an intermediate meteoritic environment. Great distance and extremal orbits, in the case of some asteroids, pose the primary accessibility problems to the Jupiter system and to asteroids. Jupiter itself is very inaccessible, not only because of its gravity and atmosphere but also because of the intense radiation belt which may render it difficult to approach within some ten Jupiter radii even with probes, because of the radiation effect on the electronic equipment. Therefore, in addition to Mars, the planet Mercury, many asteroids, and a number of Jupiter moons [probably Callisto (JIV) and beyond], as well as moons of Saturn, can be regarded as basically accessible, if we have the appropriate propulsion system to reach these bodies within reasonably short flight times and with adequate means of protection against hazardous environmental conditions. Protective devices generally are a matter of weight and, therefore, basically a matter of propulsion energy.

Absence, at this time, of a major national commitment to manned planetary flight at least has the advantage of eliminating the pressure to quickly perform some kind of mission. This provides extended lead time which should not be wasted by failure to furnish the technological and exploratory developmental basis for systems, especially propulsion systems, of very high performance and low obsolescence in the middle-eighties and nineties. To meet these standards, they must be related to the overall objective.

In this paper I attempt to define overall objectives for planetary flights and to give reasons why, in my opinion, fast transfers are at least required for manned flight, and also for selected cases of unmanned probes. But, simply to call for fast transfers is not enough. Therefore, I will conclude with a discussion of propulsion systems with sufficient power to achieve the required hyperbolic flight paths.

Vilfredo Pareto, the famous Italian economist and sociologist once said¹: "One must first obtain a general concept of the thing one is studying, disregarding details, which for the moment are

*Rapid rotation of some of these bodies can pose a serious problem of surface accessibility

taken as perturbations; and then come to particulars afterwards, beginning with the more important and proceeding successively toward the less important." The spirit in which this paper is presented could not be characterized more succinctly.

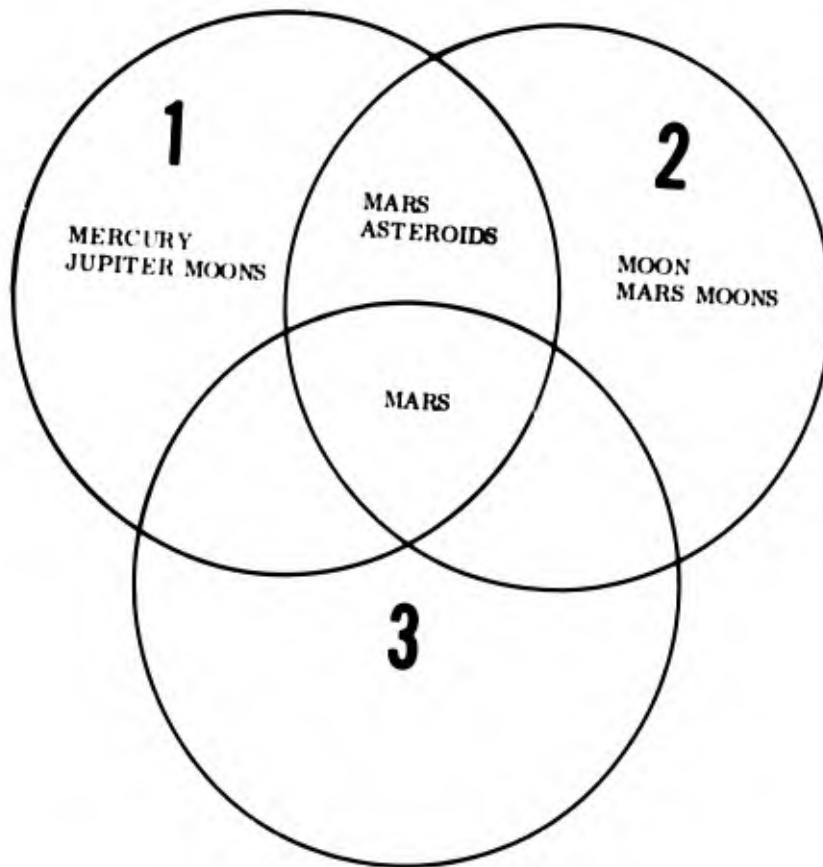
THE OVERALL OBJECTIVE

The overall objective relates to the three phases specified in Figure 1. Before discussing these phases, however, attention is called to two fundamental aspects: The importance of return-on-investment considerations; and the context in which manned missions in the 1980's and 1990's may be conceived. This is important, because it would be an obvious mistake to think of these missions in the framework of our present conditions.

What returns do flights into the solar system offer? There are direct and indirect (derivative) returns. They result from the information acquired in the course of the flights, from the technological advances required to make these flights possible, and, finally, from practical applications associated with the access to other parts of the solar system.

First of all, there are direct returns in terms of scientific knowledge. The Space Science Board of the National Academy of Sciences stated²: "The exploration of the solar system bears on three central scientific problems of our time: the origin and evolution of the Earth, Sun, and planets; the origin and evolution of Life; and the dynamic processes that shape man's terrestrial environment." Thus, there is *knowledge*, and there are the *practical* as well as the intangible benefits derived from it. These returns are obtained most economically by starting out with the deployment of probes. The resulting advances, discussed below, bring returns in *technology applications* and innovations, as well as in *lunar applications*. Finally, there should be definable returns in *solar system applications* for the investment needed to establish manned interplanetary transportation. The total might look qualitatively like the chart in Figure 2.

The second point to keep in mind is that in the 1980's, and still more so in the 1990's, manned planetary flights will take place in a different public environment. The world will have become accustomed to highly developed standards of space utility



- 1 MINING FOR INDUSTRIAL RAW MATERIALS
- 2 MINING FOR HYDROPONIC AGRICULTURAL RAW MATERIALS
- 3 CULTIVATION OF LIFE (FOOD RESOURCES) ON OTHER CELESTIAL BODIES

Figure 2. Potential returns from solar system utilization and exploitation.

and application services. Vast quantities of data will have been accumulated; hence, much more will be known about planets, asteroids, and the conditions in interplanetary space. New or different concepts will govern the mode and purpose of manned missions, due to advances in propulsion and power generation technology as well as in astronics (remote sensors, data processing, communication and microelectronics). The purpose of manned flights will be based on exploration as well as applications. Heliocentric transportation systems will be required to reach beyond just Venus or Mars; and emphasis will be placed on short transfer times, consistent with a healthy design margin for adequate mission success probability. Just barely getting there will no longer

be satisfactory, except possibly for purely expeditionary missions into the far outer solar system, because we will already have "gotten there" by means of unmanned probes.

On these premises, we will now examine the three components: exploration, occupation, and solar system utilization and exploitation (item IIID in Fig. 2). In particular, we will examine these components for evidence which permits the formulation of a meaningful strategic overall objective which is not limited to unmanned probes. This evidence hinges on (a) whether a case can be made for the eventual integration of manned flights, and on (b) whether utilization/exploitation objectives can be defined which are amenable to practical and timely implementations. The scope of this discussion must encompass short-range and long-range objectives, because strategic objectives can rarely be defined in terms of immediate needs. "Acquisition of the solar system" is an undertaking which stretches far into the future. There is nothing wrong with a long view, especially one which helps us obtain the general concept of which Pareto spoke. I believe that, for interplanetary flight, the long view is the only way in which a general concept of purpose and objectives can be obtained.

The use of unmanned probes is the logical first step in this phase. The Earth launch vehicles Atlas, Titan, Saturn; and the upper stages, Agena, Centaur, Modified Apollo Service Module, are available or can be adapted, with a comparatively modest effort, to deliver unmanned probes to virtually every planet and to many comets and asteroids in the solar system. By the middle of the next decade, a nuclear upper stage for Saturn V could be put into service enhancing injection masses or reducing transfer times. I find it difficult to accept that the NERVA engine development must be predicated on manned missions as its only principal justification. Because so much is as yet unknown, scientifically meaningful and important missions can be assigned to unmanned spacecraft. In the 10 to 20 years ahead, spectacular successes can be achieved with unmanned missions which take full advantage of existing operational capabilities to exploit the opportunities which beckon us to bring into sharper focus the existing conditions, the dynamics, and the history of our solar system. These successes mean sizeable rewards in the form of new scientific insight, historic firsts, and national pride and prestige. They can contribute to a rededication of our nation to its space program.

To accomplish this, the primary thrust of immediate technological advancements must be directed at payload or mission specific equipment (including electrical power); and at the achievement of long operating life. This emphasis could not be more compatible with that needed to utilize geospace for application spacecraft. Moreover, the resulting advances in equipment for navigation, data acquisition (sensors), data processing, data transmission and electric power; and the advances in microelectronics, reducing equipment-weight power requirements and mean time before failure (MTBF)*, constitute important prerequisites for meaningful manned planetary missions. They represent important justifications for the use of advanced propulsion systems, either for the use of the NERVA stage or for unmanned spacecraft drives, such as solar-powered electric propulsion.

Occupation introduces the human crew into the system and represents conceptually the link between Phases I and III in that it constitutes the highest level of exploration and the base level of utilization/exploration. Occupation is not intended to mean necessarily manned landings or continuously manned bases. Initially, it means man's capability of traversing interplanetary space and operating in the vicinity of other planets, moons, or asteroids; using passive or active remote sensors, as needed; and using instrumented probes or remotely controlled automatic surface laboratories. In fact, it is not obvious at all that manned landings should be made during first missions (unless for competitive reasons). Sensors, including high-resolution telescopes, can provide an extremely detailed account of the surface of Mars, Mercury, or Jupiter's moons. Unmanned shuttlecraft can descend to the surface of these bodies, or, of Venus, carry out experiments and collect specimens; then return to the interplanetary spacecraft. Because they are of much lighter weight than manned shuttlecraft, they can land at a greater number of places; thereby providing a more complete account of the variety of local planetary environments. Manned spacecraft, rather, should aim at a capability of reaching a greater number of planets than just Venus and Mars. Later we will show how a fast flight capability of bodies from Mercury to Jupiter affects propulsion energy and requires relative insensitivity to a wide range of environmental conditions (solar radiation, dust, meteoroids and corpuscular radiation).

*Particularly in combination with increased radiation hardness.

Capture missions offer far greater returns than flyby missions. Therefore, nothing less than capture is worth considering for manned missions, except where flyby en route or gravity navigation are involved. The exchange of payload for two manned shuttles to accessible surfaces (Mercury, Mars, Jupiter moons) can only be evaluated on its individual merits. As always, the investment in a crew can be properly justified only by establishing a need for its unique capabilities: intelligence; judgment; resourcefulness. In the case of manned interplanetary missions, this means (a) execution of complex mission profiles (multi-planet or multimoons or both); (b) management of a large array of probes by controlling their deployment, their experiments, directing the return and repeated use of shuttle probes, and evaluating their findings; (c) active (unpreprogrammed) on-the-spot experimentation; (d) search for possible future opportunities for exploitation; and (e) landings and surface travel. This list alone is indicative of the necessity to involve, at some point in time, manned missions in a task of such enormous scope as the exploration of the solar system.

Three principal modes of exploring the solar system are available to us: remote observations from Earth (orbit); deployment of unmanned probes; manned missions. Each has its place and each has its limitations. An orbital observatory, for example, gives us a broader spectral range to work with. But distance and diffraction limits set an upper limit on resolution which can be pushed further only by getting closer to the object. This fact and sensitivity limitations of other sensors necessitate the deployment of unmanned probes. The extent to which exploration can be conducted by unmanned probes before a state of diminishing returns is reached varies with the planet in question. Determination of the change-over point from unmanned to manned exploration is an interesting problem in itself and can contribute importantly to long-range planning. At that point, the presence and price of human intelligence and resourcefulness can be justified on the basis of efficiency, cost effectiveness, or even feasibility in the first place.

Development of credible objectives for the *direct application phase* (IID, utilization/exploitation) is the *pièce de résistance* of the overall objectives definition. The critics of our national space effort have repeatedly questioned, among other things, the reality

of any returns, beyond scientific ones, from interplanetary flight. The seeming difficulty of dispelling this notion in terms of requirements of the present state of our civilization seems to lend apparent logic to their argument. But very few new achievements ever emerged complete with the armor of fully developed measurable utility like Athena from the head of Zeus. It took just 10 years to disprove that same apparent logic so far as Earth space is concerned. The very shallowness of this logic, applied once again, does considerable damage to this nation, since it causes vacillations and uncertainties in the support of large technological projects, which relate not only to those of space; disrupts effective teams; and certainly does not encourage youthful enthusiasm for a profession so vital to this nation's future. It is one thing to decide that the Vietnam war and internal priorities make a (temporary) cutback necessary; but it is an entirely different thing to rationalize such a decision by downgrading the importance of continued technoscientific progress on which tomorrow's industry and problem solving capability of this nation, and of all mankind, rest. In a strategic frame of reference, specific missions can indeed wait in many cases; but the evolution of generic capabilities through consistently supported technological advances cannot wait. The search for returns from manned interplanetary flight, transcending scientific returns, must therefore be made from a standpoint which permits a longer view ahead. We must also keep in mind the classical pattern by which the utilization or exploitation of a new region evolves: (a) making use of what is readily available; (b) modification or cultivation to broaden the usefulness of the region. In the solar system, initial utility will be found in the exploitation of valuable, reasonably accessible mineral raw materials. Later, more elaborate biocultivation efforts will increase the usefulness of suitable bodies in the solar system.

We cannot know factually what forms the acquisition of the solar system for humanity will ultimately assume. But we do know that, within a historically brief period, a larger Earth population with higher average living standards will need more mineral raw materials than this small planet can supply and still maintain adequate living areas for people and the necessary areas for animal and plant life with which we must maintain an ecological balance for the sake of our own psychological sanity and, eventually, survival.

Earth is not a lone ship in space. She travels in a convoy of many sister ships, large and small, and as yet unused, so far as we can determine. There is a fundamental logic in boarding our companion "vehicles" and ultimately making use of them. We must see what we can find and how we may suitably transfer to some of them a number of our vastly expanded activities which are needed to sustain the huge body and mind of the entity (and it is an entity, for we are all part of the same crew) we call *humanity*. This states the general idea as simply as possible.

I do not suggest we should refrain from ocean mining and from extracting more food from the oceans. Many statistical appraisals led us to expect a greater supply than we are permitted to claim on ecological grounds. For, on this planet, we must respect the ecosystem as it exists as the product of 2 billion years of development, lest we turn Earth into an ecoslum as unfit for human habitation as the ugly slums of cities. On other worlds, such as Moon, Mercury, asteroids, we are not hampered by these constraints. We can rip Mercury's surface open, or tear an asteroid apart, in the course of nuclear mining without threatening our or any other ecosystem. We can manufacture in space or on the Moon without having to worry about waste, refuse, or environmental poisoning for a long, long time. We can raise the food we want and need in micro-ecosystems (i.e., systems involving few species compared to Earth) without having to kill off thousands of other species and destroying the living mantle of our Earth.

These, I believe, are very important, real, credible, and not-too-remote reasons why we eventually will have to tap the virtually inexhaustible and ecologically unclaimed resources of our solar system. This, I believe, means acquisition of the solar system: Utilization of the readily available resources of the solar system so that Earth may be saved as the beautiful living planet and the home of humanity. In a nutshell, why not make Earth the garden spot of this solar system and draw many of the needed supplies from resources on the abundance of our sister worlds?

We will continue for a long time to use terrestrial resources. But gradually, we will have to complement them by drawing from extraterrestrial resources, once we have grown tall enough to look beyond our horizons at the solar system as our overall supply system and are no longer overwhelmed by this thought.

Thus, we can specify the mining of industrial minerals, especially certain metals, and the mining of bioraw materials (water, oxygen, nitrogen, phosphorus, etc.) for hydroponic farms as the two initial, foreseeable returns in the third phase (utilization and exploitation, IIID). Energy sources are available in abundance. The raw materials are there (only their distribution needs to be determined) and their processing is routine industrial technology. The third, more distant return could be the cultivation of food resources on Mars. But the practicality of this cannot be gauged as yet. Figure 2 correlates these three areas of returns with relevant places in the solar system. Of course, these returns are real only on the basis of the availability of interplanetary transports which make astromining economically competitive with the mining of poor ore on land or the mining of the ocean floor, so long as this can be done within the ecological constraints referred to above.

In summary, we can identify primary scientific targets and primary utilization/exploitation targets. The Space Science Board of the National Academy of Sciences² has ranked the scientific targets in this order of priorities: (1) Mars; (2)/(3) Moon/Venus; (4) Major Planets; (5) Comets and asteroids; (6) Mercury; (7) Pluto; (8) Dust. The utilization/exploitation targets may tentatively be ranked as follows, based on the mining objectives set forth above: (1) Mercury; (2) Asteroids; (3) Mars.

Through the above process of establishing the overall objective complete through Phase III, we have established tentatively that the solar system region of primary interest encompasses the region between Mercury and Jupiter. This specification provides the needed guidance for the selection of post-Nerva propulsion systems for manned interplanetary transports.

The scope of operations implied by selection of the Mercury-Jupiter region is vastly greater than consideration of Mars or the Mars/Venus band only. But, as compared to the overall solar system (Fig. 3), it still comprises only the small central core of the solar system. Beyond Jupiter, operations will be restricted to exploration, for some time to come, by probes and with advanced propulsion systems by manned long-duration missions. Some flight corridors for reaching the far outer planets by using the gravity boost of Jupiter and Saturn are indicated in Figure 3.

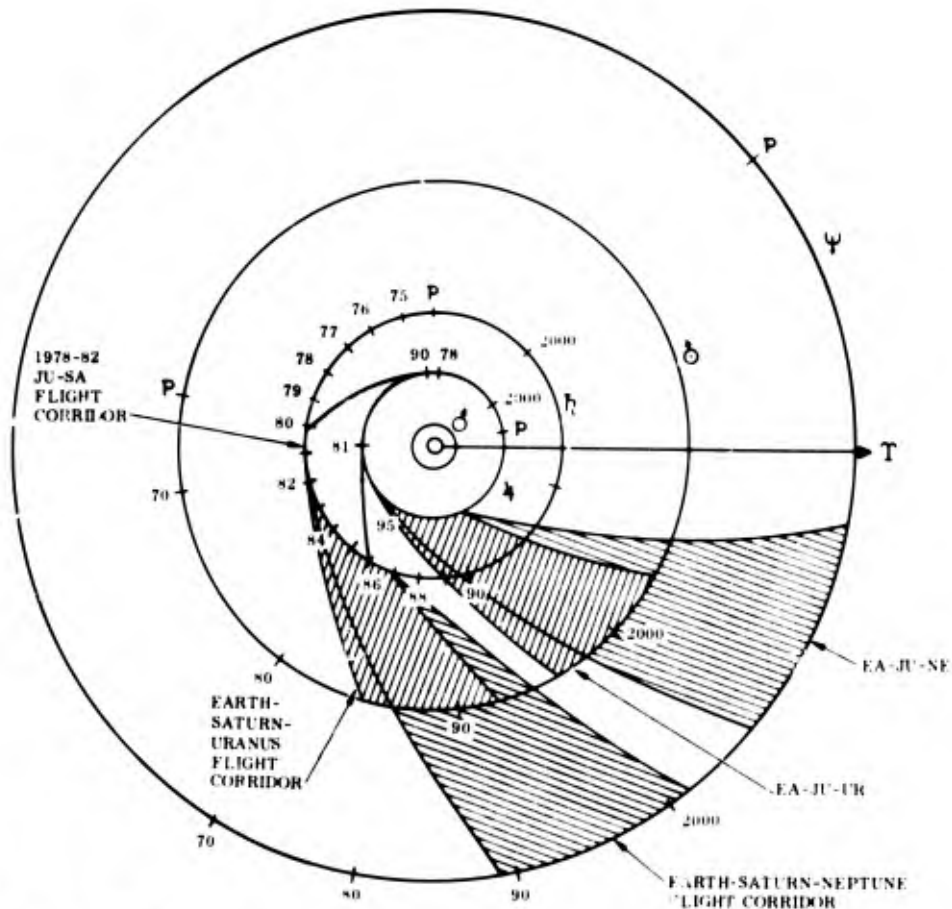


Figure 3. Overall solar system with flight corridors to the far outer planets using the gravity boost of Jupiter or Saturn.

THE STRATEGY

The matrix presented in Figure 4 emphasizes areas of particularly heavy interrelation between the evolution of interplanetary flight (categories in first column at left; systems in last column at right) and other areas of the national space program. For Unmanned Exploration, the primary interfaces are with Earth launch vehicle (ELV)/upper stages and with Geospace Applications. The first of these is well developed. In the second, integrated technological development of astronics subsystems, spacecraft mechanisms (e.g., pointing devices), and long-life spacecraft would be very effective. At the time of manned exploratory missions in the Mercury-Jupiter region, Earth satellites and deep space probes of 10-year operating life can be postulated (1985/90).

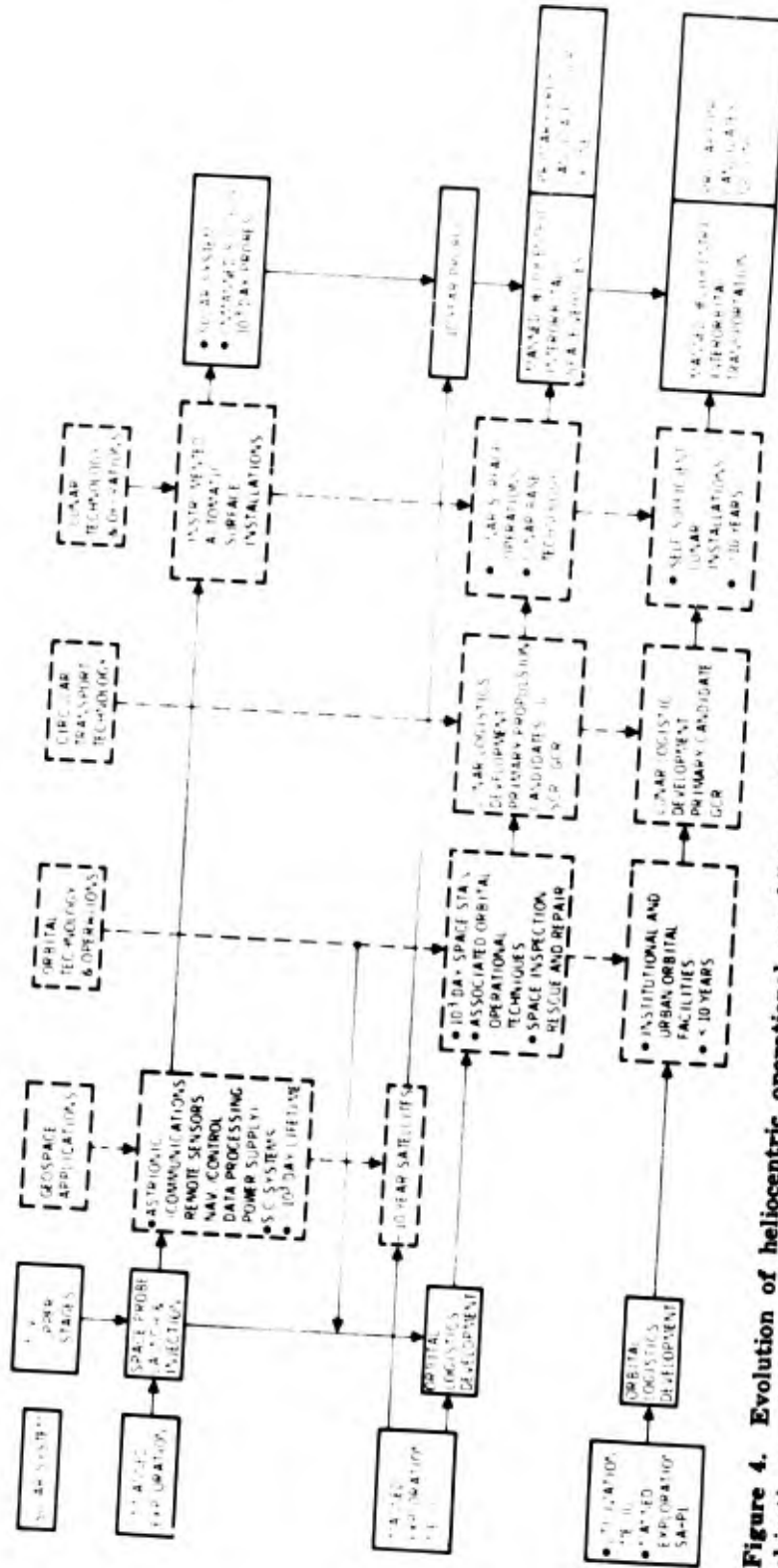


Figure 4. Evolution of heliocentric operational capability within the overall space program through development by key objectives and synergistic effectiveness.

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The combinations of short, manned mission periods and long-operating life of the probes or monitors left behind in orbit, or on the surface of the planets visited, are of considerable value in improving the cost effectiveness of manned missions. Manned missions have a greater number of interfaces with more advanced space activities in other areas, pertaining to the development of an appropriate orbital logistics system and of long-life manned space stations (Orbital Technology and Operations). Furthermore, the mechanization of manned missions will be affected by the then existing level of primary propulsion systems for lunar logistics. The experience gained from lunar surface operations and lunar base technology is of such importance for manned interplanetary flights, especially if landing on other celestial bodies is involved, that lunar operations in addition to their immediate purpose will also have to be regarded as stepping stones to manned interplanetary flight. Essentially, the same interface points in the matrix exist for utilization of the Mercury-Jupiter region, but exist on a still more advanced level. The matrix, Figure 4, attempts to show the importance of interdependence and coadvancement of the many facets of space technology. Interplanetary flight will be advanced most effectively if (a) it rides the momentum of progress in other temporarily higher priority areas whenever the advances are relevant; and if (b) its future requirements are taken into consideration, to an appropriate degree, in decisions which control the advances in other areas (orbital, lunar).

Concentration of effort on the advancement of key technologies and key operational techniques is based on the importance of maintaining some measure of cohesiveness of technological efforts. This means, of course, widest practical utilization of existing proven hardware. But, it also involves the art of knowing when *not* to enforce commonality so not to overstretch the original purpose of the system at the penalty of wasting time and resources on marginal endeavors. Key technologies, again, are those which lie at the critical pressure points or trigger points of the evolution, which provide the greatest returns ahead. But if improvements are pursued in one area without proper relation to the overall strategic approach, they can aggravate other problems to the point where the improvement is virtually negated. Electric propulsion, for example, has the desired specific impulse for missions to Jupiter or Mercury. But it is easily realized that with the large radiator surfaces as usually envisioned today, these

vehicles may never get through the asteroid belt in operative condition; and that flights into the intense solar radiation field associated with Mercury missions* cause at least serious radiator problems with the result of (a) constraining the vehicle's solar orientation (affecting its maneuverability), or (b) requiring more or less large shadow shields (reducing both, the omnidirectional emission effectiveness of the radiator, and the mass fraction of the vehicle), or (c) requiring much larger radiators for the same power rejection than at Earth distance (again degrading the vehicle's mass fraction), or (d) restricting maximum allowable thrust power as function of solar distance, or (e) a combination of all these, based on trade-off analyses to minimize the effect on payload weight or travel time. The radiator problem near Mercury is, of course, not limited to electric drives but applies also to life support system radiators; but the large radiator size of the former renders the vehicle particularly sensitive to solar radiation.

Proper choice of key technologies implies, by the very definition given above, minimum development of key operational systems. Economy and learning curve considerations (reliability, production cost, etc.) and common logic strongly suggests that the overall objectives be attained by developing as few operational systems as possible. Major commitments (such as the development of a new propulsion system; hence, a new vehicle) severely constrain future options for some time to come. A small step is therefore far more likely to be a liability and a constraint in the future than would be a larger one.

SYSTEM ANALYSIS

Three elements are involved in the present system analysis: Mission objectives, environmental constraints, and transportation system. Mission objectives result in payload definition. The transportation system consists of Earth launch vehicle (ELV), heliocentric interorbital space vehicle (HISV), and the primary transport and destination space vehicle (DSV), if any, as the secondary transport. Payloads and transports comprise the overall system. The effectiveness of a system results from comparing system performance capability with operational requirements.

*At mean distance of Mercury (0.387 A.U.) the solar constant is 9.11 kw/m², compared to 1.36 kw/m² at 1 A.U. In addition, flight profiles to and from Mercury can lead to a heliocentric distance of less than 0.2 A.U., the perihelion of the Mercury orbit.

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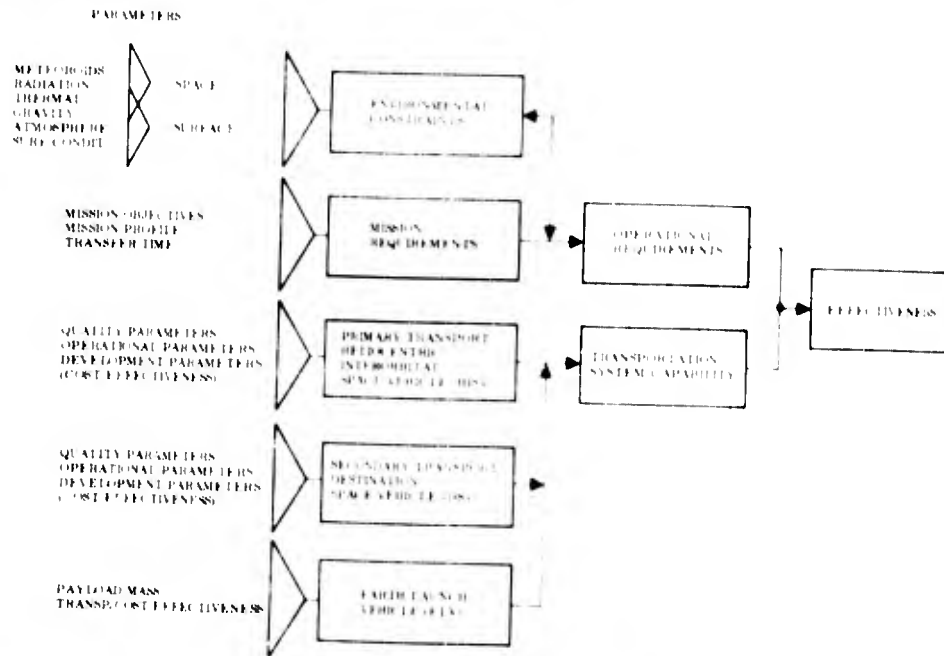


Figure 5. Top level sensitivity parameters for system analysis of manned interplanetary flight.

Figure 5 shows the top level sensitivity parameters and analyses required to assign relative effectiveness values to transportation systems. The transportation oriented specifications associated with mission objectives and mission profile are listed in Figure 6. Mission objectives, affecting primarily the payload mass, and heliocentric transfer time, affecting primarily the mission velocity requirement, result, via mission profile specification, in a given orbital departure mass (ODM) of the HISV as function of the propulsion system selected. The propulsion system of the HISV is the central influence factor by which the various components of the overall mission requirements can be balanced.

Other important influence factors are the Earth launch vehicle (ELV) and the hyperbolic Earth entry module which forms a three-way interaction with HISV propulsion (Figure 7). In addition to its services to interplanetary missions, a larger and reusable ELV also provides improved service to orbital and lunar operations. But, orbital operations will not soon have a need for larger payloads than Saturn V. Reusability is a more important advancement for orbital services than larger payload. For lunar operations, as for

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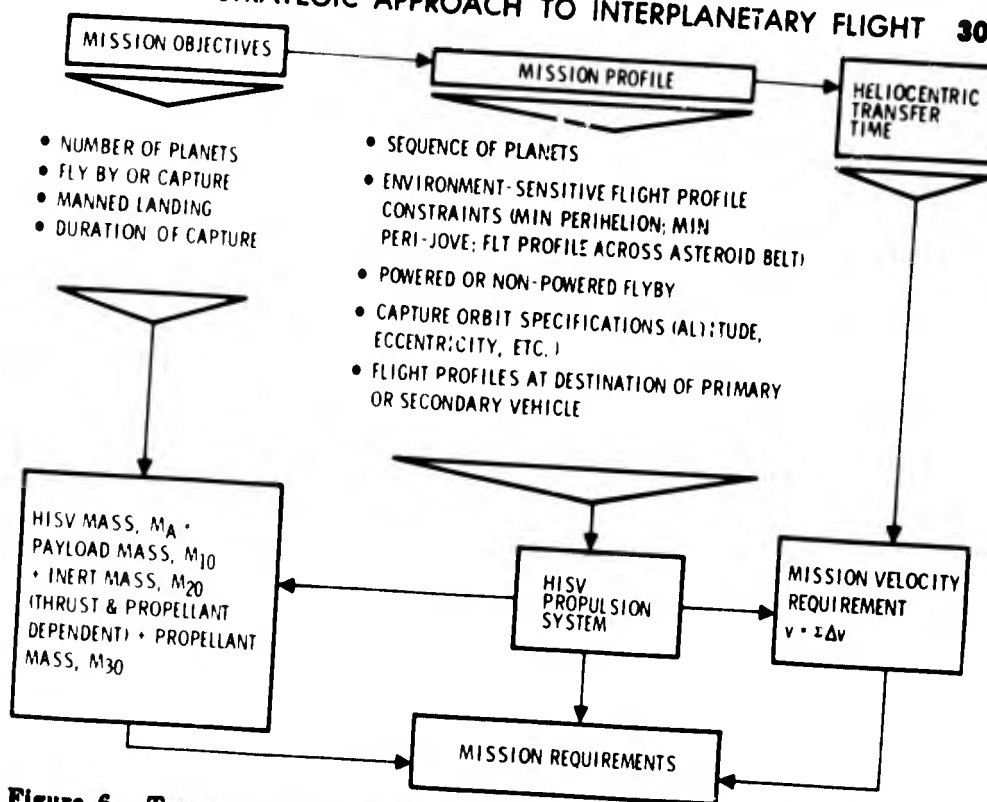


Figure 6. Transportation oriented parameters affecting mission requirement.

interplanetary operations, better ISV propulsion systems should be developed first, in order to improve the worthwhileness of the investment in a larger ELV.

The hyperbolic Earth Entry Module (EEM) has no synergistic merits, at least not where regular orbital or lunar operations are concerned. The use of the EEM is particularly effective with marginal transportation systems. The hyperbolic reentry mode merely adds another hazard to the generally high hazard level that characterizes marginal missions. It does not represent a desirable long-range solution. Its effectiveness in reducing the ODM diminishes with the advent of advanced propulsion systems in the kilosecond specific impulse range.

These considerations lead to the conclusion that indeed the HISV propulsion system constitutes the central problem to be attacked if more than marginal planetary flight capability is to be attained. At the same time, such a propulsion system can put Earth-Moon transportation on a more economical basis and reduce the flight time across cislunar space.

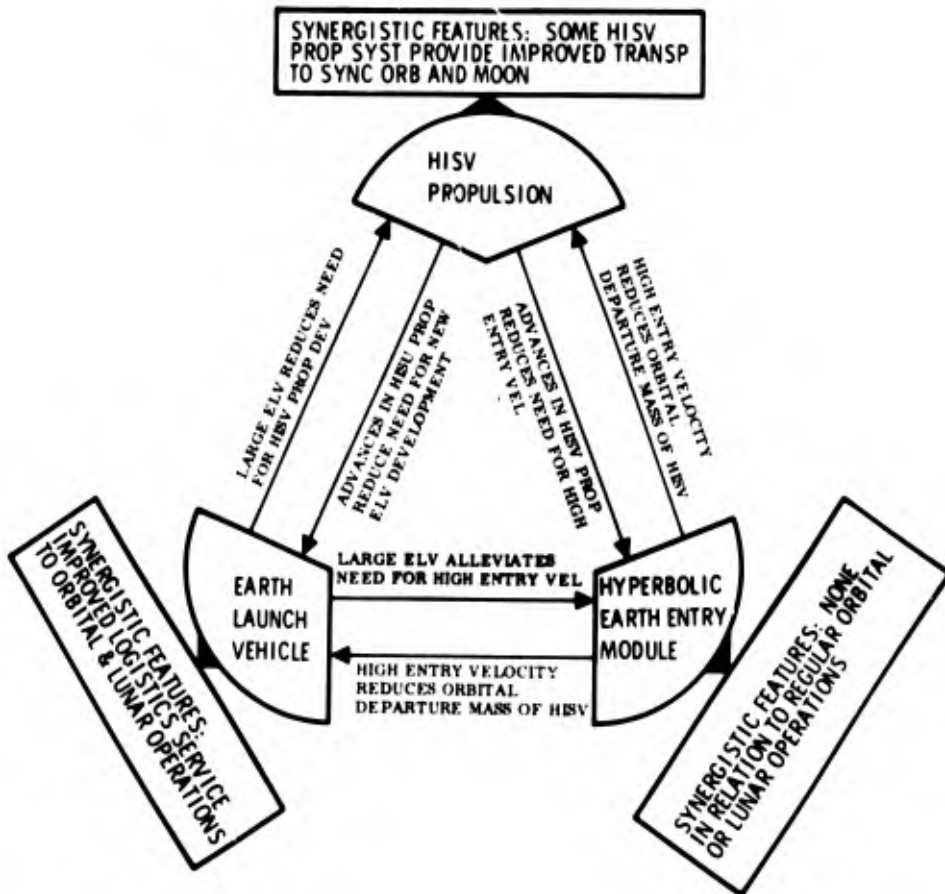


Figure 7. Comparison of key transportation features for interplanetary flight.

MISSION CONSIDERATIONS

Figure 8 summarizes the determining mission factors which provide the frame of reference for the subsequent discussion.

The region (1a) of interest encompasses the solar system from Mercury to Jupiter. In the level of intensity (1b) considerations, one-of-a-kind missions are excluded as not consistent with the region (1a) and objectives (2) specified. Employment modes (3) include crews in HISVs (without landing, but with an adequate assortment of one-way and shuttle probes) and manned landings on some planets and planet moons. Functions (4) and tasks (5) comprise transportation and transportation related parameters.

1a	MARS	VENUS/ MARS	INNER SOLAR SYST.	MERCURY/ JUPITER	OUTER SOLAR SYST.			
REGION				*				
1b	ONE-OF-A-KIND MISSION		LIMITED SERIES OF MISSIONS	REGULAR OPERATION				
LEVEL OF INTENSITY			*	*				
2	EXPLORATION		OCCUPATION	EXPLOITATION				
OBJECTIVES	*		*	●				
3	UNMANNED PROBE	MANNED HELIOCENTRIC & PROBES	MANNED SURFACE CONTACT					
			Me	Ve	Ma	Mo MOONS	Aa	Ju
EMPLOYMENT MODE	N/R	*	*	*	*	*	*	*
4 & 5	INFORMATION ACQUISITION	INFORMATION SUPPORT	TRANSPORTATION			PRESERVATION		
			EXPLORATION	LOGISTICS	FREIGHTAGE	MAINTENANCE	RESCUE	
FUNCTION TASKS	N/R N/R	N/R N/R	HIT PIT	HIT (DAT)	HIT (DAT)	N/R	HIT	

N/R - NOT RELEVANT IN PRESENT DISCUSSION
 HIT - HELIOCENTRIC INTERORBITAL TRANSFER
 PIT - PLANETOCENTRIC INTERORBITAL TRANSFER
 DAT - DESCENT-ASCENT TRANSFER

6	TRANSFER TIME (HELIOCENTRIC)		MISSION DURATION	ENVIRONMENTAL SENSITIVITY PARAMETERS			SYSTEM CHARACTERISTICS	
	ELLIPTIC	HYPERBOLIC		THERMAL	METEORITIC	RADIATION	HIGH I _{sp}	HIGH ACCELERATION
OPERATIONAL CHARACTERISTICS	●	*	NOT SPECIFIED	● ●	● ●	● ●	● ●	*

Figure 8. Summary of selected mission determinants.

Consideration of descent-ascent transfer (DAT) is restricted to propulsion system comparison for logistic and freight carriers, because of the potential economic significance of using the HISV drive to get all the way to the surface. Among the operational characteristics (6), transfer time, environmental parameters, and (transportation-oriented) system characteristics must be considered. In view of the operational characteristics, a distinguishing symbol is applied to freight conveyance, for which high specific impulse and not very fast transfers (i.e., elliptic and/or low acceleration flight characteristics) may be considered, in order to achieve a high payload fraction (low transportation cost).

The heliocentric transfer time is determined by the flight profile. Regardless of whether the spacecraft follows a powered or a

free (Keplerian) flight path, its kinetic energy is either smaller or larger than needed to escape the solar gravitational field altogether. In the former case, the orbit is elliptic (eccentricity $e < 1$), in the latter case it is hyperbolic ($e > 1$). The effect of eccentricity on transfer time can be assessed by comparing orbit sections that interconnect planet orbits (transfer orbits, T.O.). Thirteen transfer orbits, T.O. No. 0 to T.O. No. 12, can be defined, as shown in Figure 9. Some of these require considerably longer transfer times than others. Into the first category belong the Hohmann flight paths (No. 0), a half ellipse which tangentially contacts both departure and target orbit and which is practically feasible only at transfer between the nodes of two near-circular planet orbits. Long transfer times are also involved in Nos. 2, 3, 6, and 8; whereas Nos 1, 7, 9, 11, and 12 are very fast orbits. Number 4 and No. 5 take an intermediate position. Number 0 and No. 9 (tangential at departure orbit) are singularities, i.e., only one of a kind for a given set of terminal (departure and target) orbits. An

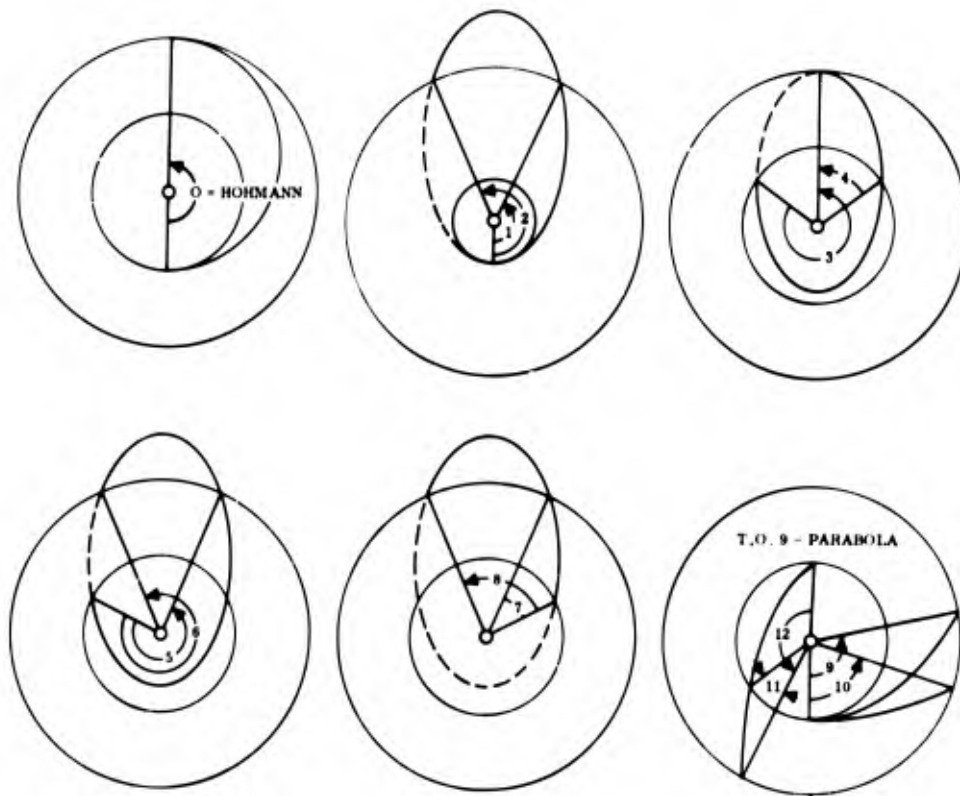


Figure 9. Twelve transfer orbit types.

infinite number of the other transfer orbits exists, depending on departure velocity and departure angle.

The more important impulse transfer orbits are surveyed in Figures 10 to 12 for transfers³ from Earth to Venus, Mars, and Jupiter, respectively. For the sake of simplicity, the planet orbits are assumed to be circular and coplanar. This causes no serious error in the case of Venus and Jupiter whose orbit eccentricities and inclinations with respect to the ecliptic are small. The greater eccentricity of the Mars orbit reduces the accuracy. But the trends shown are nevertheless correct in all cases. The plots show the heliocentric velocities of departure from Earth orbit* V_1 , the arrival at target orbit* V_2 , the transfer time t , the angle of intersection of transfer orbit with (circular) planet orbit at departure (θ_1) and arrival (θ_2) and the transfer angle η , i.e., the angle subtended at the center (Sun) between departure and arrival points (as the numbers shown in Figure 9). The parameters are shown as function of the eccentricity of the heliocentric transfer orbit. The transfer orbits are identified by number. In each figure, related parameters are arranged vertically. Thus, V and θ are needed to compute the hyperbolic excess velocity with respect to the planet

$$v_{\infty} = \left[V^2 + U^2 - 2 UV \cos \theta \right]^{1/2} \quad (1)$$

where U is the orbital velocity of the planet. If K is the gravitational parameter of the planet, r the distance from the planet at which the capture maneuver is to take place, then the vehicle's velocity at r (departure or arrival) is

$$v = \left[\frac{2K}{r} + v_{\infty}^2 \right]^{1/2} \quad (2)$$

where $2K/r$ is the square of the local parabolic velocity. The (impulsive) capture (or departure) maneuver itself becomes

$$\Delta v = \left[\frac{K}{r} \left(2 - \frac{r}{a} \right) \right]^{1/2} \quad (3)$$

*Disregarding the planets.

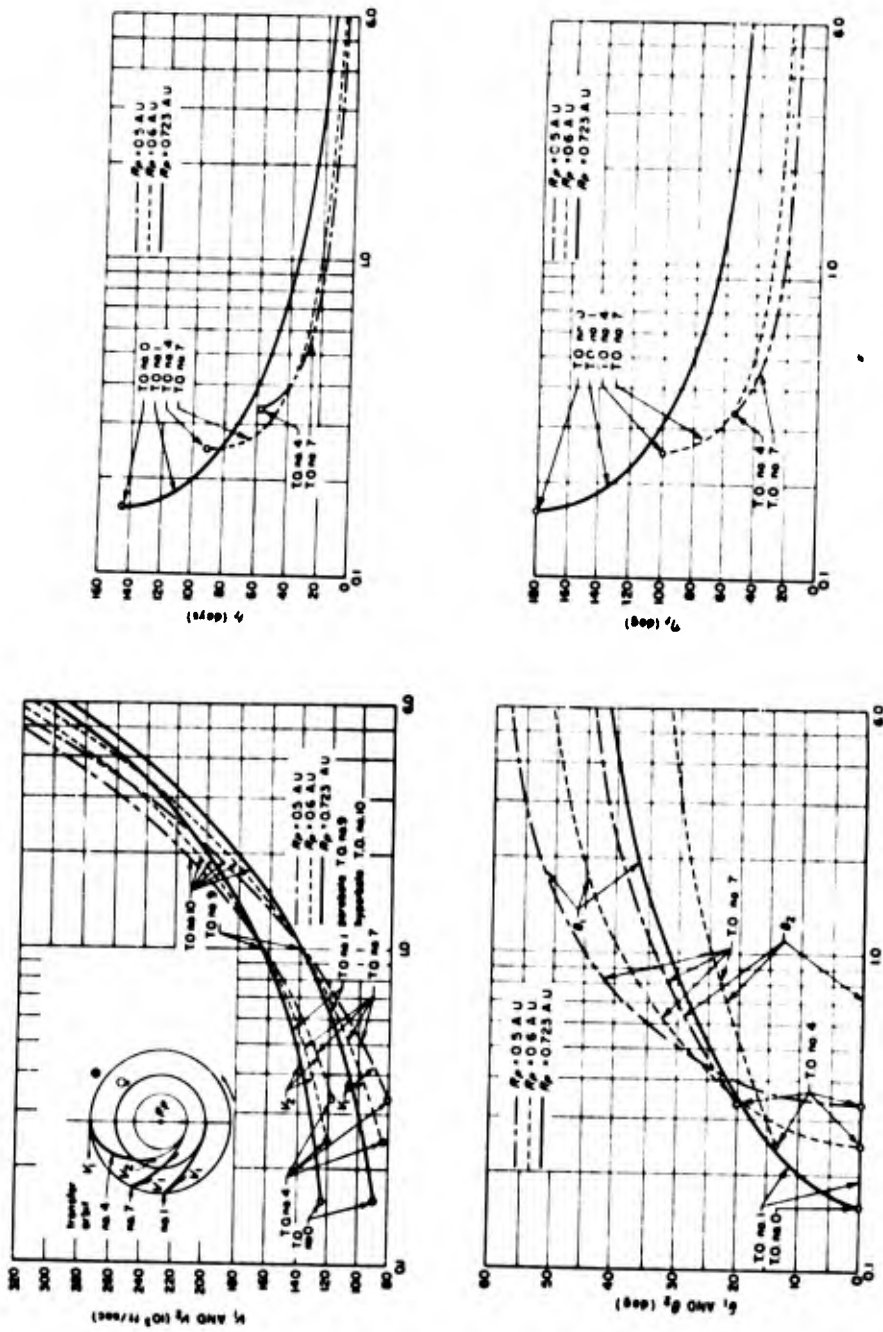


Figure 10. One-way transfer characteristics from Earth to Venus as function of eccentricity of heliocentric transfer orbit section (circular coplanar planet orbits).

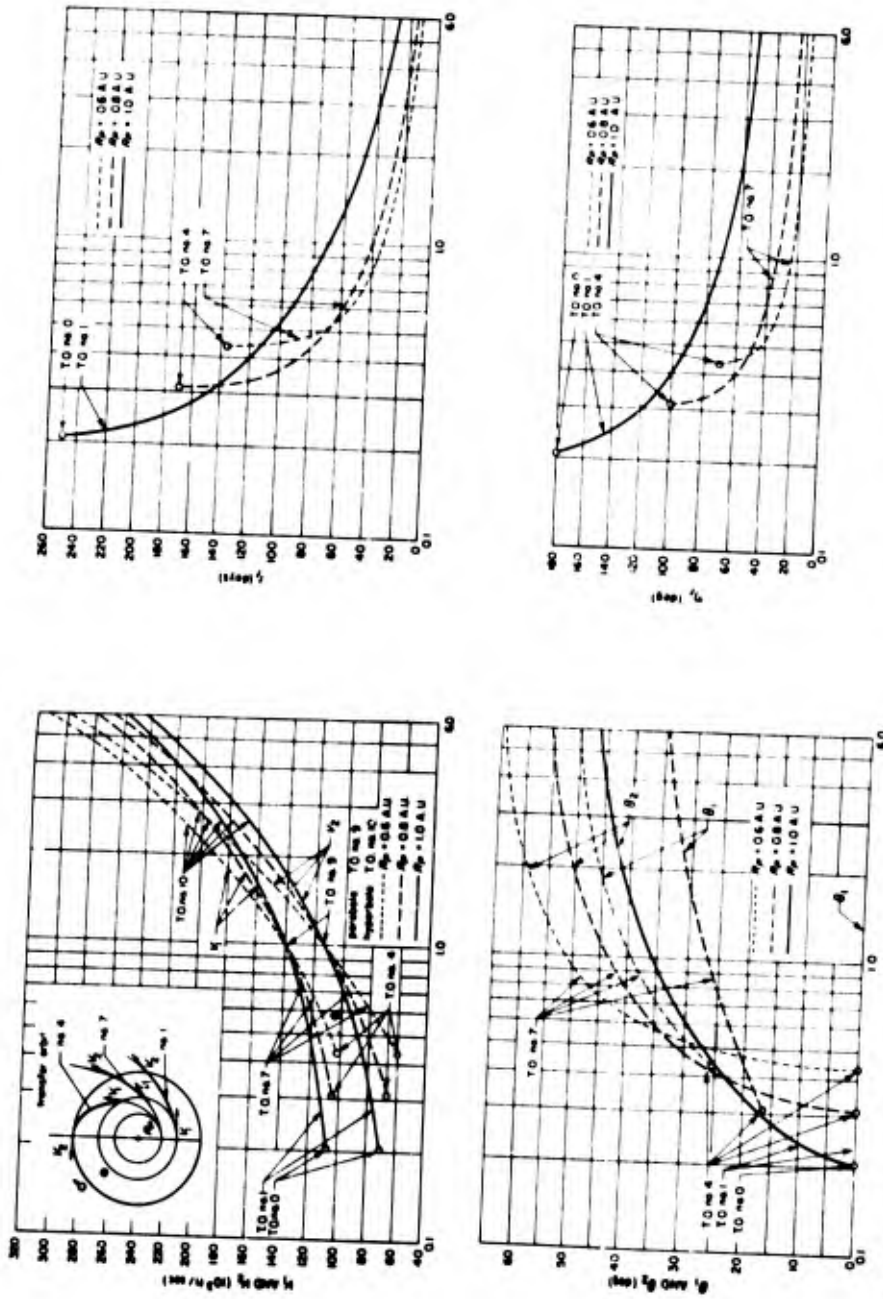


Figure 11. One-way transfer characteristics from Earth to Mars as function of eccentricity of heliocentric transfer orbit section (circular coplanar planet orbits).

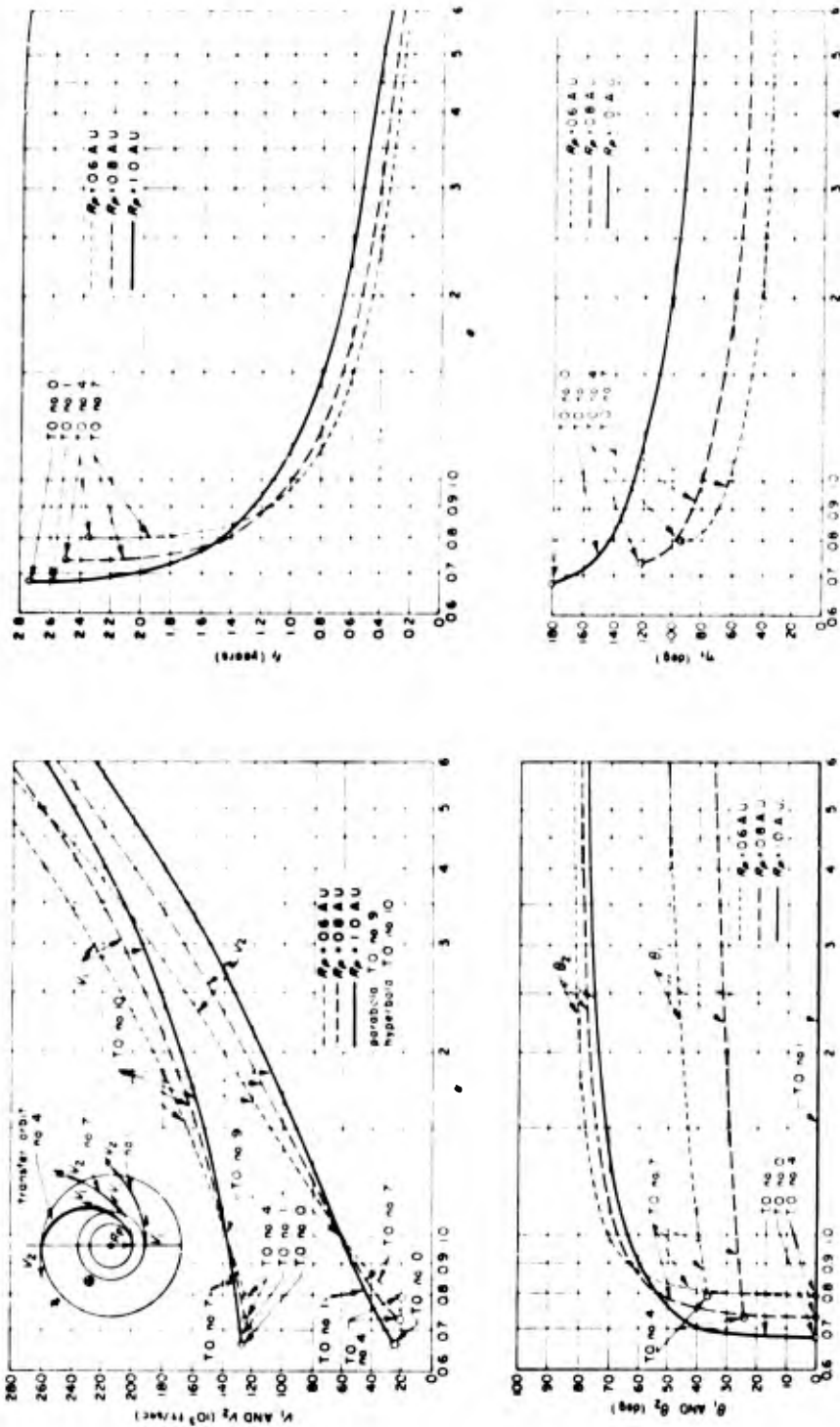


Figure 12. One-way transfer characteristics from Earth to Jupiter as function of eccentricity of heliocentric transfer orbit section (circular coplanar planet orbits).

where a is the semimajor axis of the elliptic orbit about the planet. For departure from or capture in a circular orbit, $a = r$. The charts show that with increasing eccentricity, both V and δ increase rather strongly and result in a rapidly increasing energy requirement for the maneuver Δv .

On the right-hand side of the figures, t_t and η_t are related. It is seen that hyperbolic transfer orbits are required for transfer times of less than 35 days to Venus, 70 days to Mars, 1.1 years to Jupiter; the corresponding transfer angles being less than 60° , 70° , and 125° , respectively. Figure 13 correlates transfer time and transfer angle for heliocentric transfer orbits between $e = 0.8$ (elliptic) $e = 1$ (parabolic, the singularity which separates elliptic and hyperbolic transfers), and hyperbolic eccentricities up to $e = 6$. The width of the bands reflects the range encompassed by the transfer orbits in Figures 10 through 12, with the exception of $e = 0.8$ for Jupiter where the case of perihelion distance $R_p = 0.6$ is not included. The curves show that, for a given transfer angle, Venus is reached in about half the time it takes to transfer to

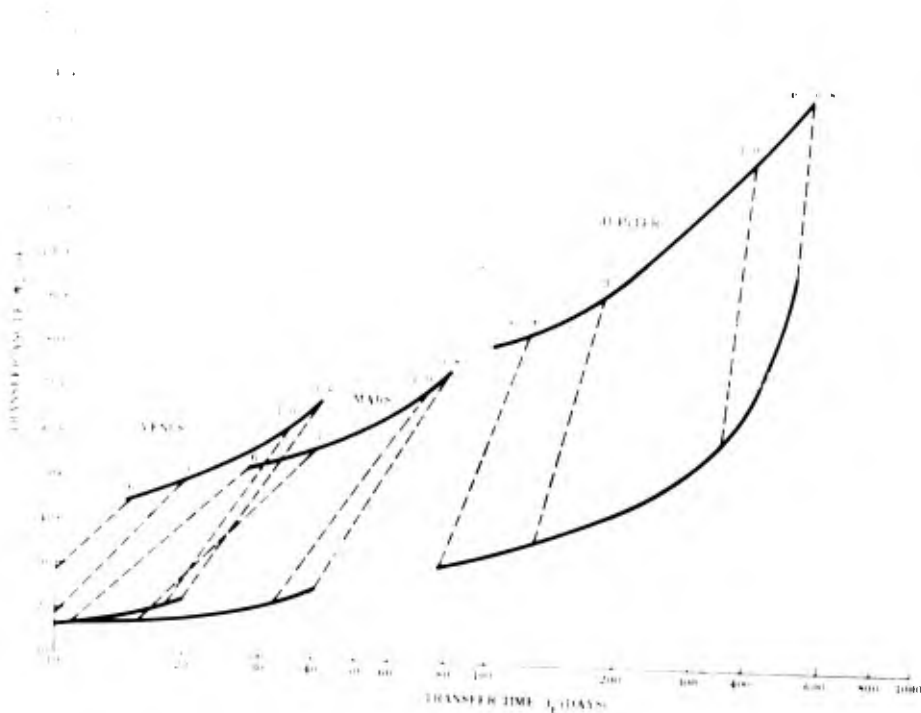


Figure 13. Flight time vs. angle subtended at the Sun for Kepler orbit sections connecting circular coplanar orbits of Earth and target planet at their mean heliocentric distance.

Mars; transfer to Jupiter is 5 to 6 times as long as it is to Mars, for equal transfer angles. It is seen that the reduction in transfer time per degree reduction in transfer angle increases with eccentricity. But v_{∞} increases rapidly with decreasing transfer angle, because V and θ increase. Therefore, the reduction in transfer time per unit velocity increase actually decreases with increasing eccentricity (decreasing transfer time), as is shown below.

In view of the increasing energy requirement (hence, propellant expenditure) with decreasing transfer time, it is necessary to justify the worthwhileness, hence the desirability, of fast transfer orbits.

Flight profiles are determined by a compromise between transfer time and an intricate network of constraints involving propulsion system capability, and a combination of mission, environment, system engineering, and human factor parameters. Key parameters are related to objectives in Table I which establishes the frame of reference for the discussion in subsequent sections.

HELIOCENTRIC INTERORBITAL TRANSFER PROFILES

Heliocentric flight profiles may be divided into several categories. In terms of thrust acceleration profile, these are (Figure 14):

- (I) Continuous high-acceleration transfer (CHAT)
- (II) Partial acceleration transfer (PAT)

PARAMETERS	MISSION		ENVIRONMENT			SYSTEM ENGINEERING	HUMAN FACTORS	
	EFFECT ON TRANSFER TIME	EFFECT ON CAPTURE PERIOD	THERMAL EFFECTS	METEOROLOGICAL EFFECTS	RADIATION (W/LAN FLUXES)	MEAN TIME BETWEEN FAILURE MODES	PSYCHOLOGICAL EFFECTS	PHYSIOLOGICAL EFFECTS
MERCURY MISSIONS	*							
MARS MISSIONS		*						
JUPITER MISSIONS	*							
OUTER MISSIONS	*							
FAILURE PROBABILITY			*	*	*	*		
CREW SAFETY			*	*	*	*		
CREW COMFORT							*	*

Table I. Correlation Between Key Parameters and Key Objectives for Fast Transfers

(III) Brief acceleration transfer (BAT)

(IV) Continuous low-acceleration transfer (CLAT)

6.1 Brief Acceleration Transfer (BAT)

The BAT results in Keplerian orbit sections as shown in Figure 9. More precise computations of these orbit sections take ellipticity, inclination, and launch windows into account. A series of fast and less fast transfer orbits were published⁷ earlier by this author which related to Venus, Mars, and Jupiter and both ways to Mercury, Venus, Mars, and Jupiter.^{5,6} An additional large number of fast transfer orbits to and from Mercury, Mars, and Jupiter were computed for missions in the late 1980's and 1990's. The results are shown in Figures 15 through 17. The sum of outbound maneuvers, Earth departure and target planet capture, $\Delta v_1 + \Delta v_2$, and that of return maneuvers, $\Delta v_3 + \Delta v_4$, are plotted for the transfer windows in the 1990/99 time period. The intermediate numbers refer to the Julian dates (12-31-1999 = 2451179.5). Outbound and return windows are arranged underneath each other so that a particular round-trip mission can readily be constructed. This is shown in Figure 17. The first arrow projected on the Julian date line from the minimum point of the $T_1 = 365$ days transfer path to Jupiter represents the departure date. Moving 365 days to the right, the second arrow specifies the arrival date. The third arrow to the right connects with an off-minimum-energy transfer back to Earth, $T_2 = 210$ days. The fourth arrow gives the Earth arrival

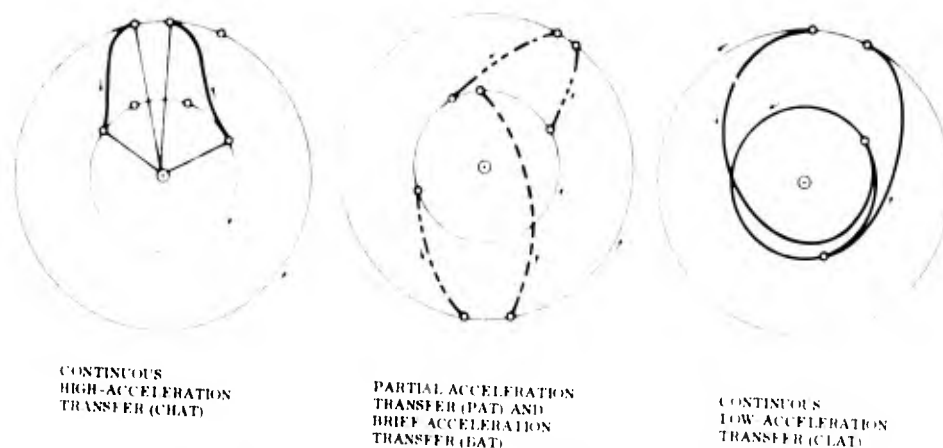


Figure 14. Interorbital transfer profiles.

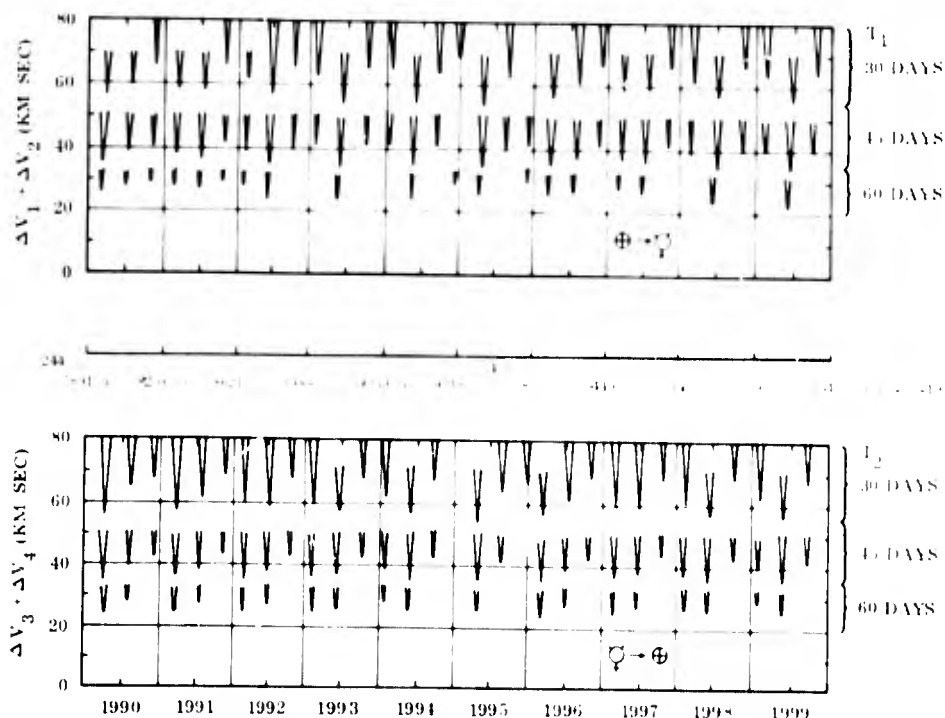


Figure 15. Impulse requirements for fast Mercury missions.

date. Earth departure is from a parking orbit at 1.08 Earth radii, Mercury capture at 1.05 Mercury radii, Mars capture and departure in a circular orbit at 1.3 Mars radii, Jupiter capture in a circular orbit at 26.38 Jupiter radii, the distance of JIV (Callisto), the outermost of the Jovian moons and the only one of the major moons expected to lie outside the most intense portion of Jupiter's radiation belt. Because of greater differences in angular velocity of the planets, more launch windows are available for flights to Mercury (3 to 4 annually) and Jupiter (1 annually) than to Mars.

The departure windows to and from Mercury are very narrow; mostly 1 to 2 weeks, although some are longer, particularly for longer transfer times (90 to 120 days) not shown here. The variations in minimum velocity for a given transfer time are considerable, due to the pronounced eccentricity and high inclination of the Mercury orbit. Particularly low minima occur only about once annually and are associated with arrival near Mercury's aphelion (256° longitude).* Capture periods of 2 to 3 months are

*Which is comparatively close to the descending node at about 227° longitude.

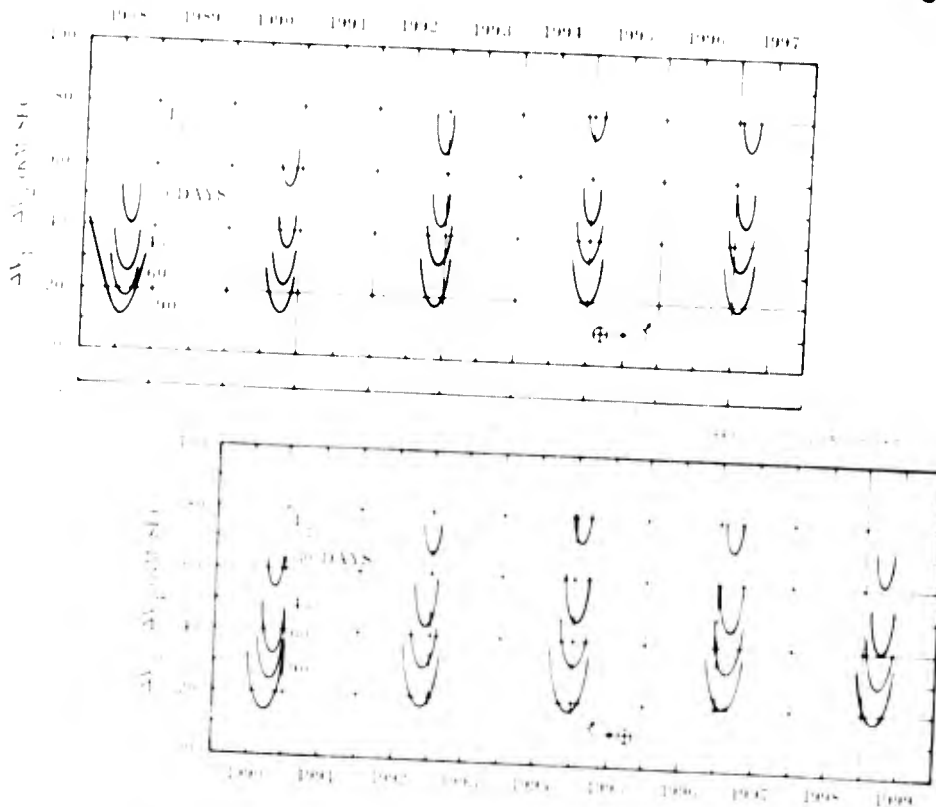


Figure 16. Impulse requirements for fast Mars missions.

readily feasible, since the average synodic period is only about 116 days. Table II shows examples of round-trip missions requiring 9 to 12 months. Case A represents short outbound and long return transfer. The latter may be less costly, in terms of velocity requirement ($\Delta v_3 + \Delta v_4$), depending on the position of Mercury whose orbital eccentricity and inclination are comparatively high. Case B exemplifies modestly fast outbound and return transfers at some 3 month's capture period. Case C represents relatively long transfers both ways. Case D shows that a comparatively low overall mission velocity can be obtained by an extended lay-over, waiting for a favorable return flight corridor (i.e., Mercury departure and Earth arrival window). Cases A, B, C show that, for Mercury missions, a capture period of as long as 2 to 3 months can be assured at a great variety of outbound and return flight profiles. Longer capture periods are never a transportation problem (Case D). The annual transfer window pattern to or from Mercury follows approximately a 7-year cycle. The chart of Figure 15 shows that, given sufficient velocity capability, a round-trip mission to Mercury could be made in a fraction of a year (5 to

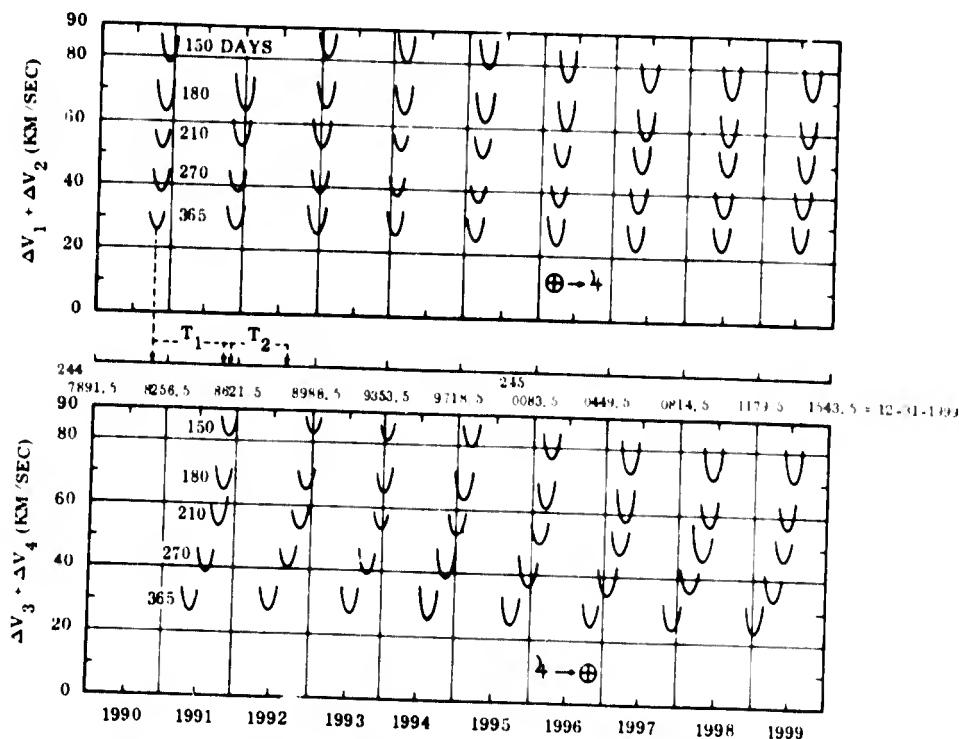


Figure 17. Impulse requirements for fast Jupiter missions.

6 months), based on 45-day transfers; or in about 3 to 4 months, based on a 30-day outbound and a 45-day return flight. The required mission velocity is of the order of 80 to 100 km/sec. For returns at optimum departure windows, a time interval between Earth and Mercury departure window of the order of 1 year (Earth) is required. In that case, the overall mission period is 1 year plus return flight time; the capture period is 1 year minus the outbound transfer time. Short mission periods are, in the case of Mercury, achieved by a combination of fast transfers and by the reduction in capture time made possible by the fast transfers.

Departure windows to Mars (Figure 16) occur at about 25-month intervals. Eccentricity of the Martian orbit, more than inclination, causes a variation in mission velocity, resulting in unfavorable mission years (UMY) when Mars arrival occurs at or near aphelion; and favorable mission years (FMY) upon arrival near the Martian perihelion. Mars is in the vicinity of its perihelion for Earth launch windows in 1971, 1986, and 2001. Thus, the 1990's do not contain a particularly favorable window. However,

Table II. Examples of Round-trip Missions to Mercury of 9 to 12 Months' Duration*

Case	Es DD	T ₁ (a)	ΔV ₁ (km/sec)	ΔV ₂ (km/sec)	T _{cpt} (d)	T ₂ (d)	ΔV ₃ (km/sec)	ΔV ₄ (km/sec)	ΣT (d)	ΣΔV (km/sec)
A	4/3-4/12 '82	80	7.8	9.75	~ 75	180	12.6	9.71	335	39.86
B	2/23-3/5 '84	80	7.8	12.6	~ 70	90	11.77	6.13	240	37.79
C	5/3-5/19 '85	110	7.35	9.75	~ 80	180	9.75	10.94	370	37.79
D	5/18-5/28 '86	80	8.15	9.75	~ 170	90	9.75	8.49	340	36.14

*Departure and arrival at 1.1 Earth radii and 1.1 Mercury radii circular satellite orbits. Es DD = Earth Departure Date; T_{cpt} = Capture Period.

conditions are relatively more favorable at the beginning and the end of the 1990's. Mars missions tend to involve long capture periods, unless a fast outbound transfer is followed by a short capture period and a longer return flight of the type No. 5, Figure 9 (but in reverse, i.e., from outer to inner orbit). A marginal propulsion capability offers only two basic alternatives. The first alternative consists of a No. 1 or No. 7 type transfer orbit (cf. Figure 13) of 160 to 190 days flight time, followed by a short (10- to 40-day) capture period and a long (220- to 250-day) return flight of the type No. 5 (but in reverse, from outer to inner orbit). The outbound velocity requirement lies between 7 and 10 km/sec; the return requirement, with capture in circular orbit at 1.1 Earth radii, lies between 14 and 20 km/sec—of which between 7 and 14 km/sec are for the Earth capture maneuver (Δv_4) which varies more strongly between FMY and UMY missions than any of the other maneuvers. The other alternative consists of flying a synodic mission; i.e., transfer during one favorable corridor, hold over in capture mode until the next launch window to Earth opens up, using a favorable corridor for return. This mission lasts approximately 750 days (25 months) plus return transfer time, including a capture period of 750 days minus outbound transfer time. Very fast, i.e., hyperbolic outbound transfers, permit longer capture periods (3 to 4 months) than the first of the above mentioned alternatives, if the return trip follows a No. 5 orbit section. Very fast transfers both ways provide capture periods of 30 to 60 days, comparable to those obtained with the first alternative, but at a significantly shorter overall mission time.

Launch windows to and from Jupiter recur in 13-month intervals. Jupiter capture periods of 2 to 6 months are feasible. The marked variation of the minimum velocity Jupiter-Earth departure date with transfer time will be noted in Figure 17. To a lesser degree this is also found for Mars return flights. The reason is that very fast inbound transfers are of the type T.O. 1 or T.O. 4, Figure 9 (in reverse); whereas, the slower transfers are of the type T.O. 3 (in reverse). Because they require longer flight times, earlier departure dates are required. This is shown in Figure 18. For this reason, outbound transfers to Jupiter tend to be longer, inbound transfers shorter, if capture periods are to be limited to the order of 1 to 3 months. For Mars, the reverse is true as pointed out before. Transfer velocities to Jupiter also show a cyclic variation, though less pronounced as for Mercury or for Mars. Transfer conditions are most favorable when the spacecraft

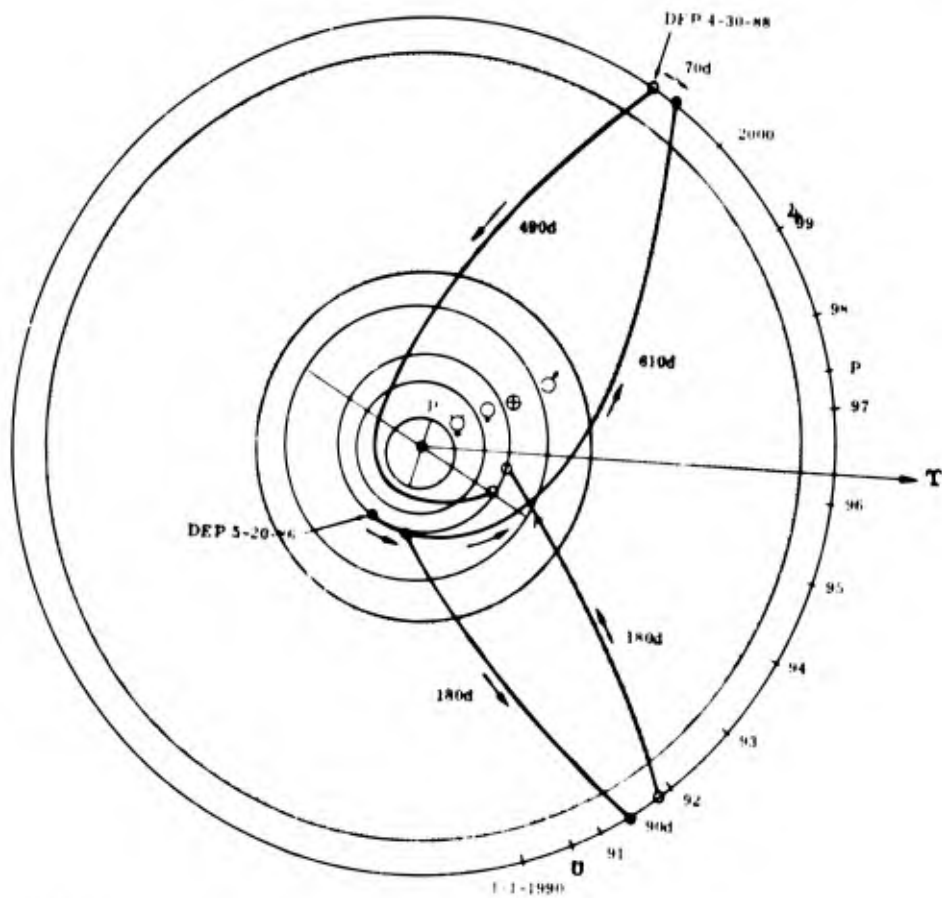


Figure 18. Hyperbolic and fast elliptic round-trip missions to Jupiter.

meets Jupiter near the perihelion (i.e., at 1975, 1987, and 1999). Fast transfers either way do not have a significant effect on the capture period. But, of course, they reduce significantly the overall mission period to that distant planet.

Velocity requirements versus time are compared for one-way missions in Figure 19. It is seen that, for a given one-way mission velocity $\Delta v_1 + \Delta v_2$, Mercury can be reached in about the same time as Mars, Venus in about half the time, while the transfer period to Jupiter is about 6 times as long. Conversely, a 150-day transfer requires 7 to 10 times as much velocity to Jupiter as to Mars. This result verifies the conclusion reached by means of simplified calculations (Figure 13). Comparisons of round-trip missions are more conditional, because various combinations of outbound transfer time (T_1) and return transfer times (T_2) can be used. Only

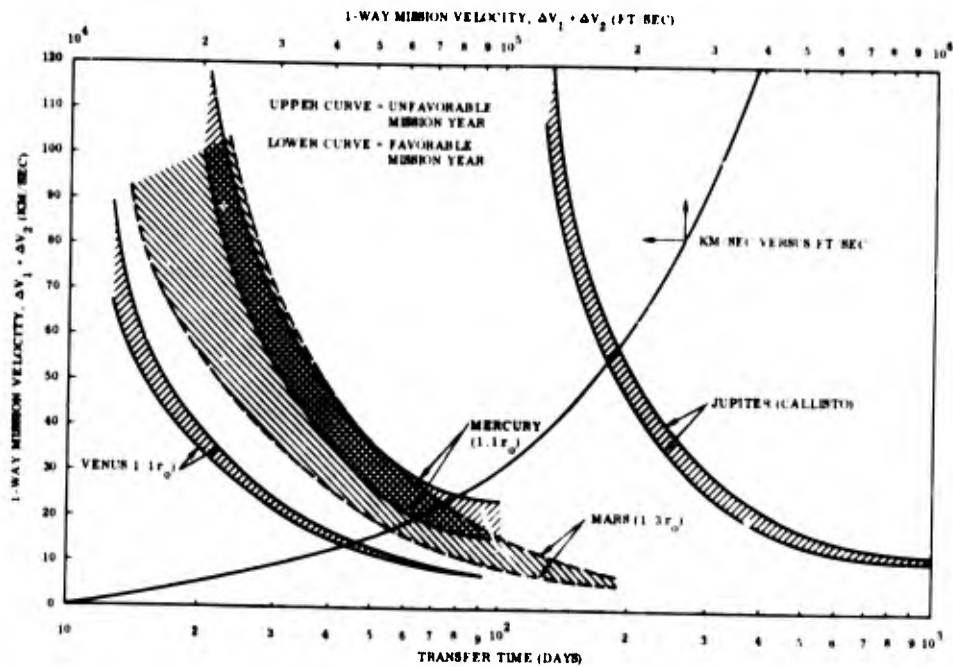


Figure 19. Comparison of one-way transfers.

extremely fast (i.e., hyperbolic) transfers, such as 1' to 2' and 3' to 4' in Figure 20 (a) permit equal transfer times both ways at their respective velocity minimum (lowest point in constant transfer time curve). Figures 10 and 11 show that, for an elliptic transfer orbit No. 1, the transfer time (days) becomes increasingly larger than the transfer angle η_1 . Since the Earth moves about 1° daily, the transfer time equals approximately the angle covered by Earth; this means Earth is ahead of Venus or Mars upon arrival at the target planet. Thus, if the same transfer time is to apply for the return, one has two alternatives. The first alternative is to either leave Earth or the target planet at an off-minimum point of the respective constant-transfer-time curve. Thereby the transfer time can be equal in both directions, but at the penalty of higher than the least possible velocity for the particular transfer time. The other alternative is to depart after a short stay time and follow a long transfer path which "undershoots" the Earth orbit when returning from Mars [3-4 in Figure 20 (a), (b)] or which "overshoots" the Earth orbit when returning from Venus [3-4, Figure 20 (b)]. Therefore, to the extent to which hyperbolic transfer orbits are involved, equal transfer times to and from Mars can be combined with brief capture periods at the planet. This applies roughly to transfer times of 50 days or less. For longer transfer times

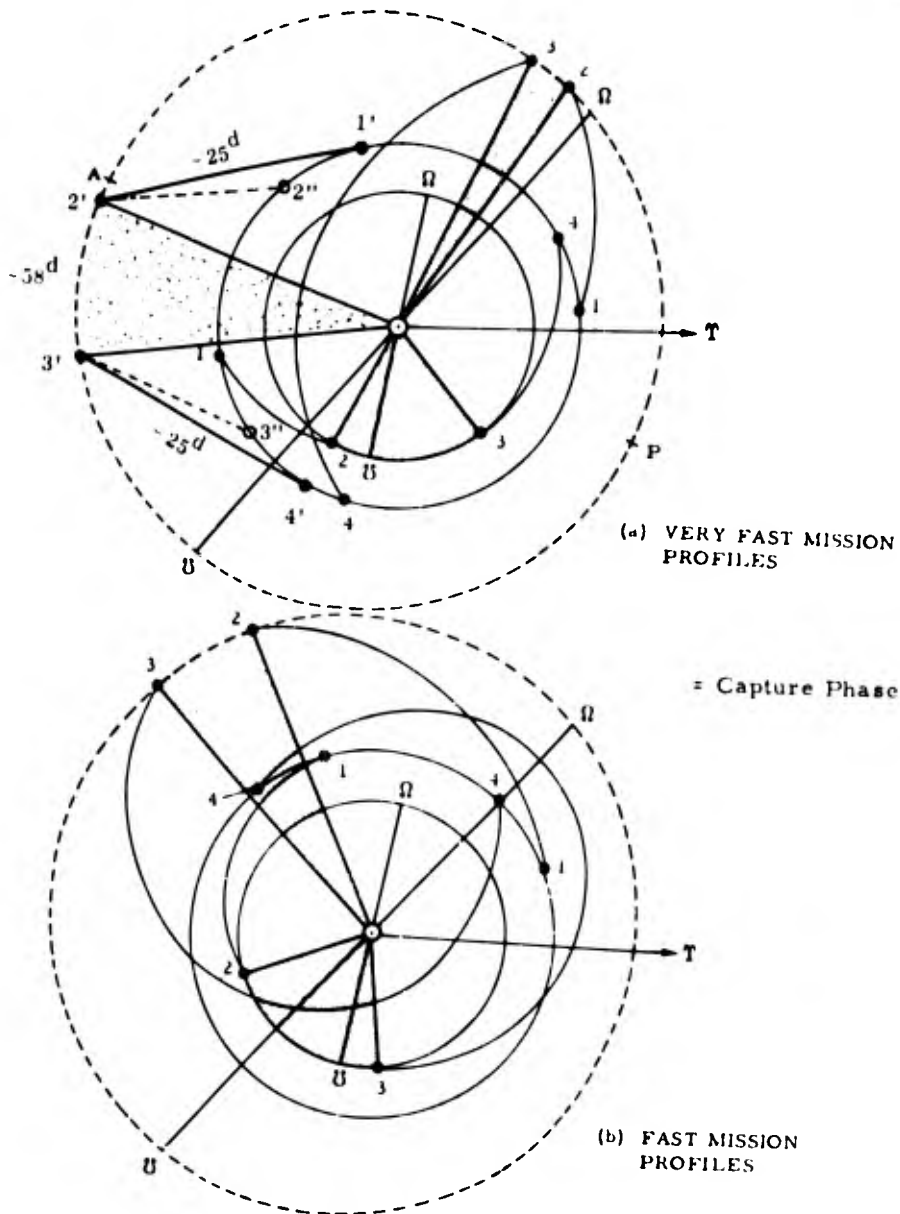


Figure 20. Very fast and fast mission profiles to Venus and Mars.

the overall mission period increases rapidly, either because a longer return path of the type No. 5 must be flown or because of the need to wait for the next launch window.

Because of the great distance of Jupiter from Earth, even hyperbolic transfer orbits of the type T.O. 10 cannot achieve a

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sufficient lead ahead of Earth at Jupiter arrival to permit a return with the same transfer time after a brief capture period. This can be deduced from Figure 12. T.O. 10 (the solid line, T.O. 1 beyond $e = 1$), with an eccentricity $e = 6$, shows a transfer time of 0.86 years (about 130 days) and a transfer angle of about 85° , meaning that, at Jupiter arrival, Earth leads by about 45° ; and when Earth leads, either a long return transfer orbit must be used when brief capture period is desired, or a waiting period to the next favorable return window must be interspersed. This waiting period is seen in Figure 17 to be of the order of 6 months.

From the data and discussions presented above, it follows that, for a velocity capability of 40 km/sec, round-trip mission periods to Mercury lie between 8 and 10 months, allowing for capture periods up to about 3 months; for 80 km/sec, between 5 and 7 months; and for 120 km/sec between 2 and 3 months. For Mars missions, the same velocity capabilities result in round-trip mission periods of 6 to 10 months, 3 to 6 months, and 2 to 4 months, respectively. For flights to Jupiter, 40 km/sec correspond to a round-trip mission period of 900 to 1000 days, 80 km/sec to 500 to 550 days; whereas 1-year round-trip missions require a velocity capability of the order of 120 km/sec.

6.2 Partial Acceleration Transfer (PAT)

Partial acceleration transfer paths involve a powered flight mode over a more or less large section of the transfer route at the two terminal portions (departure and arrival) with an intermediate coast period.

Equation (2) previously stated that, for a given interplanetary transfer, the planetocentric departure or arrival velocity is determined by the hyperbolic excess velocity v_∞ and the parabolic velocity at the planetocentric distance r where the maneuver takes place. The equation applies to impulsive or brief acceleration maneuvers of such short duration that the distance r is virtually constant during powered flight. In a nonimpulsive maneuver, the thrust acceleration is reduced to the point where the distance may change significantly during propulsion. This is demonstrated in Figures 21 through 23 where the planetocentric velocity of the vehicle (in units of the circular velocity in its initial parking orbit, $\sqrt{K/r_0}$) is plotted as function of planetocentric distance (in units

TANGENTIAL LOW-THRUST DEPARTURE MANEUVERS

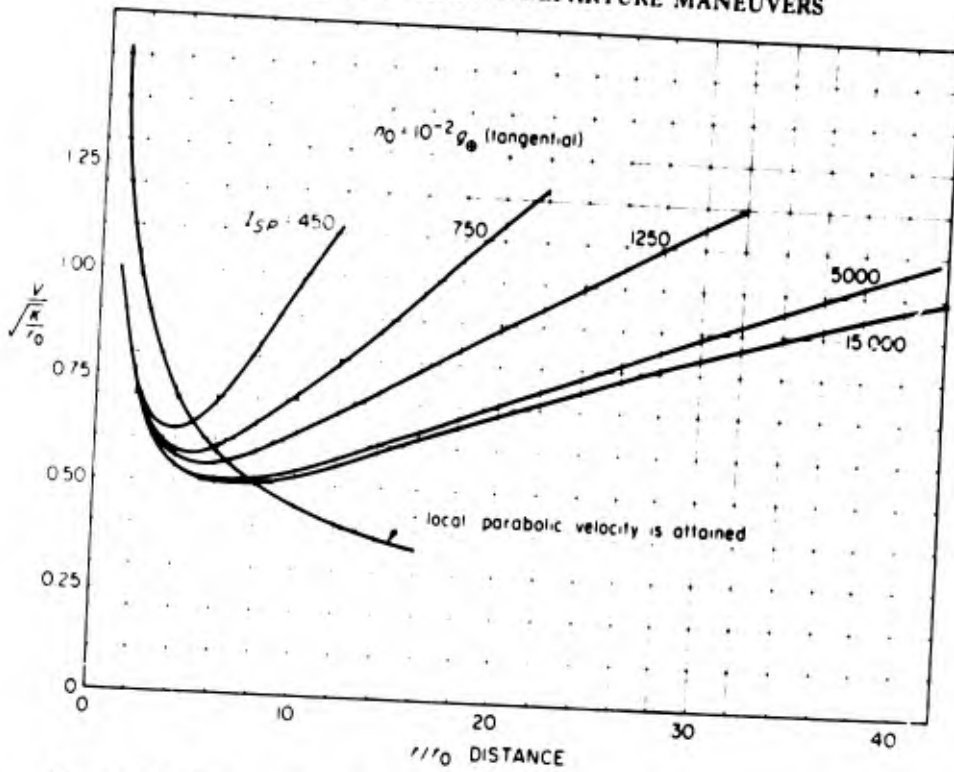


Figure 21. Path velocity vs. distance for $n_0 = 10^{-2} g_0$ (tangential).

of its original circular orbit distance r_0 at initiation of powered flight). Thrust orientation is tangential to instantaneous flight direction; thrust magnitude is constant (i.e., thrust acceleration increases). Specific impulse is used as parameter; the value $I_{sp} = \infty$ in Figure 23 signifies constant thrust and constant acceleration. The dash line indicates the local parabolic velocity vs. distance. The intersection point of dashed and solid line marks the distance at which the vehicle has reached local parabolic velocity. The initial thrust acceleration η_0 is given in Earth g units. The initial parking orbit is close to the surface ($r_0^* = 1.05$ Earth radii). The curves are valid for departure from any circular parking orbit about any other planet, if Earth g is replaced by the local g as unit. It is seen that parabolic speed is attained at distances which vary greatly as function of initial acceleration and specific impulse (the higher I_{sp} , the slower the increase in thrust acceleration with time). Because conditions change continuously during the power-on period, the flight path is computer-determined by stepwise integration of the differential

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TANGENTIAL LOW-THRUST DEPARTURE MANEUVERS

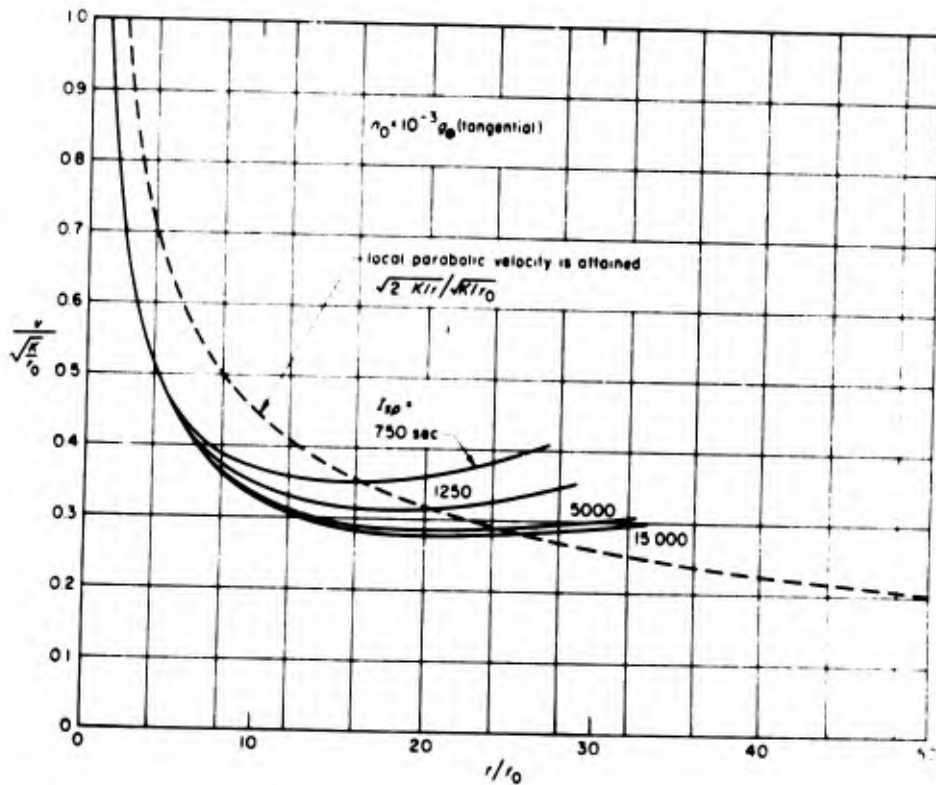
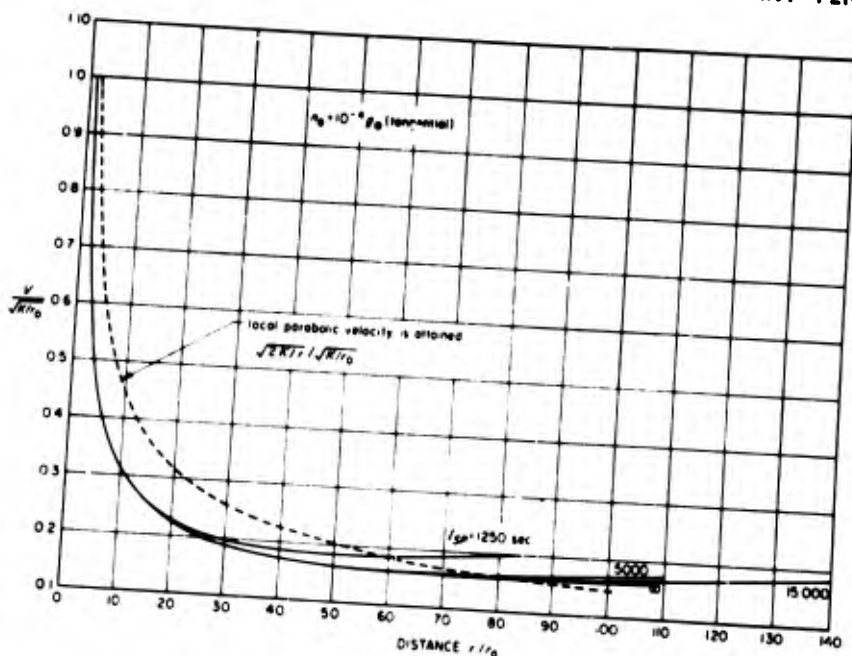


Figure 22. Path velocity vs. distance for $n_0 = 10^{-3} g_0 = 1000 \mu g$ (tangential).

equations of powered flight. The computation is extended beyond local parabolic speed (at which point $v_{\infty} = 0$) to the desired value of v_{∞} (or v_{∞}^* in units of Earth-Mean-Orbital-Speed, EMOS). Figures 24 and 25 show the powered flight time t and mass ratio μ (which includes the effect of gravitational losses) versus v_{∞}^* for Earth departure at different specific impulses and for initial thrust accelerations of 10^{-2} and $10^{-3} g$. Again, acceleration is by tangentially oriented constant thrust, starting from a circular orbit at $y_0 = 325$ -km altitude. The initial acceleration is given as thrust (F) to weight (W_0) ratio at y_0 in local g units.

Earth departure is only the first of four major maneuvers involved in a one-planet round-trip mission with capture at destination. In order to keep the overall mass ratio for the round-trip



LOW-THRUST SPACE FLIGHT

Figure 23. Path velocity vs. distance for $n_0 = 10^{-4} g_0 = 100 \mu g$ (tangential).

mission within the order of about 10, the mass ratio for the Earth departure maneuver should be about 1.5 to 2. This limits specific impulses under 2000 sec to comparatively very low v_∞^* values.

In order to render Figures 24 and 25 more meaningful, it is necessary to relate v_∞^* to heliocentric transfer times. Transfers of 30 and 60 days to Venus (relatively the planet most readily accessible) involve hyperbolic excess velocities of about 0.65 and about 0.35 EMOS, respectively, at each terminal. A 60-day transfer to Mars requires, at Earth departure, hyperbolic excess velocities of about 0.35 in favorable mission years (FMY) and 0.59 in unfavorable years (UMY); at Mars arrival, the corresponding values are 0.35 and 0.64. Mars to Earth values depend, of course, on the capture period. The following little table shows typical values:

	T_1	$V_{\infty,1}^*$	$V_{\infty,2}^*$	T_{cpt}	T_2	$V_{\infty,3}^*$	$V_{\infty,4}^*$
FMY	60	0.349	0.349	10	60	0.603	0.421
				30	60	0.753	0.563
	90	0.201	0.240	10	90	0.653	0.467
UMY	60	0.594	0.641	30	90	0.753	0.563
				10	120	0.724	0.588

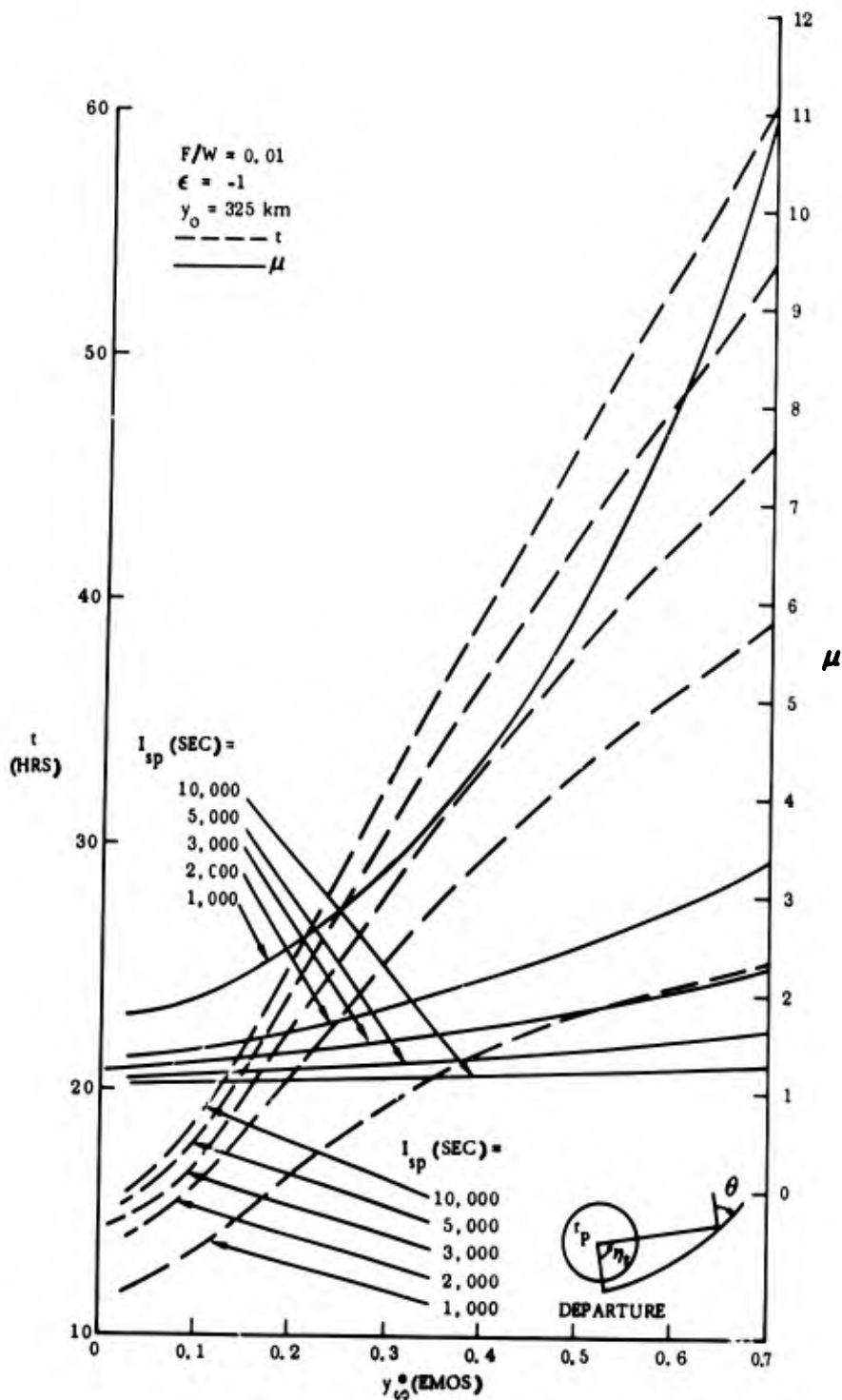


Figure 24. Earth departure: mass ratio μ and powered flight time vs. hyperbolic excess velocity for different specific impulses.

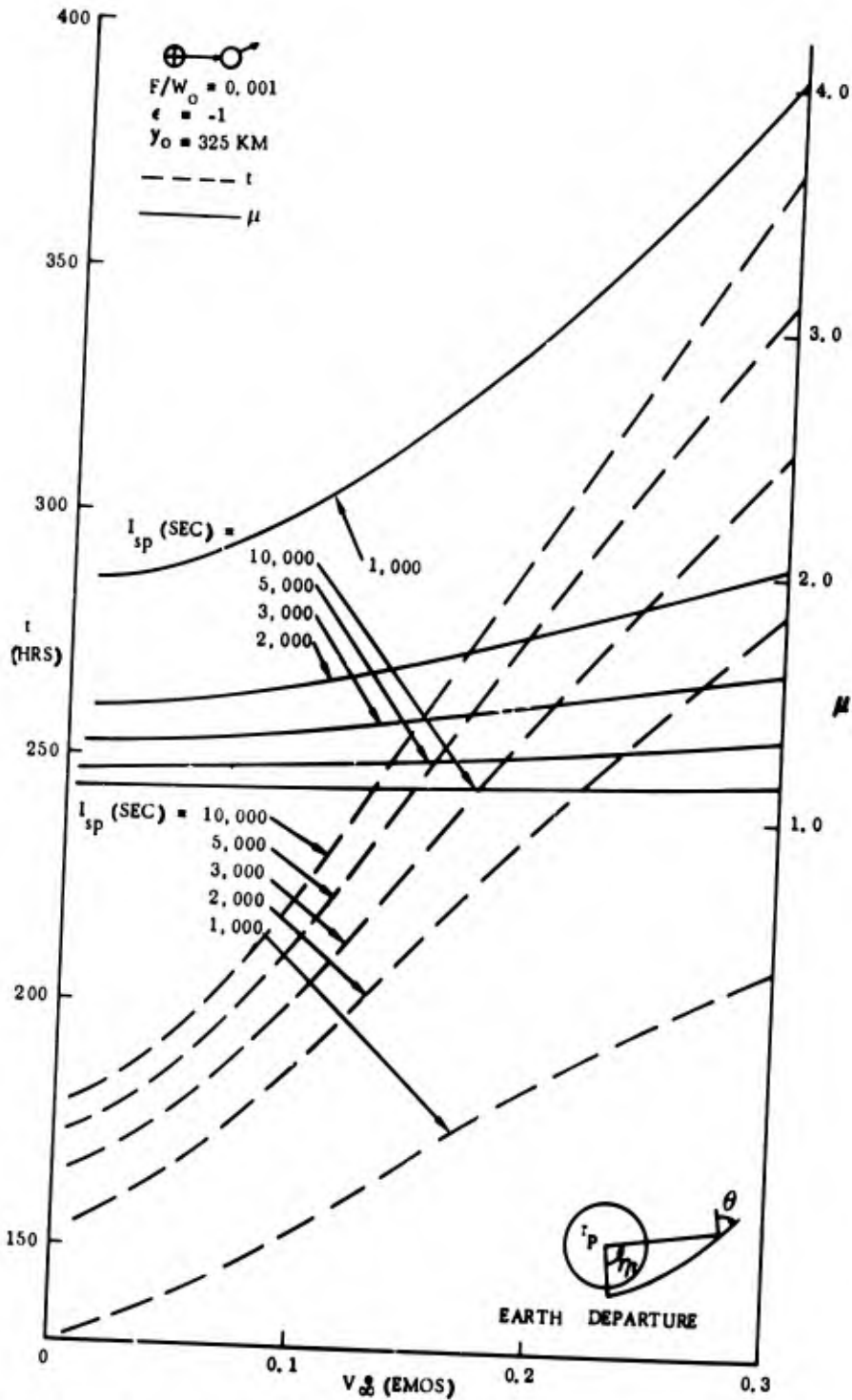


Figure 25. Earth departure: mass ratio μ and powered flight time vs. hyperbolic excess velocity for different specific impulses.

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Values for Mercury missions are of similar order as those to Mars. For Jupiter, using transfer orbit No. 1 ($e < 1$) and No. 10 ($e > 1$), the mean transfer periods to Jupiter are 550, 405, 234, 164, and 124 days for $e = 0.8, 1.0, 2, 4, 6$, respectively. The associated mean values of v_{∞}^* are:

$$V_{\infty,1}^* = 0.33, 0.41, 0.72, 1.24, 1.66; \text{ and } V_{\infty,2}^* = 0.394, 0.592, 1.14, 1.84, \text{ and } 2.24.$$

6.3 Powered Transfer

Into this group belong the previously mentioned Category I (CHAT) and Category IV (CLAT). They are distinguished from the partially powered transfer by the absence of any coast period between the accelerating (departure) and decelerating (arrival phase). Therefore, the difference between the partially powered transfer and the powered transfer, whether of high or of low acceleration, is a matter of degree. Low-acceleration powered transfer is characteristic of ion propulsion. For high-acceleration ($\geq 10^{-2}$ g), representative data are presented in Table III. The transfer times are based on near-radial transfer at inferior conjunction or at opposition, respectively, of the target planet with respect to Earth; and on continuous acceleration to the midpoint, followed by continuous deceleration in the second half of the transfer path. The maximum velocity refers to the product of thrust acceleration and time and does not represent the vehicle's heliocentric velocity. The mass ratio $\mu_{1,2} = \mu_1\mu_2$ is based on acceleration to maximum velocity (μ_1) and deceleration by the same amount (μ_2) at the specific impulse shown on top of the table for the particular acceleration. Correspondingly, $\mu_{1-4} = \mu^2_{12}$ is the mass ratio for the roundtrip, assuming the same acceleration/deceleration sequence on the return flight. The latter means holdover until the next radial transfer window occurs; or return along a longer transfer time, in which case a coast period would be interspersed if the same acceleration/deceleration profile is used. The product $n(\mu-1) = n(\mu_{1-4} - 1)$ is a performance parameter which will be used later in the comparison of propulsion systems.

ENVIRONMENT

Three important external environments must be taken into consideration: thermal, meteoroidal, and (corpuscular) radiation. A fourth item of concern is the (intravehicular) bioenvironment.

Table III. Representative Data on Continuous High-Acceleration Transfers to and from Five Planets, Assuming Near-Radial Transfer at Inferior Conjunction or Opposition

Earth ⇌	Constant Acceleration/ Deceleration: 10 ⁻¹ g		10 ⁻² g		10 ⁻¹ g; I _{sp} = 10 ⁵ sec 10 ⁻² g; I _{sp} = 3.16 · 10 ⁴ sec		
	Transfer Time (days)	Max. Velocity (km/sec)	Transfer Time (days)	Max. Velocity (km/sec)	μ _{1,2}	μ ₁₋₄	n (μ-1)
⇌ Mercury	~ 5.4	~ 230	~ 17.1	~ 73	1.254	1.57	0.057
⇌ Venus	~ 3.2	~ 140	~ 10.3	~ 44	1.145	1.31	0.031
⇌ Mars	~ 4.8	~ 200	~ 14.9	~ 63	1.222	1.49	0.049
⇌ Jupiter	~ 40	~ 1860	~ 127	~ 590	4.1 (1.8)	41 (3.24)	4.0 (0.024)

μ_{1,2} = product of mass ratios for acceleration and deceleration, oneway.
 μ₁₋₄ = product of mass ratios for acceleration/deceleration round-trip with equal distances for outbound and return.
 n = thrust/weight ratio (constant acceleration, i.e., decreasing thrust).
 () = these figures for Jupiter transfers apply to n = 10⁻³ at I_{sp} = 10⁶ sec.

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Although these environments warrant extensive attention at slow or fast transfers, we are concerned subsequently primarily with the effects of hyperbolic transfers on the environmental problems encountered by ship and crew.

7.1 Thermal Environment

The thermal environment is dominated by solar radiation, at least beyond 2 to 3 radii distance from any planet. The Sun's radiation constant is $S_E = 1.36 \text{ kw/m}^2$ at 1 astronomical unit (a.u.) distance and varies with the square of heliocentric distance. The product of solar constant and time represents the thermal energy offered by the Sun to the spacecraft in the course of its mission. The vehicle readily rejects a large portion of this energy merely by the reflection of incident sunlight. However, some energy is absorbed. The amount increases with time and proximity to the Sun. The greater the required heat rejection rate, the more elaborate becomes the required thermal protection system. Intense solar radiation flux, as for missions to Mercury, therefore imposes particular problems which can be alleviated by reducing the exposure time. The thermal energy offered by the Sun is

$$Q_0 = S_E \int_{t_x}^R \frac{1}{R^2} dR dt = \int_{t_x}^R S_R dt \quad (4)$$

where R = heliocentric distance and t_x = exposure time, the thermal input into the spacecraft is

$$Q_{in} = (1-r) Q_0 = \frac{S}{t_{ins}} \int_{T_{int}}^{T_{ext}} \int_{t_x} k dT dt \quad (5)$$

where r = reflectivity, S = total surface area, T_{int} and T_{ext} are the interior and exterior wall surface temperatures, respectively, and k = thermal conductivity of the wall. It can be assumed that T_{ext} is equal to the equilibrium temperature of the wall, because insulation material will slow down the heat flux across the wall and because of the gradual change in heliocentric distance even for very fast transfers. This equilibrium temperature is defined by the relation

$$T_{eq} = T_{ext} + \left[\frac{\alpha_o}{\epsilon_o} \frac{S}{S} \frac{S_E}{\sigma R^2} \right]^{1/4} \quad (6)$$

where α_o , ϵ_o are the absorptivity and emissivity, respectively, of

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the outer surface coating material; S_a , S_e are the effective absorbing and emitting surface areas; and α is the Stephan-Boltzmann constant.

Figure 26 shows the result of integrating Eq. (4) for transfer to and from the planets Mercury to Jupiter.⁶ The chart shows the integral radiative heat flux (IRHF) as function of transfer time

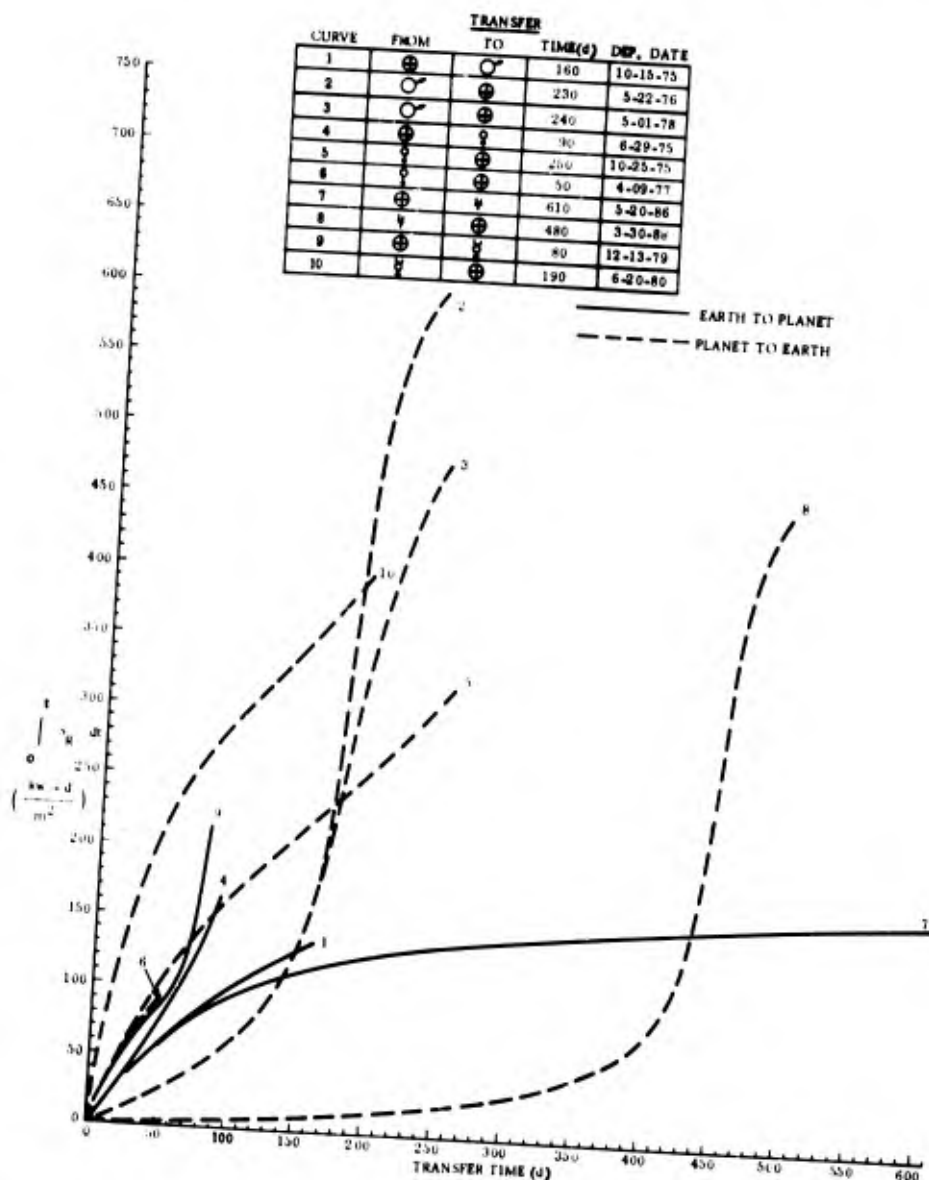


Figure 26. Time integral of solar thermal radiation flux to space ship during transfer to and from target planet for the transfers indicated.

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for outbound and return transfers separately. It is seen that the principal factors determining the IRHF characteristics of a transfer are not so much the heliocentric distances of the target planets but rather the transfer time and the perihelion distances. The effect of transfer time on the amount of radiative energy offered is clearly apparent.

Equation (5) shows that the amount of thermal energy soaked up by the spacecraft interior, Q_{in} (for given values of S , t_{ins} and k) is a direct function of exposure time t_x and of the outer wall equilibrium temperature, t_{ext} . The latter, in turn, is a function of the thermo-optical characteristics (α_0/ϵ_0) of the surface coating, of the effective vehicle aspect ratio (S_a/S_e) and, most importantly, of the local solar constant, $S_R = S_0/R^2$. The latter is the result of destination and flight profile. The effective aspect ratio can be optimized (S_a/S_e minimized) by appropriate vehicle configuration, by adjustable shadow shields and/or by vehicle orientation control. For continuously powered vehicles, thermal orientation requirements are likely to interfere with thrust orientation requirements. The α/ϵ ratio is an important parameter, because a very small value significantly reduces the temperature gradient $T_{ext} - T_{int}$ across the wall; hence Q_{in} . Surfaces such as carbon black and black laquers absorb and emit all wavelengths about equally, yielding $\alpha/\epsilon \sim 1$. About the lowest presently attainable value is $\alpha/\epsilon = 0.2$, using zinc oxide, a coating which is highly reflective to solar radiation wavelengths and highly emissive at long wavelength thermal surface radiation. Reduction of α/ϵ to still lower values is the subject of considerable material research efforts, but has not been achieved so far. Figure 27 shows the equilibrium wall temperature of rotating spheres, nonrotating spheres and planar surfaces of aspect ratio S_a/S_e of 0.1 and 1.0 normal to the solar radiation as function of α/ϵ for the mean distances of Mercury, Earth, and Jupiter. It is seen that α/ϵ has considerable influence and that, for vehicles carrying cryogenic fluids a reduction of this ratio below 0.2 would be very helpful. Among the advanced propulsion systems considered here (cf. Section 8), the gaseous core reactor carries a cryogenic fluid (hydrogen), the controlled thermonuclear reactor carries deuterium (2H), and the helium isotope (3He)*. The electric and the nuclear pulse drive use solid or easily solidifiable propellants (e.g., mercury for the electric drive). The thermo-optical characteristics of coating

*In lieu of 3He , the regular 4He is shown in the figure.

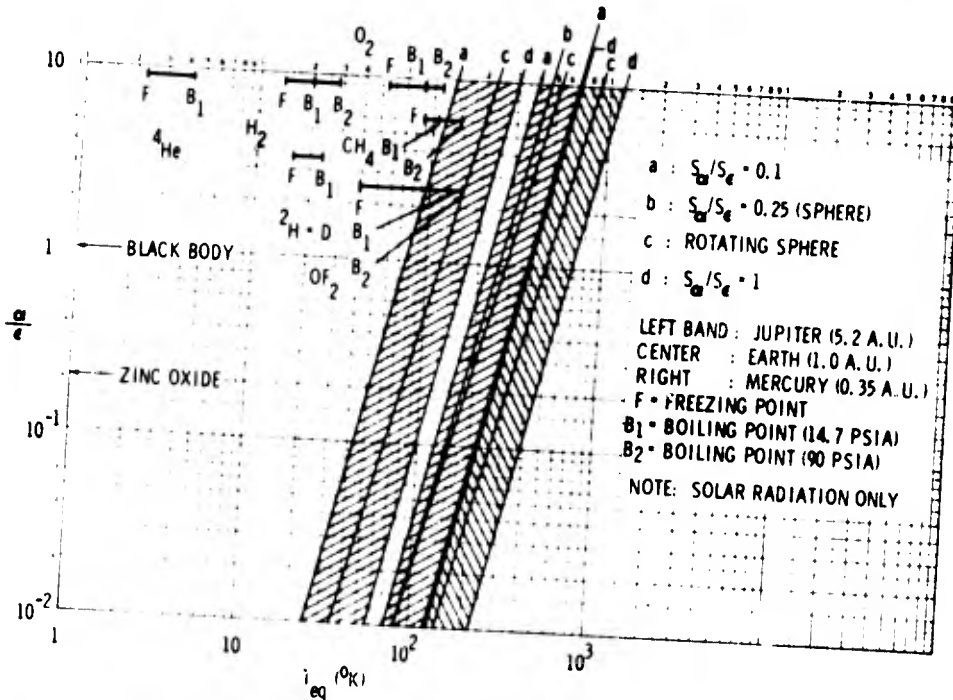


Figure 27. Equilibrium temperature of surface as function of α/ϵ and surface area aspect ratio.

materials might deteriorate (α/ϵ increasing) over long exposure times to solar ultraviolet and gamma radiation and to micrometeoroid or dust particle impacts, thereby making Q_{in} also an indirect function of exposure time.

For the storage of heat sensitive fluids on board the HISV, the following methods can be used: evaporation, use of superinsulation, shadow shields, and refrigeration/reliquefaction (RR); or combinations thereof. Figure 28 shows the approximate applicability of these methods in $S_{av} - t$ plane, where t is the storage time and

$$S_{av} = \frac{1}{t} \int_0^t S_R dt \quad (7)$$

The boundaries indicated in Figure 28 relate to liquid hydrogen. Short flight times reduce the thermal protection of cryogenic fluids* to superinsulation and shadow shielding.

*These fluids may be carried by the HISV not for its propulsion system, but as propellant for secondary vehicles.

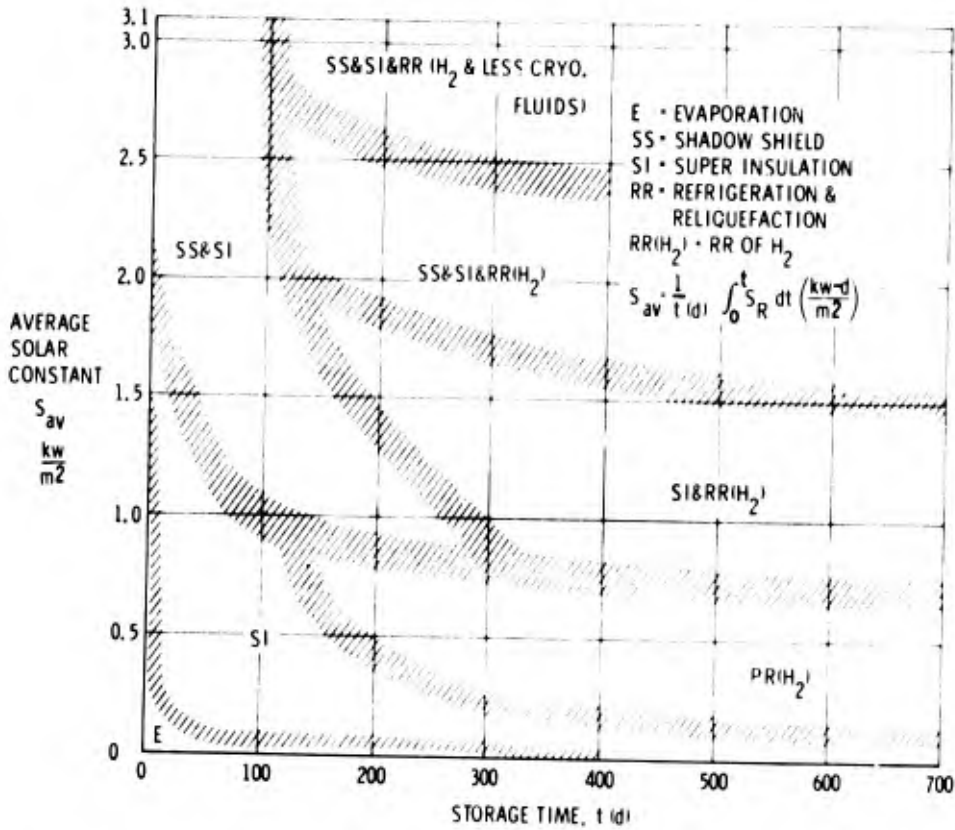


Figure 28. Methods of hydrogen storage and thermal protection in the $S_{av}-t$ plane.

Short transfer time, therefore, tends to reduce solar-thermal problems by reducing the exposure time which might increase the α/ϵ ratio; by reducing the thermal flux which must be absorbed and disposed of by the HISV; and by tending to simplify the thermal protection system. The relative importance of these tendencies depends, of course, on how much the transfer time is reduced, on the HISV propellants and propulsion system as well as on mission destination and flight profile (e.g., very close perihelion distances, say, ≈ 0.25 a.u., will constitute an enormous technological problem, even at hyperbolic flight paths of eccentricities between 5 and 10). But, if anything, hyperbolic transfers tend to reduce thermal problems rather than aggravate them.

7.2 Meteoroid Environment

Within the solar system region of interest in this paper, the two principal meteoroid danger zones appear to be the asteroid

belt and the activity sphere of Jupiter. The asteroid region extends from 2.15 to 3.65 a.u. The particles in this region are probably stony (representative density, 3.3 g/cc), based on their presumably asteroidal origin, in contrast to icy or ice-dust conglomerate particles of cometary origin whose density may be of the order of 0.5 g/cc. The Jovian activity sphere extends to a distance of 641 Jupiter radii. The assumption of a Jovian dust cloud is based primarily on the enormous gravitational power which may have enabled the giant planet to retain a cloud of primordial matter from the formative days of the solar system, perhaps adding to it during the intervening 5 billion years. No direct evidence of such a cloud has been acquired as yet and probably will not become available until the first unmanned probe reaches the planet. If the cloud consists mainly of primordial matter, the particle densities are likely to be of a similar order as those of cometary origin. However, if asteroid belts or dust belts exist farther out, for example between Jupiter and Saturn*, a "fallout" of micrometeoroids from these regions may have been captured by Jupiter, thereby adding a population of stony particles to its cloud. This is little more than speculation at this time. While keeping interplanetary debris and the Jovian dust cloud in mind, primary attention is given subsequently to the asteroid belt.

The method of appraising the effect of fast transfers so far as the meteoroid environment is concerned is presented schematically in Figure 29. The chart on top exemplifies the first step, a determination of the likely number of impacts of particles of mass m or greater per unit area and time. This number, I/AT , is a function of heliocentric distance, $f(R)$, and of the particle flux, ϕ . While I/AT is a measure of the number of particles from a certain mass upward, impacting on the spacecraft per unit area and time, ϕ resolves this impacting particle population in terms of mass. This is shown in the second graph of Figure 29.

In that graph, it is indicated that the number of particles drops less rapidly with increasing particle mass in the asteroid population than in the cometary population in interplanetary space and in the activity spheres of Jupiter and Earth. Not all impacting particles

*Just as Jupiter may have prevented the formation of a planet between Mars and Jupiter, the giant planets, Jupiter, Saturn, Uranus and Neptune, may have prevented the formation of intermediate planetary bodies between them. Pluto itself may be no more than a giant asteroid.

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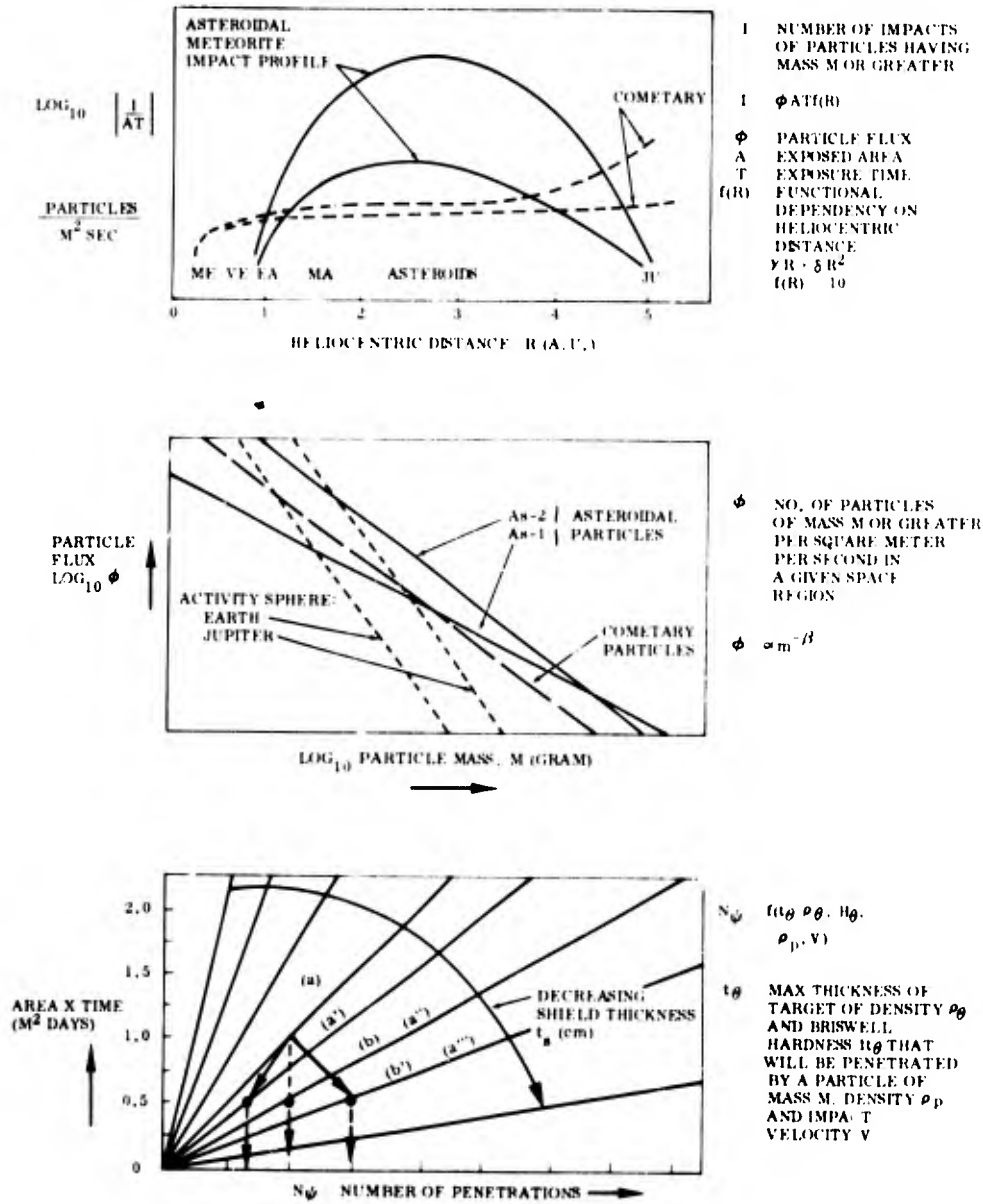


Figure 29. Methodology of determining influence of transfer time on meteoritic effects.

penetrate the walls. The number N_ψ of penetrations is, among other things, a function of particle mass and impact velocity.

N_ψ is determined in the following manner: The penetration thickness t_θ is a function of a number of parameters as explained at the bottom of Figure 29. Using a relation for the penetration

thickness in the form suggested by Herrmann and Jones', one may correlate these parameters in the form

$$t = a \rho_\theta^{\epsilon_1} \rho_p^{\epsilon_2} m^2 \ln\left(1 + \frac{\rho_p^{-\epsilon_1} \epsilon_3 v \epsilon_3}{b H_\theta}\right) \quad (8)$$

where a , b are coefficients and ϵ_1 through ϵ_3 are exponents. Their numerical values, as specified by Herrmann and Jones, are: $a = 1.119$, $b = 39.23$, $\epsilon_1 = -2/3$, $\epsilon_2 = 1/3$, $\epsilon_3 = 2$. These coefficients may or may not yield the accurate penetration thickness (i.e., they may be optimistic). What matters here is that a relationship between penetration thickness and mass can be established as function of several other parameters. By solving the relation for the particle mass m , inserting it into the relation for ϕ , and substituting ϕ in the relation for I turns I into N_ψ ; i.e., the number of penetrations (rather than impacts). The chart at the bottom of Figure 29 exemplifies the variation of N_ψ as a function of the product (area-time) for various lines of constant meteoroid shield thickness.

A method for appraising the effect of hyperbolic transfer on the number of penetrations is illustrated qualitatively in the bottom graph of Figure 29. Suppose a number of penetrations, N_ψ , are associated with shield thickness (a) at slow transfer whose area-time product is normalized as unity. Reducing the transfer time to one-half yields the product to drop to 0.5. If the impact velocity were unchanged, the shield thickness could be reduced to (b), resulting in lighter shield weight due to faster transfer. However, the impact velocity actually increases with the increasing eccentricity of the transfer path. This causes a line of constant shield thickness to rotate in a clockwise direction, such as from (b) to (b'). Thus, full advantage of the reduction in shield thickness from (a) to (b) cannot be taken, unless a higher value of N_ψ is accepted. If we stipulate that N_ψ should remain constant, or even be reduced, we must back off from (b) and increase the shield thickness. If we kept it constant, the tilting of (a) to (a') could still lead to a reduced number of penetrations. The effect of shorter exposure time outweighs that of higher impact velocity. This then, rather than reduced shield weight, would be a benefit of faster transfer. However, depending on the effect of higher impact velocity, (a) might tilt to (a''). In that case, nothing would be gained or lost by reducing the area-time product from

1.0 to 0.5; Shield thickness and N_{ψ} would remain the same, because the effect of higher impact velocity would precisely compensate that of shorter exposure time. The worst case would be one in which (a) were tilted to (a'"). In that case, the effect of higher impact velocity outweighs shorter exposure time so that faster transfer would carry the penalty of greater shield thickness (if the number of penetrations were to be held constant).

In simplified terms, the above line of thought narrows the problem to the effect of transfer time on impact velocity; and to the effect of impact velocity on shield thickness. This is simplified, because the density and consistency of the impacting particles enters into consideration, as well as the fact that different shield designs may be most weight-effective, at different impact velocity regions. But, the two above mentioned effects and the nature of the particles will no doubt be the principal influence factors. We will subsequently restrict ourselves to the asteroid belt. This, tentatively, eliminates particle density/consistency as a variable.

Figures 30 and 31 show the transfer time and the relative particle velocity for crossing the asteroid belt. Figure 32 summarizes these data in terms of time in asteroid belt and the relative velocity of HISV, and particles in asteroid belt as a function

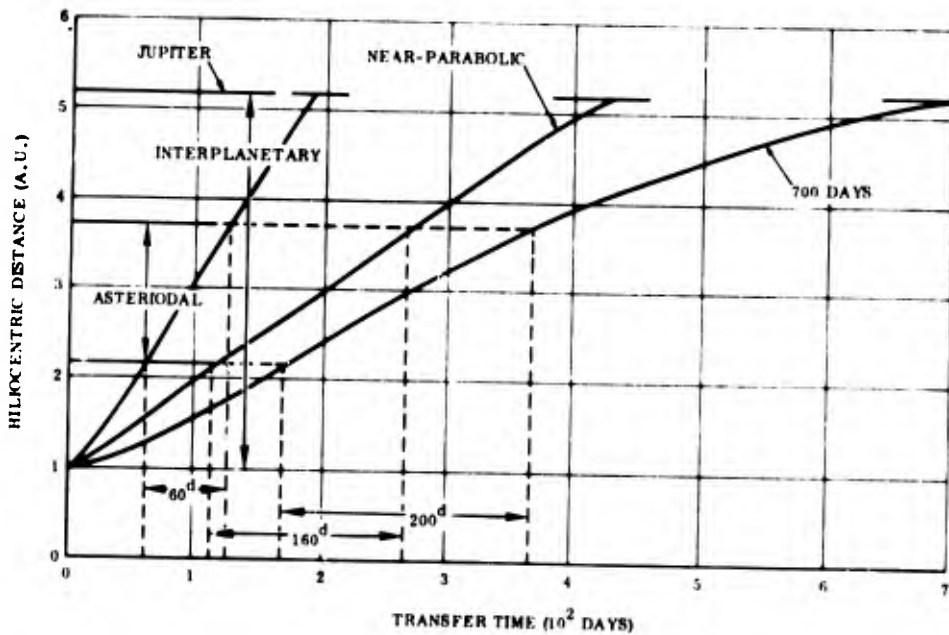


Figure 30. Transfer time through asteroid belt of Jupiter-bound spacecraft.

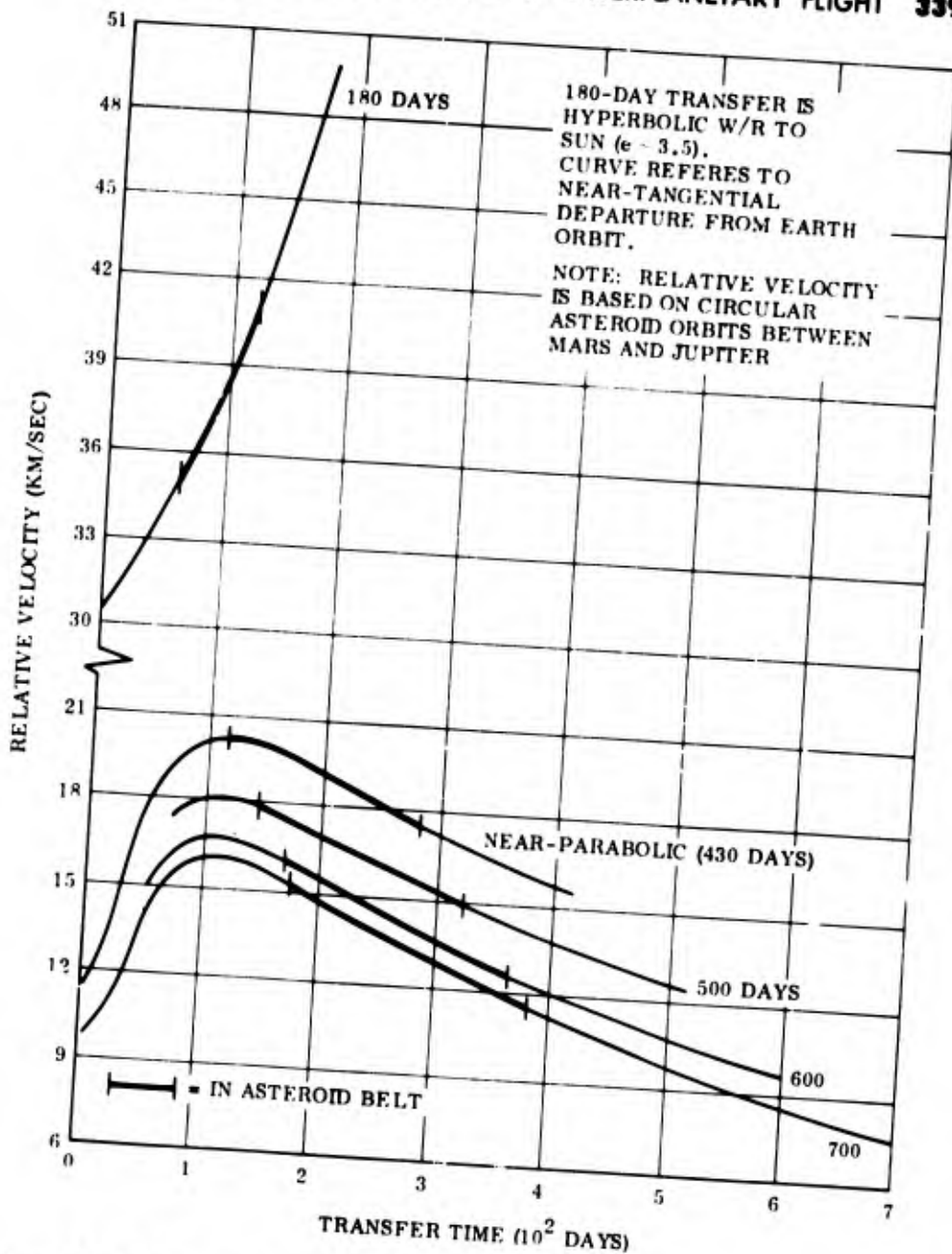


Figure 31. Relative particle velocity vs. transfer time through the asteroid belt.

of transfer time to Jupiter. In all cases, the computation of the relative velocity is based on the assumption that the meteoroid particles follow circular heliocentric orbits. This is certainly not true in all cases. Therefore, the upper and lower velocity limits

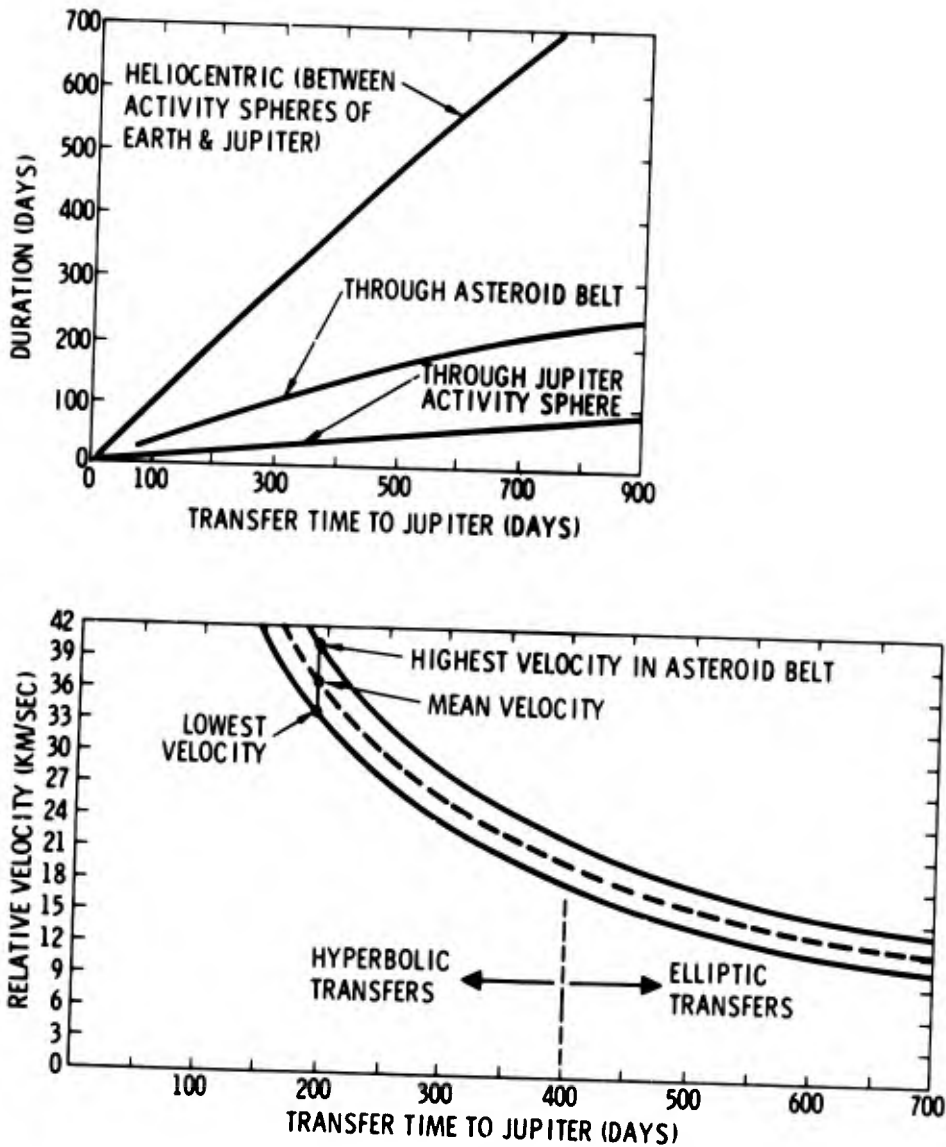


Figure 32. Transfer characteristics through asteroid belt.

will exceed, in reality, those indicated in Figure 32. Taking an arithmetic mean value, the velocity varies roughly between 42 km/sec at 55 days in the asteroid belt and 12 km/sec at 200 days.

Next we compute the particle flux $\phi = \alpha m^{-\beta}$. Flux intensity α and flux gradient β in the asteroid belt are not known from measurements. Typical values in interplanetary space between Venus and Mars $\alpha = 10^{-14}$ to 10^{-15} , $\beta = 1$ to 1.4. If the asteroid belt is the source of most of the stony meteoroids, the flux intensity

must be higher than that in interplanetary space, near Earth, and possibly near Jupiter. Typical values may range from 10^{-14} to as high as 10^{-9} . The flux gradient may range from 0.7 to 1; i.e., the decrease in particle flux with particle mass may be less or comparable to that of cometary particles in interplanetary space. Selecting $\alpha = 10^{-9}$, $\beta = 1.0$, it follows that the flux of particles of 1 g mass or more per-square-meter and second is 10^{-9} ; the number of particles of 10 g mass or greater is 10^{-10} ; and the number of particles of 10^{-6} g mass or greater is 10^{-3} per m^2 sec.

Next we will, for the sake of simplicity, set $\lambda = \delta = 0$ in the term $f(R)$ in the relation for I in Figure 29. This means we assume that the number of impacting particles of given mass or greater is the same at any distance in the solar belt. The probable inaccuracy of this assumption has no significant bearing on the present discussion. This simplification renders $\phi = I/AT$.

By inserting a relation between particle mass m and penetration thickness t_p to substitute t_p and associated parameters for m yields $I/AT = N_p = f(AT)$. Using, as examples, the equation and coefficients suggested by Herrmann and Jones and assuming a skin of aluminum sheet for the sake of simplicity ($H_T = 120 \text{ kg/mm}^2$, $\rho = 2.78 \text{ g/cm}^3$), a particle density $\rho_p = 3.3 \text{ g/cm}^3$ and an impact velocity of 14.5 km/sec, corresponding to 1.5 years (550 days) transfer time to Jupiter, Figure 33 is obtained depicting the number of penetrations versus the area-time product for different shield thicknesses.

Finally, the effect of impact velocity on shield thickness must be established. For the sake of simplicity, velocity ratio will be related to shield thickness ratio. Using the equation by Herrmann and Jones and taking the ratios obtained with it as Case I of several alternatives, it follows,

$$(I) \frac{t_{p,2}}{t_{p,1}} = \frac{\ln\left(1 + \frac{\rho_p^{2/3} \rho_\theta^{1/3} v_2^2}{39.23 H_T}\right)}{\ln\left(1 + \frac{\rho_p^{2/3} \rho_\theta^{1/3} v_1^2}{39.23 H_T}\right)} \quad (9)$$

Using $V_1 = 12 \text{ km/sec}$, the thickness ratio is plotted versus the velocity ratio as Curve I in Figure 34. It is seen that the relation by Herrmann and Jones suggests a relatively small effect of

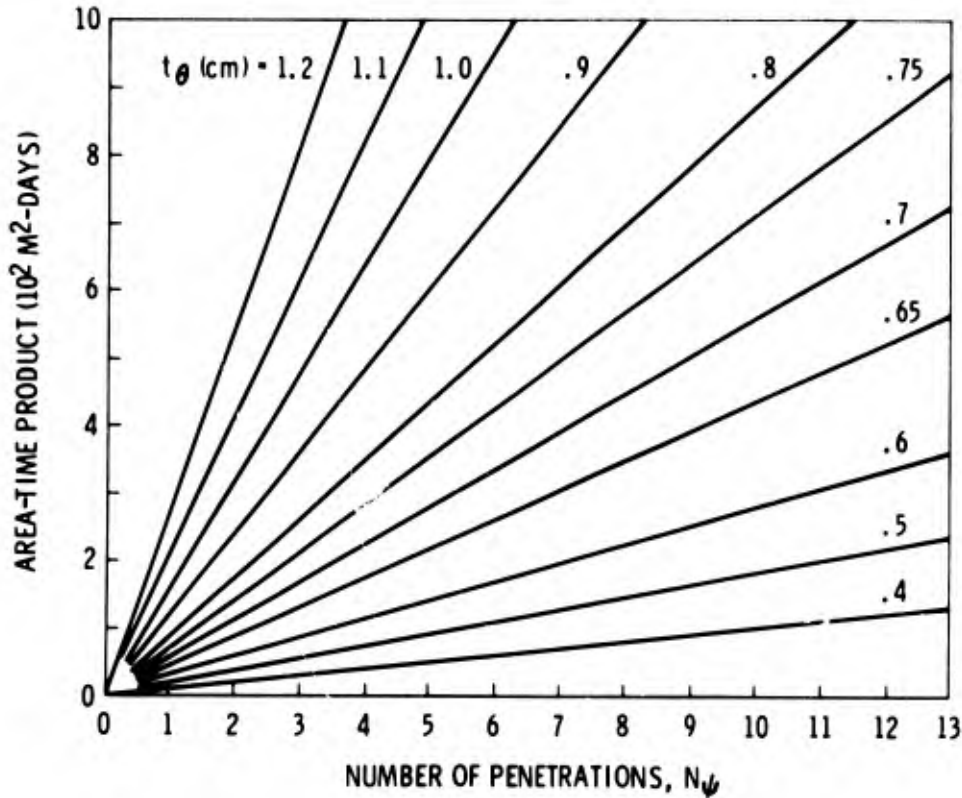


Figure 33. Number of penetrations of aluminum skin in asteroid belt for particle flux $\phi = 10^{-1} \text{ m}^{-1}$ (high density model).

velocity on shield thickness. Since this may be too optimistic, several other functional relations, not based on the Herrmann and Jones equation, are also plotted:

$$\frac{t_{\theta, 2}}{t_{\theta, 1}} = \left(\frac{V_2}{V_1} \right)^\zeta \tag{10}$$

where (II) $\zeta = 1/3$, (III) $\zeta = 2/3$, and (IV) $\zeta = 1$. The actual correlation may be represented by $\zeta = 1/3$ or $2/3$; $\zeta = 1$ and case (I) may be regarded as extremely unfavorable and favorable limits, respectively.

We are now ready to apply the methodology of estimating the effect of faster transfer on N_ψ and/or t_θ . Returning to Figure 33, we select arbitrarily $N_\psi = 3$ and $t_{\theta, 1} = 1.0 \text{ cm}$ as reference, yielding a reference area-time product of $AT = 480 \text{ m}^2 \text{ days}$ (Figure 35). Since the values in Figures 33 and 35 are based on $V = V_1 = 14.5$

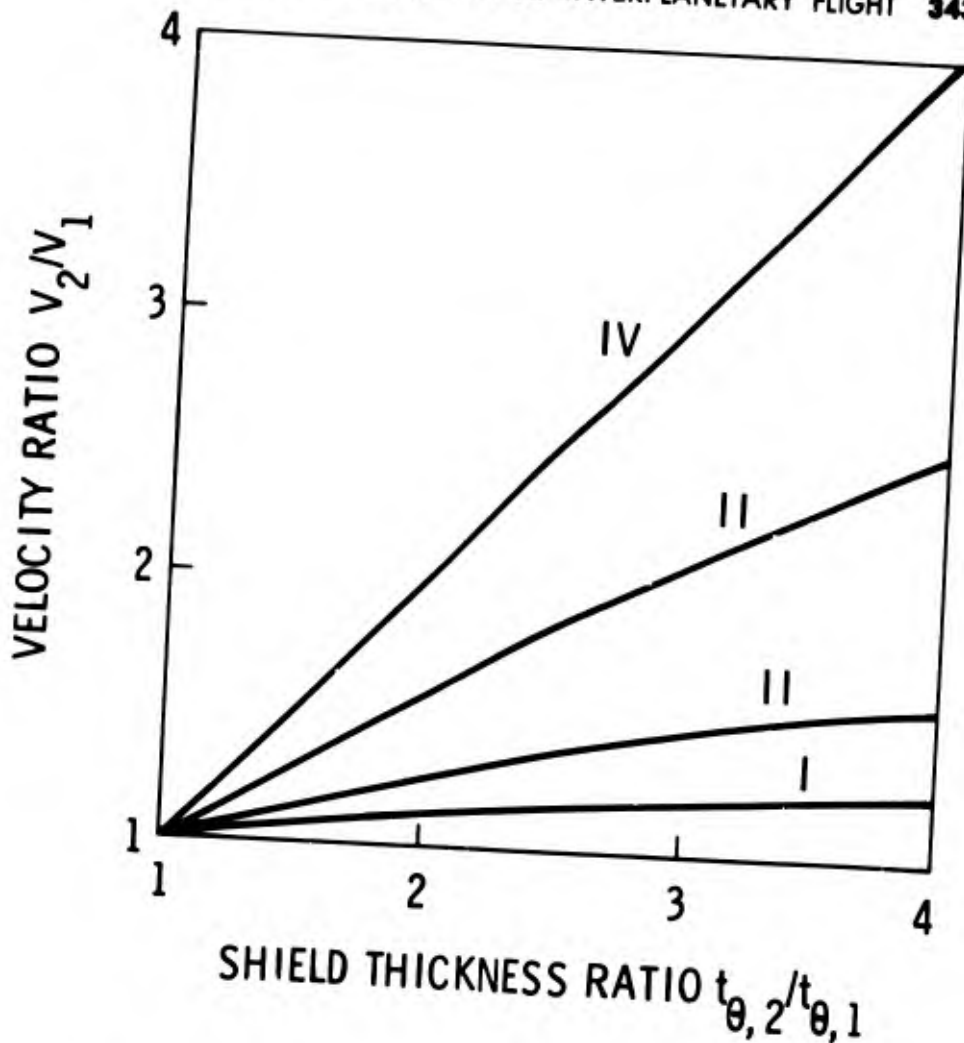


Figure 34. Velocity ratio vs. meteoroid shield thickness ratio.

km/sec, the corresponding transfer time to Jupiter is 550 days (Figure 32). Reducing the transfer time to one-half (more exactly to 270 days) doubles the mean impact velocity; hence, $V_2/V_1 = 2$ for $AT \approx 240 \text{ m}^2 \text{ days}$. If the velocity change had no effect, the wall thickness required on account of the smaller AT-product is indicated by the point 0 in Figure 35, namely, $t_{\theta,2} \sim 0.78$. For case (I), Figure 34 yields $t_{\theta,2}/t_{\theta,1} = 1.12$ for $V_2/V_1 = 2$. Thus, the effective shield thickness of $t_{\theta,1} = 1 \text{ cm}$ at V_1 becomes $t_{\theta,2} = 1/1.12 = 0.893$ for V_2 . Inserting this line, it is seen to intercept with the horizontal AT-line at point I, indicating that the reduction of exposure time outweighs the increase in velocity to such a degree that for equal wall thickness the number of penetrations is reduced from 3 to 2. Taking case (II), Figure 34 yields

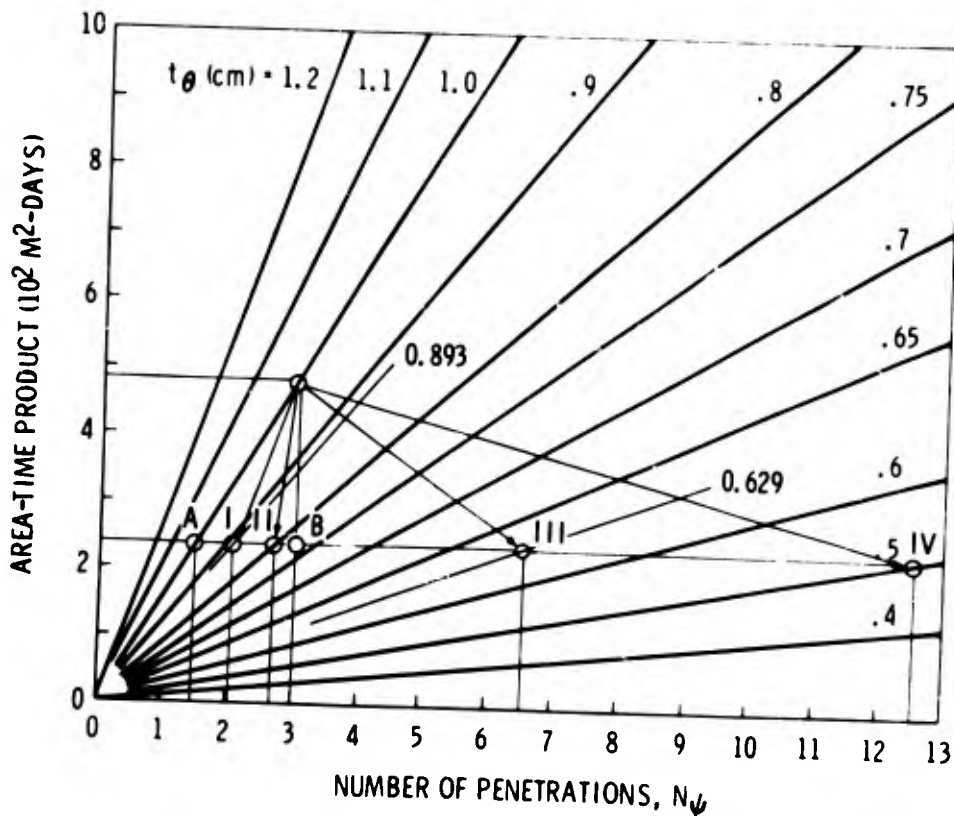


Figure 35. Number of penetrations of aluminum skin in asteroid belt for particle flux $\phi = 10^{-1} \text{ m}^{-1}$ (high density model).

a thickness ratio of 1.26, reducing the effective wall thickness to $t_{e,2} = 1/1.26 \approx 0.8$ and leading to point (II) in Figure 35. Thus, even for $\zeta = 1.3$ the effect of shorter transfer time would be favorable. However, for $\zeta = 2/3$ and 1.0, points (III) and (IV), respectively, in Figure 35, the effect of reducing the transfer time to half would be clearly unfavorable: Either a larger number of penetrations or great wall thickness would have to be accepted.

For design purposes, the analysis would have to be more complicated. The purpose of the simplified example presented here is to point out that the effect of faster transfers on the meteoroid-induced environment may be favorable or unfavorable. Shorter exposure time reduces the number of penetrations for a given impact velocity because the number of penetrations is directly proportional to the exposure time for a given shield thickness. Faster transfer leads to higher impact velocities and, therefore, to an increase in the meteoroid population capable of penetrating

a given shield thickness. If this penetrating meteoroid population increases faster than the exposure time decreases (i.e., if ζ is larger than a given threshold value), the meteoroidal effects associated with hyperbolic transfers are likely to be unfavorable (i.e., more penetrations or heavier meteoroid shields).

The exponent ζ in Eq. (10) is likely to be larger in the case of stony meteoroids than of the cometary ice/dust meteoroids expected to dominate the interplanetary population between Mercury and Mars. Furthermore, the cometary meteoroid population is likely to decrease with decreasing distance from the Sun (the measurements of Mariner II and V to Venus versus those of Mariner IV to Mars verified this expectation). For these reasons, the same increase in transfer speed that aggravates the situation in the asteroid belt may not have this effect in transfers to Mars, Venus, or Mercury. At least, the negative effect, if any, is almost certainly far less pronounced.

It is therefore concluded that the net effect of faster transfers on the meteoroid-induced environment cannot be stated generally as positive or negative, because that effect depends decisively on the effect of velocity increases on shield thickness. A corollary conclusion is that the technology of meteoroid shields should strive for a choice of materials and a design which minimizes the effect of impact velocity on shield thickness (i.e., minimizes ζ). Generally, this may be desirable. It is particularly important for spacecraft capable of hyperbolic heliocentric transfer.

7.3 Radiation Environment

Planetary radiation belts (Earth, Jupiter) are not relevant to this discussion because they do not relate to transfer times, unless capture periods are related to transfer times. The latter is true for Mars, but Mars has no radiation belt. The radiation environment of relevance therefore is solar flare induced.

Solar flares have a profound effect on manned heliocentric missions regardless of the speediness of transfer, but not entirely independent of it. The frequency and intensity of the vehicle's solar flare induced radiation environment are a function of heliocentric distance, level of solar activity and, of course, exposure time.

In the course of earlier studies for NASA, a computer program was developed for calculating mean solar flare fluxes encountered during interplanetary transfers.⁴ The purpose was to establish a workable method for predicting mean annual solar flare fluxes, flare encounter probability and probable flux doses filtering through the crew shielding. The solar distance was approximately accounted for by assuming alternatively an inverse square law spatial dependence or propagation according to inverse cube power of distance up to 1 a.u. and according to inverse first power of distance beyond Earth. Despite the paucity and uncertainty of solar flare data at various heliocentric distances, the program yields probable mean radiation doses by running the same mission profile some 50 to 100 times against the background of a Monte Carlo probability distribution of solar flare occurrence, modulated by the 11-year solar cycle. Therewith, missions can at least be compared on a consistent basis (Figure 36).

Figure 37 shows a number of examples of missions to Mercury, Venus, Mars, and Jupiter.⁶ It also shows the required solar flare shield thickness, using polyethylene as shield material, for eight sample missions. For each mission, two columns are shown. The left column indicates the shield thickness required if the mean crew dose is not to exceed 0.25 rad/d; the right column refers to 1 rad/d. Each column has two heights, referring to the two alternate modes of flare propagation as indicated. The effect of heliocentric distance (characterized, but not fully defined by perihelion distance) constitutes the dominant influence factor. This becomes quite apparent when comparing the Mercury mission (380 days) with the 1975/78 synodic Mars mission (400 days) or the Venus mission (1170 days). Next in importance is the solar cycle, as is reflected in the growing shield thickness requirement for the second through fourth Mars missions, having almost identical mission duration but occurring at progressively greater solar activity. The overpowering effect of heliocentric distance is further evidenced by comparing these three Mars missions with the Venus-Mars round trip (1010 days) which occurs in the same time period of increasing solar activity, but never approaches the Sun as closely as the Mars missions. The same case also indicates a subordinate influence role for exposure time. However, the Jupiter mission (whose profile is depicted in Figure 18) shows that high transfer speed can be an important influence factor. In spite of a very close perihelion, the required shield thickness is

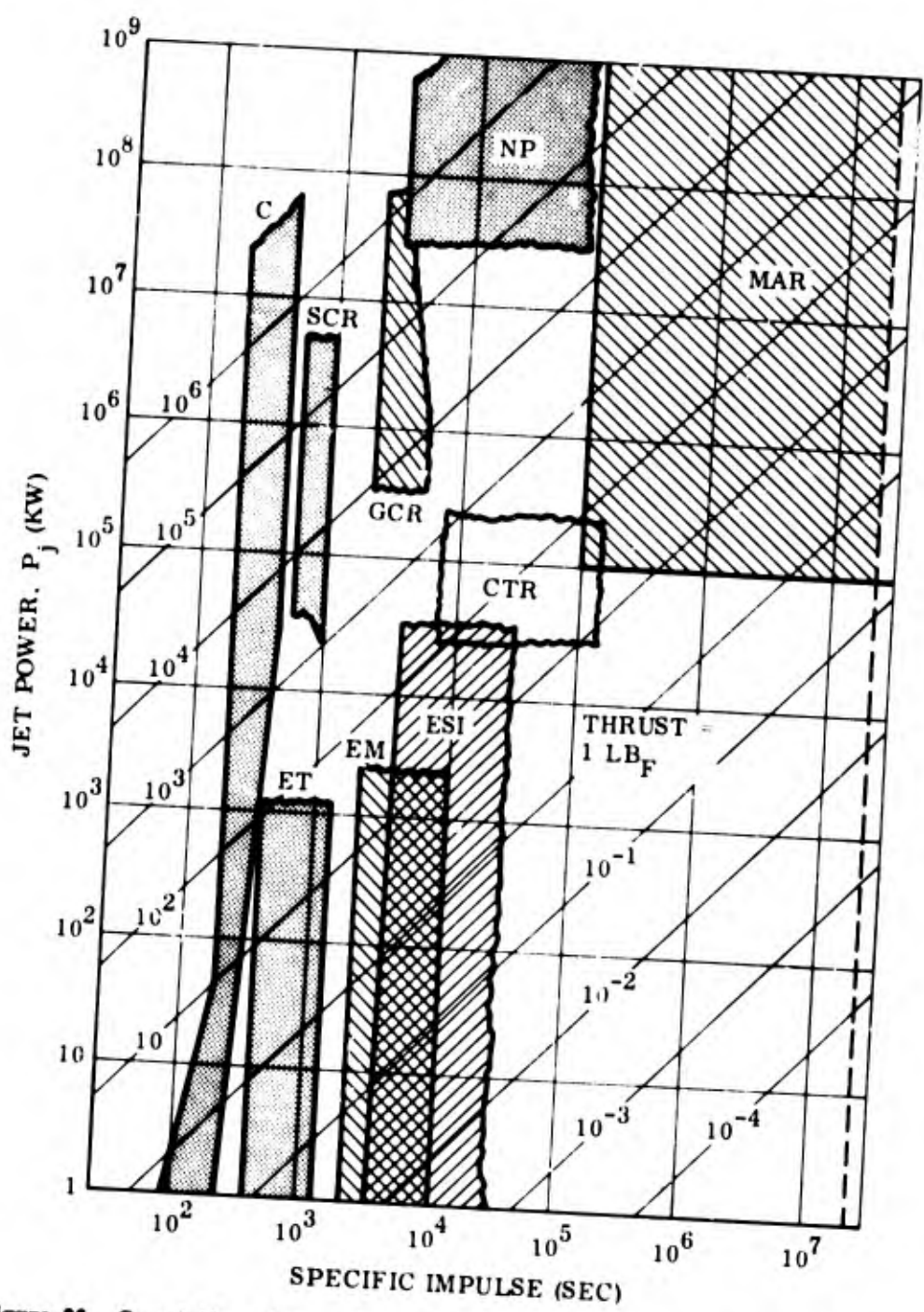


Figure 36. Correlation of propulsion systems in the jet power vs. specific impulse plane for various thrust levels.

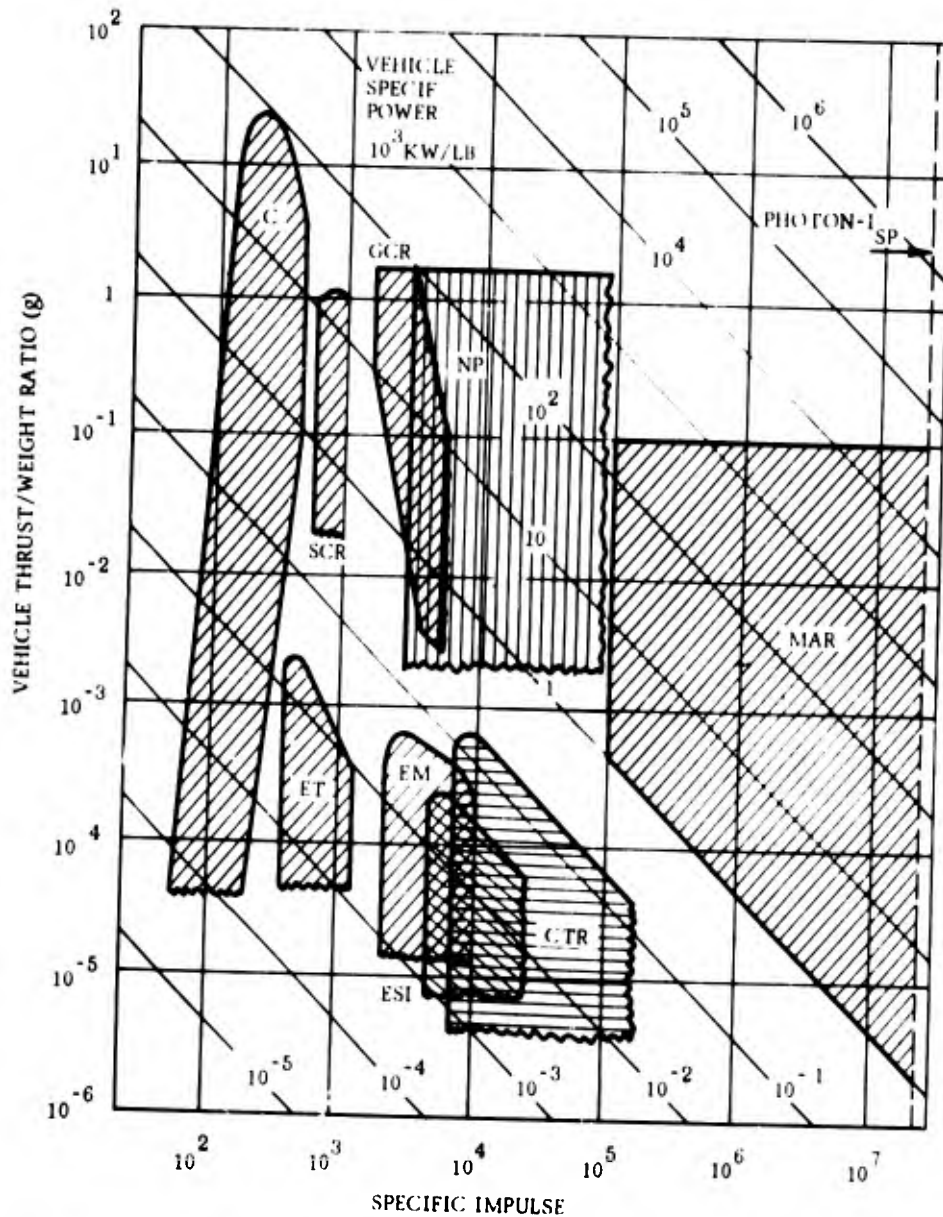


Figure 37. Vehicle thrust/weight ratio vs. specific impulse for various propulsion systems.

small because, due to very high speed inside the Venus orbit, the vehicle is exposed to close solar proximity for a far shorter time than in the second Mars mission; for example, one which involves a comparable perihelion distance. It must be added, however, that this comparison is somewhat biased because the Jupiter mission occurs in a year of minimum solar activity. Nevertheless, a proportionality exists between exposure time and the number of solar

flares to which the HISV is likely to be exposed. The exposure time, of course, is essentially equal to the overall mission duration (assuming that planets offer no significant protection to orbiting spacecraft, unless they have a magnetic field and the spacecraft can find shelter inside the planet's radiation belt). But, since transfers can occupy a significant portion of the mission duration, fast transfers can have a beneficial effect in terms of reduced radiation shielding requirement.

7.4 Bio-Environment

We use the term *bio-environment* here to designate the complex of physiological and psychological factors which make up the intravehicular crew environment.

Many bio-environmental factors are not affected by the speediness of transfer. Most of the fast transfers considered in Section 6 (with the exception of some listed in Table III) still involve mission periods long enough to warrant life support with air and liquid waste reconstitution. They are brief enough to make solid waste reconstitution unnecessary, but so are missions which are longer than those considered here. Stronger time dependencies can be expected to exist in the areas of artificial gravity and psychological equilibrium. Because of absence of space-related data, only a qualitative discussion is possible.

For extended mission durations, artificial gravity will be required for medical, as well as, incidentally, for engineering reasons (which reason will make itself felt first as function of time is not yet clear). For brief orbital and for lunar missions, artificial gravity is known to be unnecessary. The threshold beyond which artificial gravity must be provided for the crew is not accurately known at this time. However it is possible or even likely that, for transfers of a few months' duration, artificial gravity will not be required. If a long capture period is interspersed between transfers with the crew in orbital flight, artificial gravity may have to be provided during that time.

Psychologically, speediness of transfer will have, if anything, a beneficial effect. The flight phase between terminals is comparatively one of lowest activity level and greatest monotony. Up to a point, therefore, reduction of transfer time will have a favorable effect.

PROPULSION

We have surveyed the heliocentric transfer velocity requirements in Section 6 and the environmental aspects in Section 7. The heliocentric interorbital spacecraft (HISV) provides the means of transfer between the orbits of Earth and the destination body elsewhere in the solar system. The HISV may serve as personnel/equipment transport (HISV/PET), as logistic carrier (HISV/LC) and as freight carrier (HISV/FC) according to the transportation requirements for exploration, logistics and freights outlined in Figure 8. The principal difference between the PET and LC is that capability of descent/ascent transfer (DAT), in case the destination is one of the planets or the larger moons previously classified as accessible, LC is of greater importance than PET. For heliocentric interorbital transfer (HIT), the difference is slight, if the LC carries personnel along with cargo to supply extraterrestrial establishments. Hyperbolic HIT is desired in either case. Therefore, these two versions are summarily referred to as HISV. For the HISV/FC, the capability of transporting high-mass cargo at high payload fraction (high cost effectiveness) is of greater importance than very fast transfer. The key to either capability is the propulsion system. For the HISV, high specific impulse at thrust accelerations of $n \geq 10^{-3} g$ is necessary and desirable. For HISV/FC, the need for high absolute thrust values is emphasized still further because of the more massive payloads which may be involved.

8.1 General Aspects

The purpose of propulsion systems is to provide a mechanism for the conversion of energy at a prescribed rate (power) into thrust. Accordingly, the two principal components of a propulsion system are the power generator and the thrust generator. The energy sources presently within our technological grasp are chemical, solar, and nuclear (radioisotope, fission, fusion). Nuclear fission and fusion provide the most concentrated energy sources and, therefore, they are of primary interest here. Thrust generators convert "static" power (heat, electricity or both) to "dynamic" power in the form of high-speed discharge of matter (jet power). The principal conversion mechanisms are: (a) thermal power/adiabatic expansion [chemical combustion (C); solid core reactor

(SCR) and gaseous core reactor (GCR) heat exchangers]; (b) electric power conversion [electrothermal arcjet (ET); (c) electromagnetic arcjet (EM) and electrostatic systems (ES), represented here by the ion drive (ESI)]; (d) pulsating nuclear fission or fusion converters [nuclear pulse (NP)]; and (e) steady thermonuclear fusion with subsequent momentum exchange between fusion reaction products and a low-atomic-weight working fluid in a thrust augmentor [controlled thermonuclear reactor (CTR)]. A futuristic possibility is the matter-antimatter reactor (MAR) which might be envisioned as controlled release of matter and magnetically stored antimatter into a magnetically confined reaction chamber where mixing and reaction takes place. The prodigious amounts of radiation energy released by the reaction must, in part, be emitted in rearward direction, producing thrust directly (at a specific impulse of 30 megaseconds).

A propulsion system must convert large amounts of energy per unit time (i.e., large amounts of thermal, electric, etc., power) to jet power which, in turn, produces a thrust force proportional to jet power per unit mass and the discharge mass per second. The classical problem of present propulsion engineering lies in the fact that: (a) where conversion is readily accomplished (i.e., power generated per unit mass of conversion equipment is large), the jet power per unit mass ejected is small, so that large amounts of energy can be stored only at the penalty of accumulating large masses of propellant, making it necessary to spend large quantities of propellants pushing propellants, rather than payload (example: chemical rocket); and that (b) where the jet power per unit is large, conversion is not readily accomplished (power generated per unit mass conversion equipment is small), so that large amounts of jet power can be generated only at the penalty of heavy conversion equipment whose mass limits the magnitude of thrust and reduces the payload, though not necessarily to the same degree as in the opposite case (example: electric drives). Specific impulse, $I_{sp}(\text{sec}) = v_e/g$, jet power $P_j = m v_e^2/2$ and propellant consumption w (kg/sec) = mg are related by the equation

$$I_{sp} = \left[\frac{20.855}{w} P_j \right]^{1/2} \quad (11)$$

and thrust $F(\text{kg})$ is related to these parameters by

$$F = 20.855 P_j / I_{sp} \quad (12)$$

Figure 35 compares the above mentioned propulsion systems in the I_{sp} - P_j - F plane. The graph shows that, with increasing specific impulse, most propulsion systems are no longer capable of achieving high thrust values. This means that, for a given thrust acceleration, the vehicle mass (hence, the payload mass) must either decrease with increasing specific impulse or, for a given vehicle mass, the thrust acceleration must decrease. Exceptions are the NP, CTR, and the hypothetical MAR.

The jet power per unit vehicle weight, i.e., the concentration of usefully available power in the vehicle (vehicle specific power) is a function of the jet power per unit thrust, P_j/F and of the thrust/weight ratio F/W of the vehicle, i.e., its thrust acceleration in g units,

$$\frac{P_j}{W} = \frac{P_j}{F} \frac{F}{W} = c_1 I_{sp} n \quad (13)$$

where $c_1 = 2.18 \cdot 10^{-2}$ if P_j in kwj (kw jet power) and W and F in lb; and $c_1 = 4.795 \cdot 10^{-2}$ if W and F in kg. The principal propulsion systems are compared in Figure 37 in terms of Eq. (13).

The mass ratio (ratio of vehicle mass with full propellant load to vehicle mass without propellant) can be shown to be a function of the energy per unit mass of the spacecraft, transferred to the spacecraft after all propellant has been expended. This energy per unit mass (joules/kg = m^2/sec^2 kg) is a function of the time rate of energy transfer; i.e., the power per unit vehicle mass ($1 \text{ kw/kg} = 1 \text{ m}^2/sec^3$) transferred to the vehicle during the duration of powered flight. The power transferred to the vehicle is given by the integral $\int f^2 dt$, the product of time rate of power transfer ($1 \text{ m}^2/sec^4 = 1 \text{ kw/sec kg}$) and duration of powered flight, where f is the thrust acceleration in m/sec^2 . It can be shown that

$$\int_0^{t_p} f^2 dt = 2000 (\mu - 1) \frac{P_j}{F} n_0 \quad (14)$$

where t_p is the powered flight time, μ the mass ratio and n_0 the initial thrust acceleration (in g units). The above equation is based on constant thrust, F . Replacing the term P_j/F with the aid of Eq. (12) yields

$$\int_0^{t_p} f^2 dt = 95.9 I_{sp} n_0 (\mu - 1) \quad (15)$$

Figure 38 compares several propulsion systems in the $I_{sp}-\int a dt-n_0(\mu-1)$ plane.

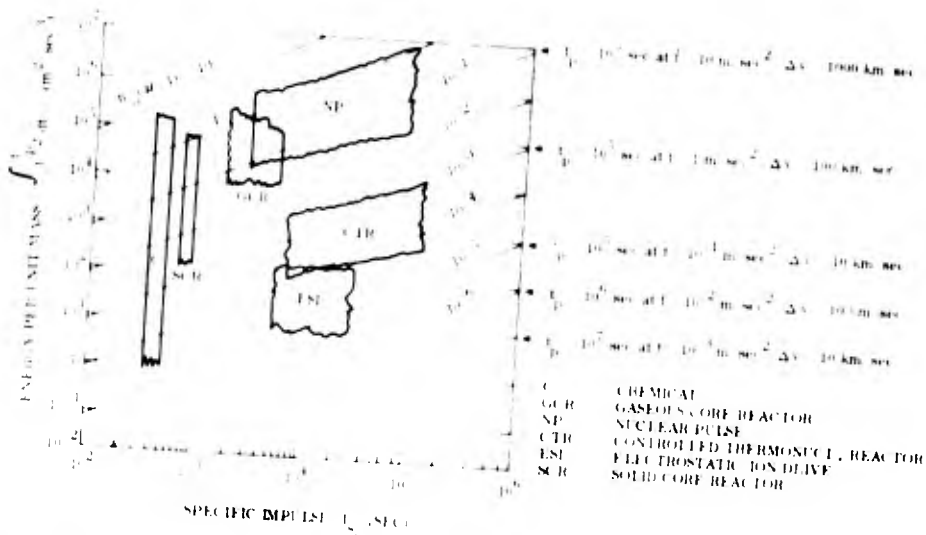


Figure 38. Energy per unit mass vs. specific impulse and different acceleration—mass ratio products for several propulsion systems.

In Figures 36 to 38, the classical propulsion problem shows up as a trend from the upper left to the lower right. The truly desirable region is the upper and middle right-hand side. Disregarding the hypothetical potential of the matter-antimatter reactor (MAR), only the nuclear pulse (NP) offers presently the engineering possibility of a "breakthrough to the upper right"* in the 1 to 10^{-2} g acceleration regime, because of the relatively low conversion equipment mass required. On a somewhat lower, but still acceptable acceleration level, only the controlled thermonuclear reactor (CTR) drive offers this breakthrough, if its power-specific mass can be reduced to the point (less than 2 lb/kwj) where vehicle acceleration levels in the milli-g region become possible. Here again, power conversion, while not exactly simple, is at least by direct reaction and by particle energy exchange in the thrust augmentor, offering the promise of lower conversion equipment weight and higher efficiency than electric drives.

In the solid core reactor (SCR) drive and the gaseous core reactor (GCR) drive, such a "breakthrough to the upper right" is not feasible because of basic temperature limitations. However,

*To specific impulses above 10^4 sec.

Table IV. Representative Initial Performance Characteristics and Initial Operational Availability of Four Advanced Propulsion Systems

Propulsion System	Estimated Feasible Initial Operational Availability	
Gaseous Core Reactor Drive GCR	<ul style="list-style-type: none"> • $2000 \lesssim I_{sp} \lesssim 2500$ sec; Engine Thrust/Weight Ratio $10 \lesssim F/W_E \lesssim 20$ • Thrust Level $50,000 \lesssim F \lesssim 100,000$ kgf • Fuel Temperature in Critical State (Reactor Temperature) $8000 \lesssim T_R \lesssim 12,000^\circ \text{K}$ • Silica Light Bulb Walls 	1980-1985
Nuclear-Electric Drive (for Manned Spacecraft) NE	<ul style="list-style-type: none"> • $5000 \lesssim I_{sp} \lesssim 20,000$ sec • Corresponding Thrust $180 \lesssim F \lesssim 45$ kgf for Representative Jet Power $P_j = 40$ mw • Generally: $30 \lesssim P_j \lesssim 50$ mw; Expellant: Mercury or Cesium • Power/Thrust Ratio: ~ 220 kw/kgf @ $I_{sp} \sim 5000$ sec to 800 kw/kgf @ $K_{sp} = 20,000$ sec • Power-Specific Weight $10 \lesssim s \lesssim 15$ kg/kw (including Power Conditioning and Control) • $F/W_E \lesssim 5 \cdot 10^{-4}$ (at above Values of s); Voltage/Atomic Weight, $5 \lesssim V/A \lesssim 50$ • Voltage Gradient $\sim 10^6$ Volts/Meter; Thrust/Emitter Area $F/A_E \sim 1$ kgf/m² 	1980-1985

Table IV. (Contd.)

Propulsion System	Estimated Feasible Initial Operational Availability
Nuclear Pulse Drive NP	<ul style="list-style-type: none"> • $3000 \lesssim I_{sp} \lesssim 5000$ sec • $3 \lesssim F/W_E \lesssim 4$ • Fission Pulse Units • Thrust $300,000 \lesssim F \lesssim 400,000$ kg (not I_{sp}-related)
Controlled Thermonuclear Reactor CTR	<ul style="list-style-type: none"> • $10,000 \lesssim I_{sp} \lesssim 600,000$ sec • Corresponding Thrust $250 \lesssim F \lesssim 4$ kgf for Representative Jet Power $P_j = 100$ mw • Generally: $50 \lesssim P_j \lesssim 150$ mw • Power/Thrust Ratio: ~ 400 kw/kgf @ $I_{sp} \sim 10,000$ sec to 25,000 kw/kgf @ $I_{sp} \sim 600,000$ sec • Ratio of Thermonuclear Plasma Pressure to Magnetic Pressure $0.2 \lesssim \beta \lesssim 0.4$ • Corresponding Power-Specific Weight 1.5-2 kg/kw (at ~ 55 kilovolt Electron Temperature) • $F/W_E \lesssim 1.2 \cdot 10^{-3}$ (at $\alpha \sim 2$ kg/kw and 250 kgf Thrust) • Magnetic Field Strength B $\sim 150,000$ Gauss at Mirrors (@ $\beta \sim 0.35$) • Current Density $\sim 150,000$ ampere/cm²

*Based on Technological Considerations and a Medium-Priority Development Program with Definition Phase Beginning 1970-72. Except as Noted in Second Footnote.

†Definition Phase for Space Flight Article Beginning About 1980.

the GCR promises specific impulses as high as 5000 sec at not too low thrust/weight ratio. This performance renders the GCR drive very attractive for cislunar transfers as well as for a number of interplanetary missions. In the electric drives*, the breakthrough is very unlikely because the multiple energy conversion processes involved in thrust generation take a heavy toll in terms of energy utilization efficiency. This does not mean, of course, that these propulsion systems cannot have a useful function. However, for high-energy missions with manned HISV, only drives which offer the possibility of a "breakthrough to the upper right" promise the greatest return on the investment in their development.

8.2 Description of Selected Propulsion Systems

On the basis of their potential performance, the nuclear pulse (NP) and controlled thermonuclear reactor (CTR) are of primary interest as drives for manned HISV. Of secondary interest are the gaseous core reactor (GCR) and the nuclear-electric-ion (NE) drive. Since the NE drive is well known, only the other three are described briefly in order to identify the reference concepts. Table IV shows representative initial performance characteristics and possible initial operational availability of the principal four advanced propulsion systems.

Among the various GCR concepts, the "light bulb" concept developed by United Aircraft Corp. looks particularly attractive (Figure 39). The "fuel" [fissionable material (FM)] is contained in an enclosure whose walls are protected by a layer of helium or neon gas surrounding the FM and serving as buffer gas to protect the light bulb walls, made of SiO_2 or BeO_2 , from direct contact with the FM. Both buffer gas and light bulb walls are, to a high degree, transparent to the thermal radiation and the neutron flux. Their energy is absorbed by hydrogen flowing around the light bulb, protecting at the same time the outer walls of the engine. Fuel enclosure satisfies basic safety requirements against nuclear contamination and also results in high fuel economy.

The nuclear pulse drive (Figure 40) uses small nuclear explosive charges (pulse units) which are stored in the vehicle. The pulse units are sequentially ejected and detonated at a given distance

*Electromagnetic (EM) and electrostatic-ionic (ESI).

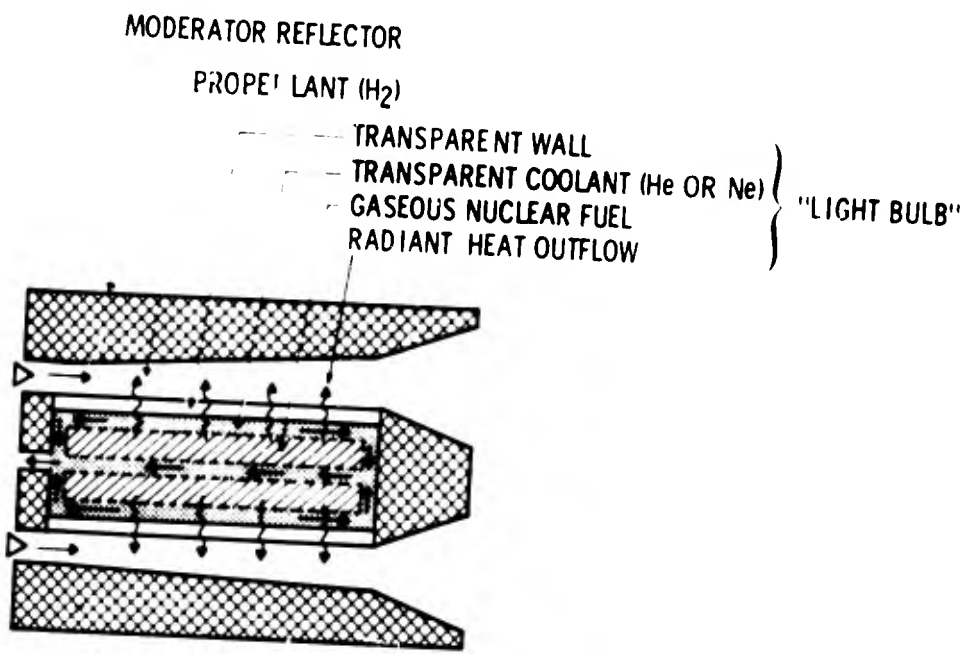


Figure 39. Light bulb gas core reactor engine (schematic).

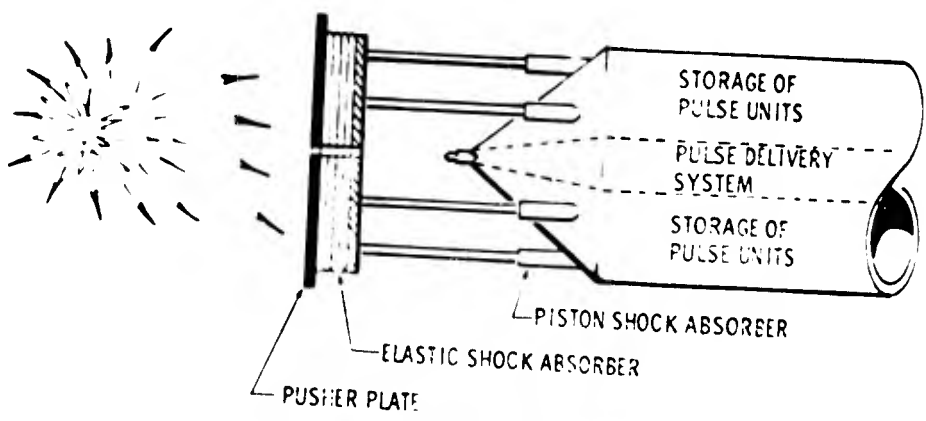


Figure 40. External nuclear pulse engine concept.

behind the vehicle. A certain percentage of the expanding gaseous debris from each detonation, in the form of dense high-velocity plasma, is intercepted by a "pusher plate" at the base of the vehicle. The momentum of the intercepted plasma is transferred to the pusher plate. The impact on the pusher plate is moderated by a sequence of shock absorbing devices to levels of less than

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2 g in the main body of the vehicle. The number of pulses is determined by the required velocity increment of the vehicle. While the technical problems appear to be less severe than with any other of the four major drives, a political problem is presently associated with the NP due to the Nuclear Weapons Test Ban Treaty, seeking ultimately "the discontinuance of all test explosions of nuclear weapons for all times" and excluding all nuclear explosions, except for underground tests. In that form, the treaty prohibits in effect (though not necessarily by intent) the development, testing, and operation of nuclear pulse vehicles. The system can release large amounts of energy per pulse, in accordance with the thrust required, without encountering the engineering problems associated with handling prodigious energy releases in a confined space. The pulse method avoids the problem areas connected with steady-state fusion processes. For these reasons, fission or fusion pulse units can be used if they are of appropriate size; and virtually any desirable thrust level can be attained. The nuclear fuel detonates in all directions. Therefore, only a fraction of the nuclear energy is used. This is true for the NE drive also. But in the NE drive, the loss of some 65 to 75% of the nuclear energy unfortunately is associated with heavy power conversion and conditioning equipment and with large radiators. In the NP this is not the case, resulting in the lowest conversion equipment except for the chemical drive. The propellant consists of solid material which is turned into a plasma by the nuclear detonation. This plasma blast is, of course, not omnidirectional, as is the nuclear detonation, but oriented toward the pusher plate. The percentage of the propellant plasma which bypasses the pusher plate, rather than the nuclear material, constitutes a loss which reduces the effective specific impulse. If 50% of the nuclear energy were absorbed by the propellant, and if all propellant were focused precisely on the pusher plate (transferring all of its momentum to the vehicle), a specific impulse of at least 200,000 sec could be obtained. Initial performance values on small nuclear pulse vehicles with a pusher plate diameter not exceeding the diameter of Saturn V are probably of the order of 3000 to 5000 sec. However, a growth potential to 100,000 sec or better is not an unrealistic expectation. Only the CTR offers a comparable specific impulse level, albeit at a lower thrust. The nuclear pulse alone among all advanced propulsion concepts presently within our technological grasp offers high specific impulse *and* sufficiently high thrust to drive freight carriers which are characterized by a particularly

large payload mass. A fusion charge constitutes a still more concentrated energy source than a fission charge, but its main advantage is the absence of radioactive fission products which constitute an unavoidable by-product of propulsion by fission pulse units. The dissemination of fission products is not a problem for powered flights beyond the Earth's radiation belt and certainly not in interplanetary space. The use of fusion pulse units, triggered by means other than fission charges, could, however, render the operation, at least occasionally, of nuclear pulse drives acceptable within the Earth's radiation belt.

The CTR (Figure 41) is based on the production of power from exothermal nuclear fusion reactions. Essentially, three reaction types can be considered: Deuterium-Deuterium (D-D), Deuterium-Tritium (D-T) and (Helium 3)-Deuterium ($^3\text{He-D}$) reactions. The D-D and the D-T reactions release large amounts of energy in the form of neutrons (approximately 50 to 75%, respectively). For this reason, the CTR system suggested by Dr. John Luce of Aerojet General Corporation is based on the thermonuclear reaction of deuterium with a Helium-3 isotope to produce Helium-4 and protons, according to the equation:

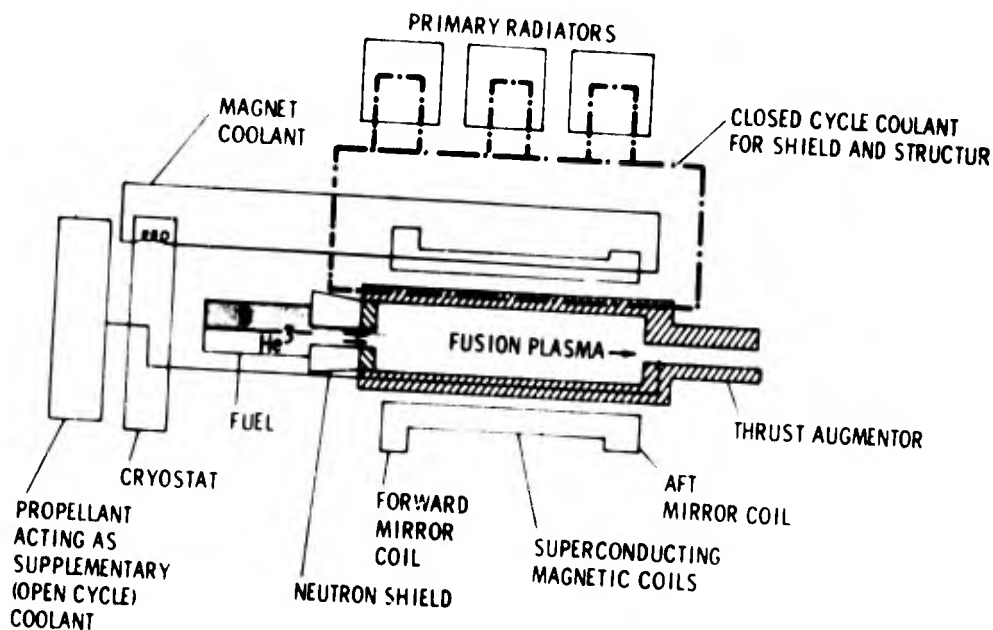


Figure 41. Schematic of D-He³ CTR drive.

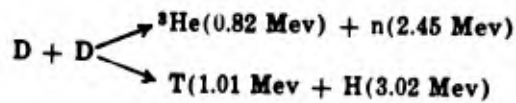
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Both reaction products are charged particles and can, therefore, be confined by magnetic fields, thereby isolating the plasma from the wall. A small amount of reactions of the type:



and



will also occur as the result of intermediate formations.

These secondary reactions, however, can be minimized so as to produce only a small fraction (1 to 2%) of the total system power in neutrons. The plasma is envisioned as being confined in a magnetic geometry which combines the cusp and the regular mirror geometry and which has both the needed resistance to instabilities and a long adiabatic confinement time needed for adequate reaction efficiency. The magnetic field is maintained by superconducting coils made of the intermetallic compound of vanadium and gallium. The superconductive characteristics of certain intermetallic compounds, such as niobium-zirconium (Nb-Zr), niobium-tin alloy (Nb₃-Sn) and vanadium-gallium (V-Ga), provide the basis for developing relatively lightweight, low-power systems for generating and maintaining very strong magnetic fields equal to, and in excess of, 200,000 gauss without the heavy coils used earlier, without extensive power conversion system, large radiators, structural parts, and without large electric power requirements. Principal "building blocks" of the CTR engine include:

- Bremsstrahlung and Neutron Heat Shield
- Superconducting Coils
- Coil Support Structure
- Thermal Protection Subsystem (Coolant Cycles)
- Coolant Circulation Subsystem (Cryostat)

The CTR drive must meet *three basic requirements*: Stable, self-sustained nuclear reaction must be achieved. A proper geometry of the magnetic field must be developed which permits a steady-state reaction condition and a stable fusion plasma which

can be confined without excessive magnetic pressure. A lightweight system must be developed to generate and maintain the magnetic field necessary to contain the thermonuclear plasma. A critical parameter in fusion plasma physics is the ratio β of plasma pressure to confining magnetic pressure. Depending upon plasma stability and magnetic geometry, β can range from 0.2 (i.e., magnetic field pressure required is 5 times the plasma pressure) to 1.0. The motor weight is closely dependent upon β -value and electron temperature in the plasma gas.

The limitations in electron temperature have important implications on the attainable thrust and specific impulse. The maximum electron temperature is determined by the nuclear reaction involved. In the deuterium-helium reaction, the maximum electron temperature is around 73 kilo-electron volts (kev). The thermonuclear plasma jet alone would provide a specific impulse of about 600,000 sec at a very small thrust (about 6 lb at 100-mw jet power output). To redistribute the energy between thrust and specific impulse in a manner that is more meaningful for most propulsive purposes, the specific impulse must be reduced to values around 10,000 sec, raising the thrust proportionately. This redistribution is achieved by admixture of cold hydrogen or deuterium in a thrust augmentor section behind the reactor. Increasing the cold gas admixture raises the thrust and lowers the specific impulse. Ionization of the cold gas releases relatively cold electrons, many of which enter the fusion chamber where the static pressure is lower than in the thrust augmentor, even though the dynamic pressure in the fusion chamber is higher. The tolerable influx of cold electrons is limited, in order to prevent eventual plasma losses due to instabilities. Ultimately, self-sustaining fusion would be terminated due to excessive energy losses through Bremsstrahlung. These factors limit the practically attainable minimum electron temperature to about 46 kev. The corresponding amount of deuterium used in the thrust augmentor reduces the specific impulse to about 5000 sec, raising the thrust to about 924-lb/100-mw jet power output. In the CTR, therefore, one of the problems is not how to attain a high specific impulse, but how to reduce it to the desired level.

The fuel mixture consists of 60% ^3He and 40% D. At a characteristic engine jet power output of 100 megawatt (mw), the fuel consumption is $6 \cdot 10^{-6}$ kg/sec (0.52 lb/day) at 100% reaction

efficiency. At 100-mw jet power a specific impulse of 20,000 sec requires a weight flow of $5.1 \cdot 10^{-3}$ kg/sec; i.e., a three orders of magnitude greater flow rate than the fusion plasma flow rate.

In order to yield a high energy release per unit volume and per unit weight, the D-³He fusion reaction must take place at a temperature of about 10^8 °K. This represents a major temperature control problem. Keeping the magnet at such low temperature is facilitated by using the intermediate load carrying structure as a shield. The magnet requires its own (liquid helium) cooling cycle. The intermediate structure may be cooled by the propellant (hydrogen or helium) acting as open cycle coolant. However, relying exclusively on propellant cooling would deprive the CTR of one of its operational advantages, namely, the wide range of interchangeability of thrust and specific impulse. With increasing specific impulse, the propellant flow is reduced. In order to maintain an adequate cooling level, a closed cooling cycle is added which can be stepped up or reduced in response to thrust variations, varying the number of primary radiator modules accordingly.

The energy losses are not restricted to neutron escape. Losses by Bremsstrahlung and cyclotron radiation must also be considered. Cyclotron radiation caused by oscillatory motion of the particles in the confining magnetic field is stronger in the D-³He plasma than in the D-D and D-T plasma, because the D-³He nucleus has two charges, compared to one for the D or T. However, theoretical considerations indicate that most of the cyclotron radiation will be absorbed by the plasma under the conditions of temperature, mass, and plasma density in the CTR engine. Because cyclotron radiation is caused by particle oscillation in the magnetic field, its intensity increases with magnetic pressure (magnetic field strength). At $\beta = 0.1$, the magnetic pressure is 10 times the plasma pressure and cyclotron radiation losses tend to become prohibitive. Therefore, the requirement for steady-state reaction in the CTR dictates β -values between at least 0.2 and 0.4 or higher. Plasma instabilities, on the other hand, require that β be less than 1.0. With greater experience in maintaining a stable fusion plasma in steady-state reaction, permissible β -values will increase. Bremsstrahlung is the gamma-ray frequency to which the fusion plasma is transparent. This radiation and the relatively small amount of neutron radiation constitute the major source of energy which heats up the intermediate structure between plasma and

magnetic coils. The resultant thermal energy is removed by propellant and closed-cycle coolant.

A mirror-type magnetic field appears to be particularly promising for maintaining high plasma stability while keeping the magnetic pressure low (i.e., for attaining a high β -value). In the mirror configuration, the magnetic field intensity is highest at the forward and aft end of the cylindrical plasma confinement region. This gives the field a cusp geometry in accordance with the experience that a plasma is more stably confined if the magnetic field "bulges" into the plasma (like one side of a biconvex lens), rather than if it provides a concave confinement front. By adjusting the magnetic strength of the rearward mirror coil to be slightly weaker than the forward mirror, the plasma is allowed to escape in the aft direction, therefore providing thrust.

All four advanced drives have a significant growth potential over their estimated initial performance characteristics. Table V summarizes what appears today as the limiting performance level of each of these propulsion systems. Briefly, the principal growth potential of the GCR lies in the area of specific impulse, but at the expense of engine thrust-weight ratio (which, for $I_{sp} = 10,000$, probably will fall below 0.1) and complexity as well as vulnerability to inclement space environment. This is due to the need for increasing radiator surfaces which cool the engine structure as the specific impulse rises above 2500 sec.

In the nuclear-electric drive, the most important growth is associated with reduction in the size of radiators by achieving high radiator operating temperatures $T_{rad} > 1500^\circ\text{K}$. This is the key to growth of the nuclear-electric drive in many directions: (a) improved engine thrust/weight ratio and, consequently, a higher level of optimum specific impulse for a given mission; (b) reduced vulnerability to hostile space environment due to reduction in radiator area as will most likely be needed in flights into or through the asteroid belt (this is predicated on the assumption that the radiator temperature can be raised without significantly increasing the penetrability of the radiator surface to micrometeoroids; and this assumption perhaps contains the most severe obstacle to a significant increase in radiator temperature; entirely new energy rejection concepts, not associated with conventional radiator design may have to be developed); (c) reduced sensitivity to solar thermal radiation; hence, improved operating

Table V. Estimated Performance Limits of Four Advanced Propulsion Systems

Propulsion System	Estimated Upper Limits of Performance Characteristics	Reason for Limitations
Gaseous Core Reactor Drive	$T_R \sim 25,000 \text{ }^\circ\text{K}$ $I_{sp} \lesssim 10,000 \text{ sec}$	<ul style="list-style-type: none"> • Radiation heat transfer to nozzle walls. • UV radiation transfer to light bulb walls. • Weight of radiators needed for cooling of confining structure at specific impulses in excess of about 2500 sec.
Nuclear-Electric Drive	<ul style="list-style-type: none"> • I_{sp}: no theoretical limit • Practical limit in accelerating voltage is $\sim 300,000 \text{ V}$ • Associated I_{sp} For Mercury $\sim 50,000 \text{ sec}$ For Cesium $\sim 60,000 \text{ sec}$ • Thrust: no theoretical limit • Practical limit of jet power output probably $P_j \sim 100 \text{ mw}$ • Associated thrust $F \sim 450 \text{ kgf}$ ($@ I_{sp} \sim 5000 \text{ sec}$) $F \sim 140 \text{ kgf}$ ($@ I_{sp} \sim 15,000 \text{ sec}$) • Jet power specific weight of propulsion system 1 to 1.5 kg/kw 	<ul style="list-style-type: none"> • System weight, complexity and intrinsic reliability. • Size of radiators and thrusters and associated reliability and sensitivity to hostile space environment. • Limitation to Saturn V launch vehicle compatibility restricts maximum thrust level to 40 ~ 60 kgf.

Table V. (Contd.)

Propulsion System	Estimated Upper Limits of Performance Characteristics	Reason for Limitations
Nuclear Pulse Drive	<ul style="list-style-type: none"> • $I_{sp} \lesssim 100,000$ sec • Fusion pulse units • Thrust: no theoretical limit, but is function of pusher plate diameter. 	<ul style="list-style-type: none"> • Degree of perfection of focusing propellant plasma jet on pusher plate of spacecraft. At imperfect focusing, I_{sp} is also a function of pusher plate diameter. • Limitation to Saturn V compatibility limits maximum thrust level to $F \lesssim 500,000$ kgf.
Controlled Thermonuclear Reactor Drive	<ul style="list-style-type: none"> • $I_{sp} \lesssim 5000$ sec; $> 100,000$ sec • Jet power specific weight of engine 0.3 to 0.6 kg/kw <p>1) Depending on thrust acceleration attainable at very high I_{sp} values.</p>	<ul style="list-style-type: none"> • Limitations in handling influx of cold electrons into thermonuclear reactor. • Maximum attainable ratio of plasma pressure to magnetic field pressure is $\beta \rightarrow 1$. • Minimum mass of cryogenic cooling system for superconducting coils depends on how much temperature of superconductors can be raised and on the extent to which radiation and particle energy losses from thermonuclear plasma to the superconductive coils can be reduced.

capability at closer proximity to Sun, as in flights to Mercury. The absolute thrust level of nuclear-electric drives [electrostatic (ES) and electromagnetic (EM)] does not indicate significant growth potential because of inherent limitations due to many energy conversions involved (ES and EM) and due to space charge limitations (ES).

Growth of the NP drive is in the direction of increased specific impulse and increasing absolute thrust force. Thrust (F) and specific impulse (I_{sp}) are not interchangeable in the NP as in the NE or CTR drive where the power output is constant and can be expended either in a jet of lower mass flow and higher specific impulse or of lower specific impulse and higher mass flow. Nevertheless, in the NP, thrust and I_{sp} are not entirely independent of each other. The I_{sp} is a function of the degree of perfection in focusing the propellant plasma jet on the pusher plate of the spacecraft. Pusher plate mass (largely determined by its diameter) and shock absorber system must be compatible, so that there is an upper limit of thrust force which can be absorbed by a pusher plate of given diameter. For larger thrust forces, the diameter must be increased. A larger diameter, in turn, facilitates plasma focusing, hence, improves the I_{sp} . A third influence factor is the magnitude of the nuclear pulse unit (in terms of TNT-equivalence). Obviously, the smaller the spacecraft, the smaller the pusher plate and the smaller is the maximum tolerable thrust pulse. If nuclear pulse units cannot be made small enough to be compatible at lesser size levels, the quality of focusing is degraded intrinsically. In addition, intentional defocusing may be necessary in order to keep the thrust pulse within acceptable limits. Therefore, Saturn V compatibility (meaning primarily a pusher plate diameter of about 10 M) limits the thrust value. Size of pusher plate, limiting thrust value and minimum available nuclear pulse unit determine the range of specific impulse. Initially the I_{sp} is expected to lie in the 3000- to 5000-sec area. With maximum pulse unit size compatibility and refined focusing, values in excess of 10,000 sec may be attained. For very large NP-driven freight carriers, whose payload mass is of the order of several thousand tons and whose pusher plate diameter measures 30 to 50 m or more, specific impulses in the high 10,000-sec range or of the order of 100,000 sec should be attainable.

CTR growth concerns (a) the increase in the range over which thrust and I_{sp} can be interchanged, (b) growth in engine thrust/

weight ratio, and (c) attempts to maximize the efficiency of the fusion process. The first objective amounts to reducing the lower limit of specific impulse, that is, maximizing the influx of cold electrons from the thrust augmentor that can be tolerated without quenching the nuclear reaction process. The goal here is to attain as high an engine thrust/weight ratio as possible for a given CTR, thereby maximizing the flexibility of the CTR to operate in as wide a range of gravitational field intensities as possible. Growth in engine thrust/weight ratio can be achieved through a variety of means, all of which add up to reducing the engine weight from a value of 1.5- to 2-kg/kw jet power (kwj) which might be anticipated as initially attainable goal, to the order of 0.3 to 0.6 kg/kwj. This improves the thrust acceleration level and raises the optimum specific impulse for a given mission, thereby improving the propellant economy.

8.3 Propulsion-Vehicle Integration

The gross weight W_A of a space vehicle consists of three components: payload, W_{10} ; propulsion hardware (inert weight), W_{20} *; and propellants, W_{30} . The weight at beginning of a powered maneuver is, therefore, $W_A = W_{10} + W_{20} + W_{30}$; the empty weight is $W_B = W_{10} + W_{20}$ and the overall mass ratio $\mu = W_A/W_B$. Figure 42 shows the functional breakdown of a nuclear pulse driven HISV concept. The NP drive imposes particularly stringent constraints on the shape of the payload section, in order to prevent exposure to nuclear blast. Therefore, if artificial gravity is to be generated during coast periods†, a deployable crew module system might be considered, among other things, in addition to the central mission modules which contain the command and information handling center. The one shown in Figure 29 consists of swing-out telescopic booms at whose ends cylindrical mission modules are mounted. During powered flight, the mission modules are tucked against the center axis of the spacecraft, downward direction being toward the vehicle base. Figure 43 is an artist's concept showing the HISV in powered flight mode. After termination of the acceleration phase, the telescopic booms swing outward and expand. Artificial gravity is generated by a slow spin of the spacecraft

*Including electric power generation, where relevant, even though power may also be delivered to the payload.

†For short transfer periods of the order of months, artificial gravity en route may not be required.

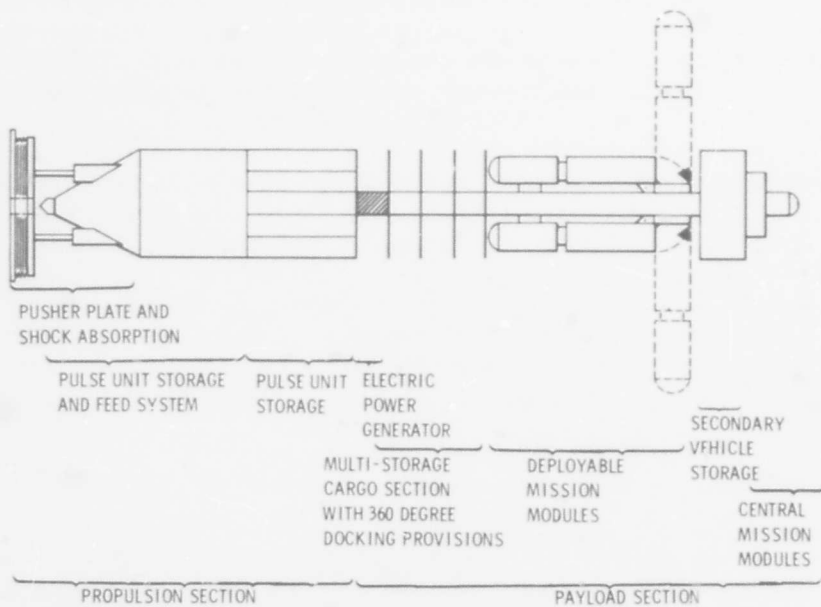


Figure 42. Nuclear pulse interplanetary vehicle concept.

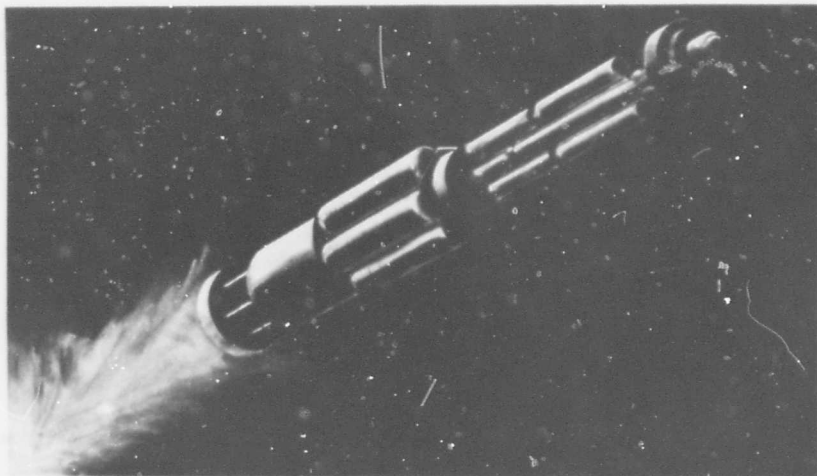


Figure 43. Nuclear pulse-driven interplanetary spacecraft during powered flight.

about its center axis. Downward is now at right angle to the center axis, but in the same direction within the frame of reference of the cylinders. Figure 44 shows the vehicle in coast mode. Figure 45 depicts the functional arrangement of a CTR driven HISV concept.

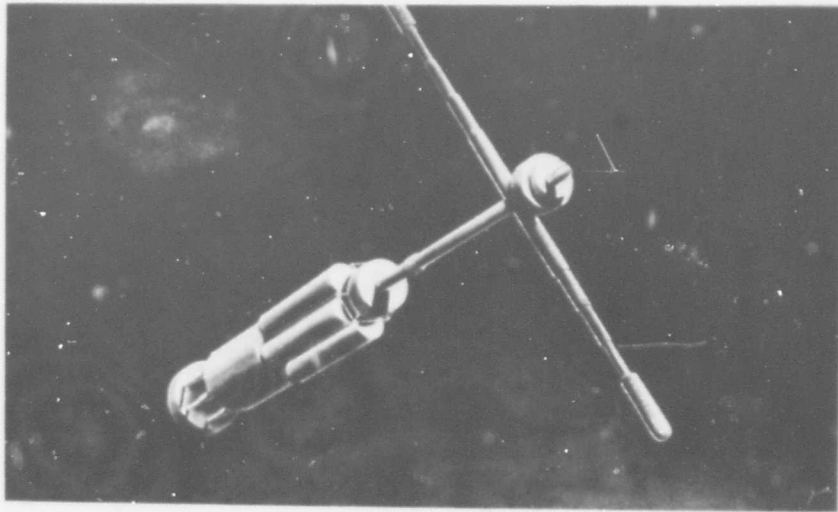


Figure 44. Nuclear pulse-driven interplanetary vehicle during coast with extended mission modules, spinning slowly to provide artificial gravity.

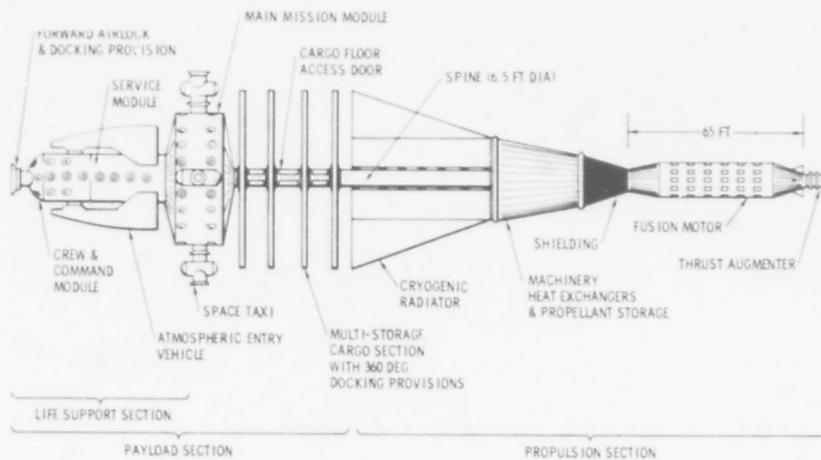


Figure 45. Controlled thermonuclear reactor vehicle concept (schematic).

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The front end shows an alternate design without provisions for artificial gravity en route other than that provided by the continuously operating engine. A three-dimensional view of this concept is shown in Figure 46. Vertical light guards are shown at the rim of the radiators to assure greater flexibility of orientation during missions closer to the Sun to avoid excessive solar irradiation causing degradation of the radiator's heat rejection efficiency. Figure 47 shows an artist's concept of the HISV in the vicinity of an asteroid.

The HISV design details are not important in the broader context of this paper. They were explained briefly in relation to the concepts shown above exemplifying the integration of the propulsion system into the overall vehicle.

Important integration parameters are

Mass fraction

$$X = \frac{W_{30}}{W_{20} + W_{30}} \quad \text{(propellant mass per unit mass of propellant and inert mass)} \quad (16)$$

Propellant fraction

$$\frac{W_{30}}{W_{\Delta}} = \Lambda = 1 - \exp(-\tau/I_{sp}) \quad \text{(propellant mass per unit initial mass)} \quad (17)$$



Figure 46. Controlled thermonuclear reactor vehicle concept.

Payload fraction

$$\frac{W_{10}}{W_A} = \lambda = 1 - \frac{\Delta}{x} \quad (\text{payload mass per unit initial mass}) \quad (18)$$

Propellant mass factor

$$\frac{W_{30}}{W_{10}} = p = \frac{\Delta}{\lambda} = \frac{x}{(x/\Delta) - 1} \quad (\text{propellant mass expended per unit payload mass transported}) \quad (19)$$

and the inert mass factor

$$\frac{W_{20}}{W_{10}} = i = p \left(\frac{1}{x} - 1 \right) = \frac{-1-x}{(x/\Delta) - 1} \quad (\text{inert mass required per unit payload mass transported}) \quad (20)$$

It is obviously desirable that x and λ be large and that p and i be small. The propellant fraction Δ relates the vehicle integration

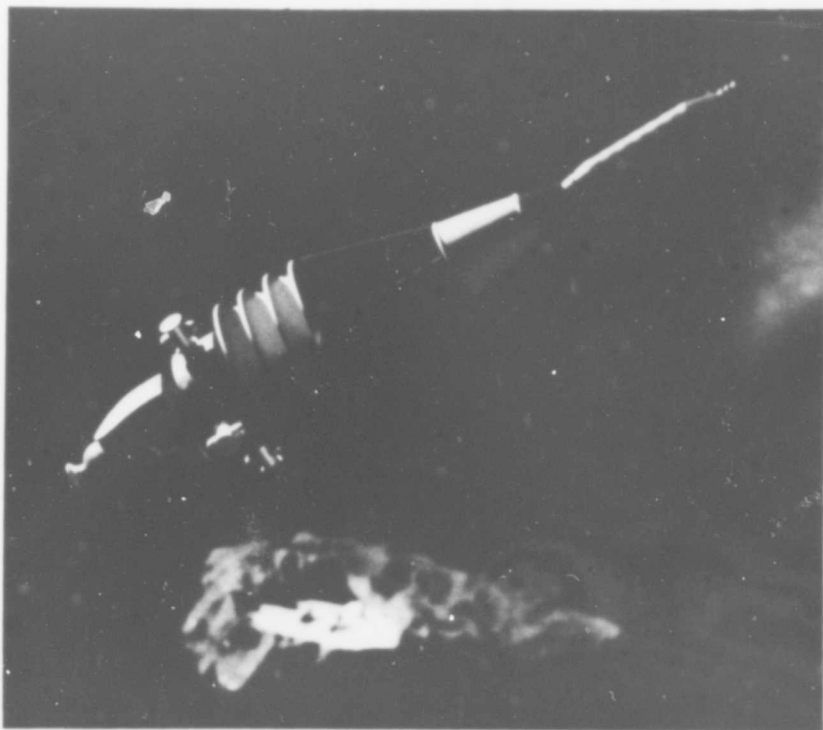


Figure 47. Thermonuclear powered interplanetary carrier approaching asteroidal mining station.

parameters x , λ , p , and i to propulsion performance (I_{sp}) and mission velocity requirement, represented by the sum of all maneuvers to be carried out by the particular vehicle or stage, divided by g , to make the term $\tau = \Sigma \Delta v/g$ dimensionally compatible with the specific impulse. Figure 48 shows the variation of p and i with x for discrete values of τ/I_{sp} . A small value of τ/I_{sp} indicates that the specific impulse is high, compared to the velocity requirement. It

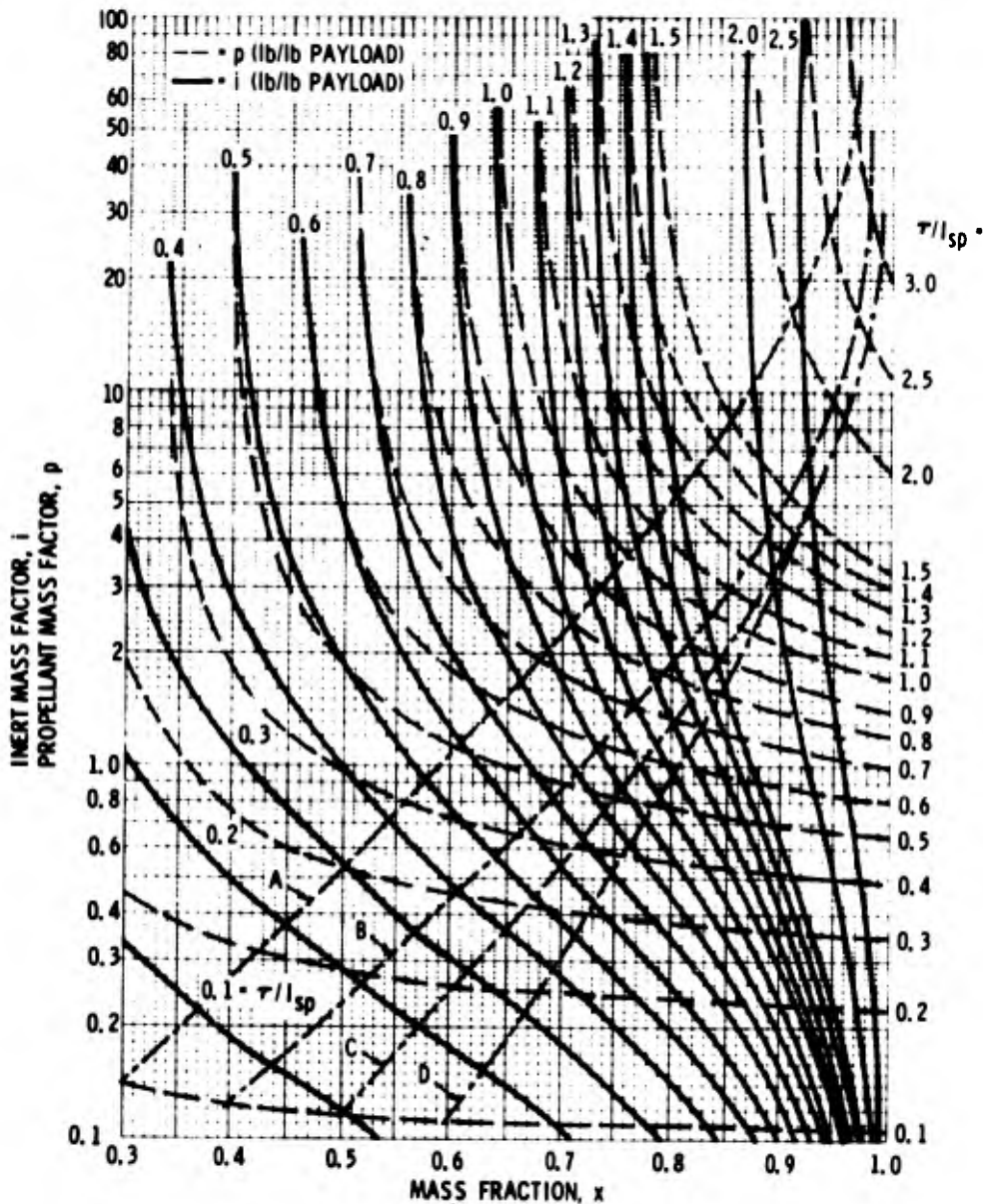


Figure 48. Propellant factor and inert mass factor vs. mass fraction.

is seen that at small τ/I_{sp} , both i and particularly p are relatively insensitive to variations in mass fraction x . This is of considerable importance so far as the development and operation of a new vehicle/propulsion system is concerned, because the mass fraction which actually can be realized under operational conditions is a major uncertainty factor in the development of advanced, high-energy propulsion systems. To this is added the uncertainty of the effect on x of environmental conditions encountered in solar system missions.

For nuclear-electric, fusion, and gaseous core reactor drives, the mass fraction tends to decrease with increasing specific impulse, because the inert mass increases with the number and rate of power conversions. Only for the nuclear pulse drive is this trend not apparent or at least not as pronounced. Decreasing x with increasing I_{sp} has two undesirable effects: It reduces the payload fraction attainable as a result of the increased specific impulse. Moreover, it increases the development risk, because the sensitivity of p and i to variations in mass fraction increases at a growing rate with decreasing mass fraction, except for low values of τ/I_{sp} ($\lesssim 0.2$). This is demonstrated in Figure 48 by the sharp upswing of the curves $\tau/I_{sp} > 0.2$. For example, for $\tau/I_{sp} = 0.9$, a drop of x from 0.7 to 0.65 raises p from 3.9- to 6.7-kg propellant/kg payload, almost doubling the propellant requirement for the mission. An error in over estimating the expected mass fraction at the outset of a development program can, therefore, have serious consequences so far as later logistic requirements and mission costs are concerned, since the reduced mass fraction increases the hardware and propellant mass to be accumulated in orbit for a given mission. With increasing specific impulse, the τ/I_{sp} values for a given family of missions decreases and so does the development risk resulting from inability to attain a projected mass fraction.

Actually, the mass fraction increases with increasing vehicle size. For a given vehicle, the mass fraction increases with increasing τ/I_{sp} , because the addition of propellants adds less inert weight than the enlargement or addition of an engine system. The curves A through D in Figure 48 exemplify possible growth of x with τ/I_{sp} , where A is representative of a relatively high inert mass and D of a low inert mass. Values of $x \gtrsim 0.9$ are attainable with chemical, SCR, NP, and possibly GCR drives but are extremely difficult to attain with NE or CTR drives. But, with NE, CTR, and NP drives, many hyperbolic solar system missions require

τ/I_{sp} values low enough to permit values of $x < 0.9$. Using curves A and D as the two boundary cases of the $x = f(\tau/I_{sp})$ curves, the variation of payload fraction λ with τ/I_{sp} is shown in Figure 49. This chart is read as follows: (a) given mission velocity $\Sigma\Delta v$ [point (I)] and I_{sp} (II), one proceeds from (I) to (II) and up (or down) to the point of intersection (IIIa, IIIb) with one of the λ vs. τ/I_{sp} curves; (b) given Σv (I) and desired payload fraction (IIIa or IIIb), one proceeds from point (IIIa) or (IIIb) down (or up) to the point of intersection with the horizontal line extending from (I), defining the required I_{sp} (II); (c) given I_{sp} (II) and λ [(IIIa) (IIIb)], one proceeds from (IIIa) or (IIIb) up (or down) to the given I_{sp} (II) and from there horizontally to the right determining the attainable $\Sigma\Delta v$. Approximate regimes of heliocentric transfer characteristics are shown at the right in Figure 37, based in part on the data presented in Section 6. The chart illustrates, among other things, that for missions involving hyperbolic transfer and 10% payload mass ($\lambda = 0.1$), specific impulses upwards of 2500 to 3300 sec are required, depending on whether reference is made to curve D or A. Considering that $\Sigma\Delta v = 80$ km/sec covers more adequately than $\Sigma\Delta v = 50$ km/sec the fast mission spectrum into the asteroid belt and to Jupiter, $I_{sp} = 3300$ to 5200 sec or

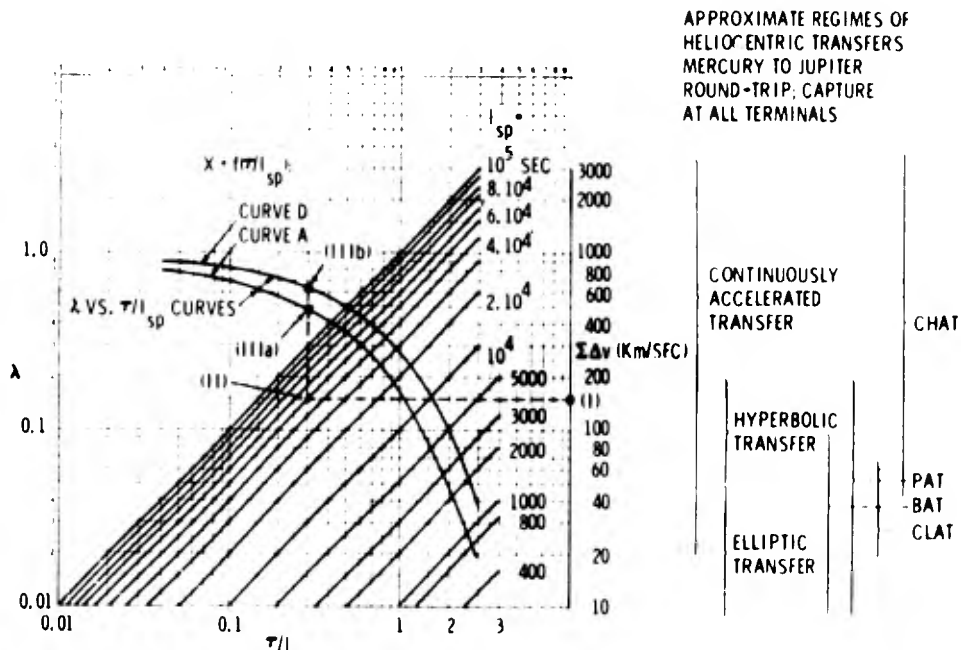


Figure 49. Variation of payload fraction with τ/I_{sp} , I_{sp} , and $\Sigma\Delta v$.

higher is more appropriate. The associated τ/I_{sp} -values are 2 and 1.3, respectively. Figure 36 shows that this implies a mass fraction of 0.91. Therefore, while the GCR, NE, CTR, and NP could meet the I_{sp} -requirement, only the NP would most likely be able to meet the mass fraction requirement, followed by the GCR drive as the second likely prospect. The NP, NE, and CTR, however, can operate at higher specific impulses. Taking $I_{sp} = 15,000$ sec for the NE, 20,000 sec for the CTR or NP and $\Sigma\Delta v = 80$ km/sec, the payload fractions, for $I_{sp} = 15,000$ sec, are 0.35 to 0.5, $\tau/I_{sp} = 0.5$, the mass fractions 0.61 to 0.79; and for $I_{sp} = 20,000$, one finds $\lambda = 0.4$ to 0.56, $\tau/I_{sp} = 0.4$, $x = 0.56$ to 0.76. The enormously greater design and performance safety margin, associated with raising the specific impulse above the bare minimum required, is apparent.

Figure 50 shows the corollary parameters to λ in Figure 49, namely, the propellant factor p and inert mass factor i . The latter is comparatively small within the mass fraction boundaries assumed. It reaches a maximum and falls off at still higher flight performance levels; i.e., values of τ/I_{sp} . The post-maximum dropoff indicates that the high mass fractions required for these performance levels can be attained only by a reduction of i , i.e.,

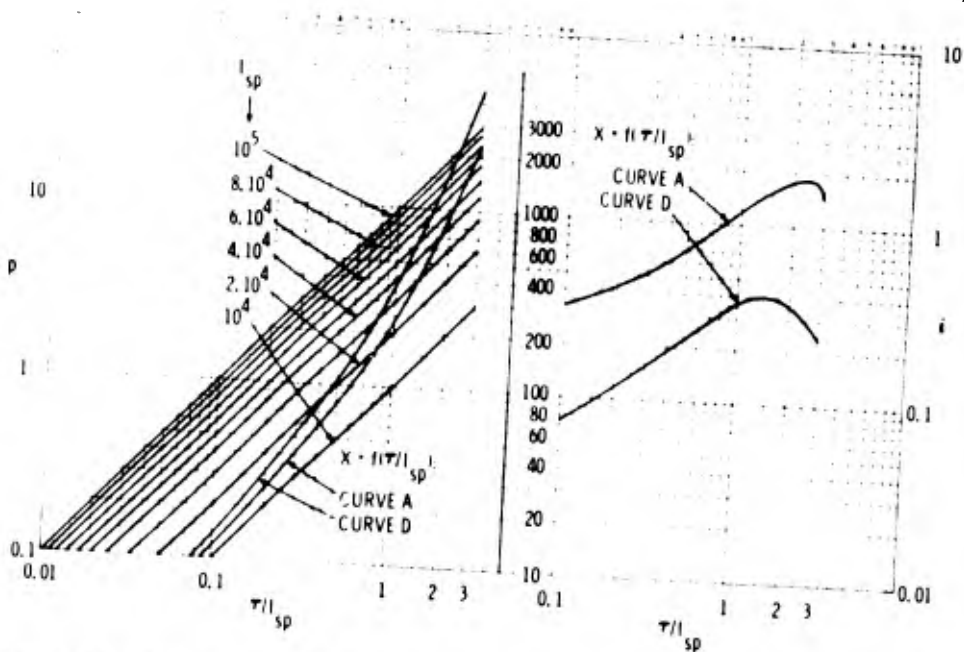


Figure 50. Variation of propellant factor and inert mass factor with τ/I_{sp} , I_{sp} , and $\Sigma\Delta v$.

by modular or vehicular staging. The larger x , the higher the performance threshold beyond which this becomes necessary. For reusable interorbital spacecraft, p is more important than i , because propellant must be resupplied after every mission and becomes, therefore, a major factor in determining the operating cost of the system. The acceptable upper limit of p depends on too many factors to be discussed here. But if p values of 2 to 4 are not to be exceeded, for example, a limit is placed on τ/I_{sp} of the order of 1. This, again, points at values above 10^4 sec (myria-seconds).

For a given set of I_{sp} , $\Sigma\Delta v$ and x values, the payload fraction is defined. Ultimately, the performance of a propulsion system is reflected by the product of the two most important outputs, namely, payload fraction and velocity. Representing the latter, for greater generality, by $\tau(\text{sec}) = \Sigma\Delta v/g$, this product $\lambda\tau$ is presented in Figure 51 as a function of $\Sigma\Delta v$ for five discrete specific impulses, based on the payload fractions shown in Figure 49. These curves show a pronounced maximum in the vicinity of $\tau/I_{sp} = 1$. This is expected on the basis of the mechanics of propulsion in general, whose discussion exceeds the purpose of this paper. The declining

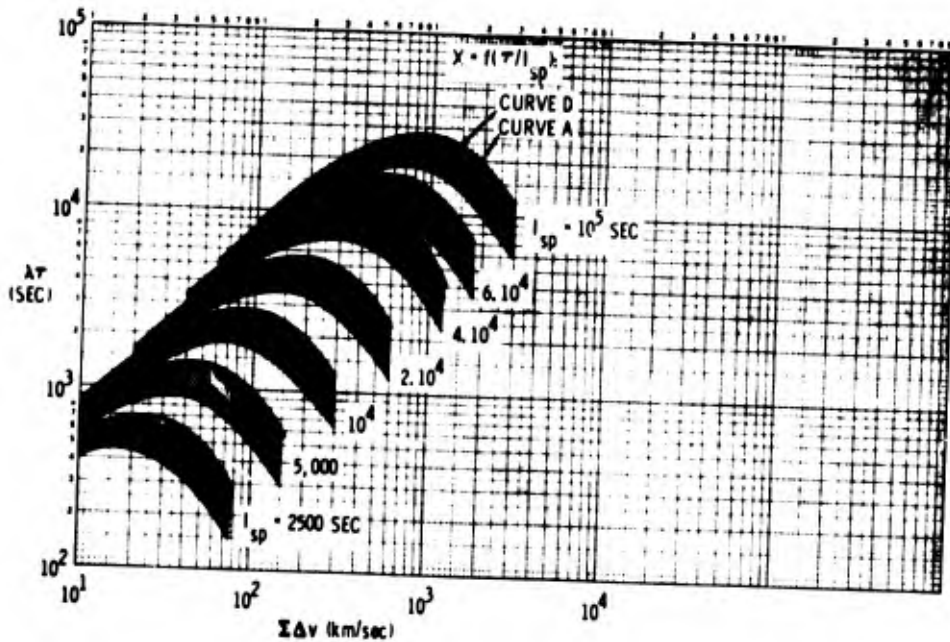


Figure 51. Variation of $\lambda\tau$ as function of $\Sigma\Delta v$ and I_{sp} for certain boundary values of x .

portion to the left of the maximum represents the region in which flight velocity is sacrificed for very large payload fractions. This region might be used by freight carriers, sacrificing rapidity of transfer to maximize payload (minimize p , hence, transportation cost). In the declining portion to the right of the maximum, payload is sacrificed for speed. Personnel transports can be expected to operate near the maximum and slightly to the right from it. Emergency missions are likely to operate in the far right. To the left of the maximum, the effect of specific impulse on λ_T is less pronounced. In other words, if $\Sigma\Delta v$ is small, increasing the specific impulse is less rewarding. However, while doubling the specific impulse from 5000 to 10,000 sec brings limited gains for a mission of $\Sigma\Delta v = 10$ km/sec, the opposite is true if $\Sigma\Delta v = 100$ km/sec. The importance of high specific impulse, in terms of flexibility of mission velocity, is clearly apparent. For example, if mission velocities are to vary between 20 and 100 km/sec, the specific impulse should be at least 5000 sec. A variation of mission velocities between 20 and 200 km/sec is accommodated by a specific impulse of at least 10^4 sec; and a vehicle with a specific impulse of $I_{sp} \geq 60 \cdot 10^4$ sec can operate effectively over a mission velocity range from 20 to 2000 km/sec.

The preceding discussion has pointed out the importance of high specific impulse ($\geq 10^4$ sec) in terms of reduced development risk and improved design and performance safety margin; in terms of low transportation cost (low propellant factor); in terms of broadened mission velocity flexibility and of hyperbolic transfer capability, both of which are of particular importance for solar system missions, in distinction from orbital or lunar missions. For these latter mission categories, high specific impulses are desirable; but reusability offers an effective alternative in attaining high transportation cost effectiveness. In fact, for launch vehicles, reusability (> 100 times) is a more effective means of attaining high Earth-to-orbit transportation cost effectiveness than high specific impulse. For manned interplanetary flight above bare minimal missions to Venus or Mars, high specific impulse is more than desirable; it is necessary. In the time period ahead, the period preceding manned solar system missions, we can for the first time seriously plan and act to translate this capability into reality. In the light of this fact, the many attempts to justify the use of marginal and submarginal nuclear and chemical propulsion systems for manned interplanetary missions in the eighties or even later are difficult to understand.

One of the principal elements of a strategic approach to manned interplanetary flight—and a significant breakaway from past propulsion development philosophy—must be the development of propulsion with a reserve capability, or at least a definite, significant growth potential, of specific impulse beyond minimum needs for initial missions.

8.4 Comparison of Propulsion Systems

A detailed comparative analysis of the four principal propulsion systems would exceed the frame of this paper. Based on the preceding discussion, two quality charts were constructed. Each chart combines a number of "yardsticks" representing important criteria. Each of the four propulsion systems is rated relative to every one of the criteria listed. The number of rating points ranges from 1 (very poor) to 10 (very good). The first chart, shown in Figure 52, measures the propulsion systems against eight performance and flight operational criteria. Each system forms a characteristic quality pattern as shown. An octagonal pattern at any point level (e.g., all ratings being 2 or 5, etc.) would indicate that the system measures up evenly to all eight requirements, though not to the maximum degree desired. An octagon at level 10 would depict a virtually ideal system so far as these criteria are concerned, since the criteria are so formulated that a high number indicates a high rating. An uneven pattern shows at a glance the particular strengths and shortcomings of the system. A very uneven pattern indicates a highly specialized system (from a mission standpoint). The second chart, Figure 53, shows nine additional criteria related to transportational and developmental aspects.

The point ratings are by necessity somewhat subjective because they cover a very wide range of interplanetary missions and a large time span, about 1985 to 2000, in which the performance of systems may grow more or less spectacularly, depending on the effort devoted to their development and improvement. Therefore, the pattern reflects the general "complexion" of the respective systems, based on anticipated initial performance and growth potential, as outlined in Tables IV and V. It is also assumed that the potential promised by the individual systems can indeed be realized, i.e., each system is given the benefit of the doubt. Finally, it should be kept in mind that the patterns obtained refer to the

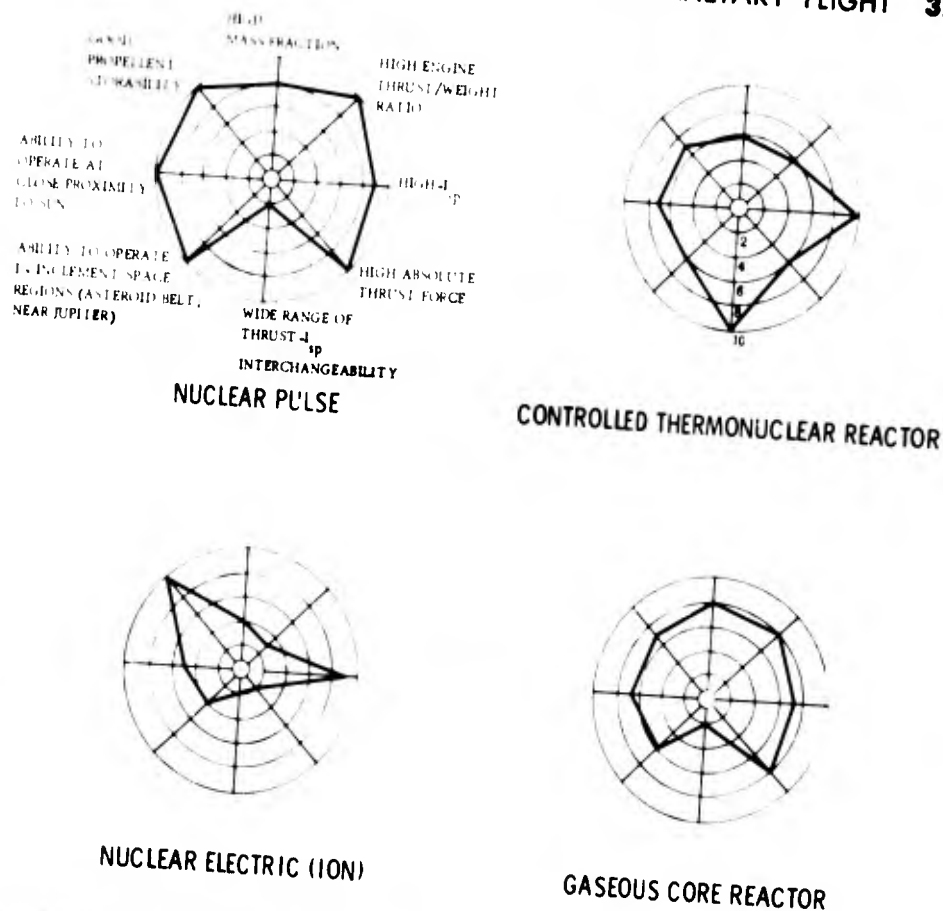


Figure 52. Propulsion system quality charts for manned flights between Mercury and Jupiter.

application to manned interplanetary flight within the Mercury-Jupiter belt of the solar system. The patterns would look different if applied to unmanned circular transportation or to propulsion for unmanned interplanetary probes.

It is seen that the NP shows the best pattern. This is due (in Figure 52) to its capability to generate high thrust as well as high specific impulse, to it having a high engine thrust/weight ratio, to a fairly high mass fraction (though less than a chemical system, certainly one with a noncryogenic propellant would have), to its propellants (solids) which are easily movable, and to its ability to operate in just about any unfavorable environment better than any of the other systems. It falls short in thrust- I_{sp} interchangeability. In Figure 53, the major shortcomings of the NP are seen to be the radiation contamination caused by the operation

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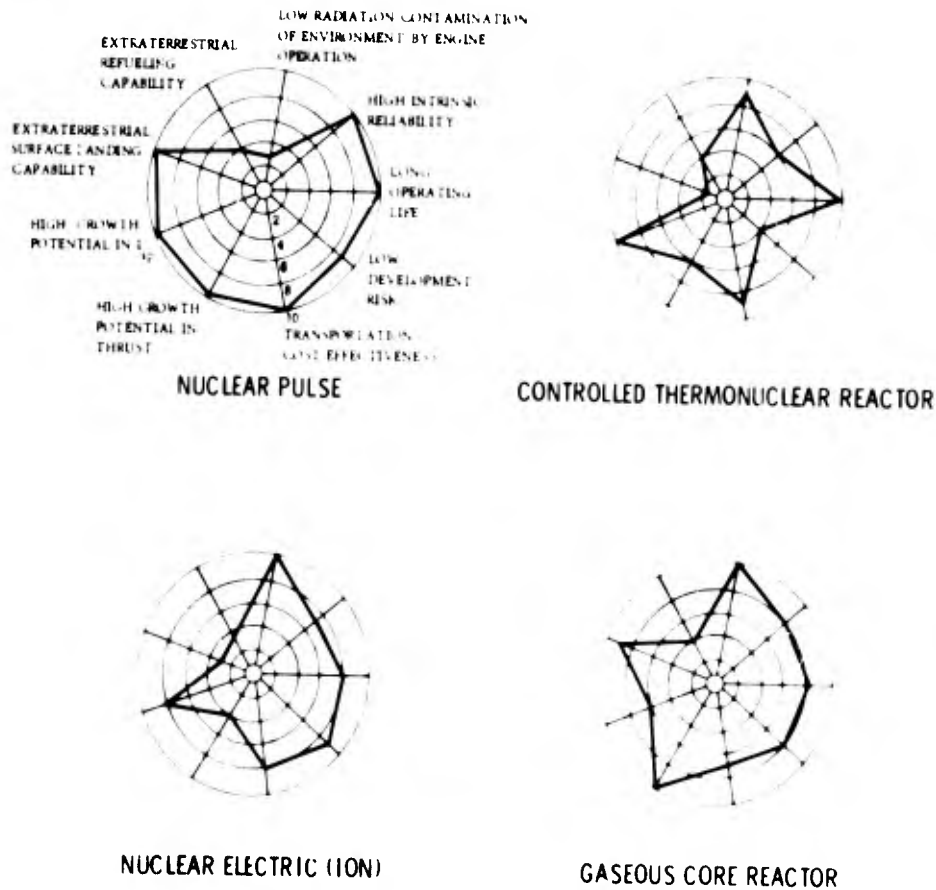


Figure 53. Propulsion system quality charts for manned flights between Mercury and Jupiter.

of its engine and its capability of extraterrestrial refueling. The former is not really important in interplanetary or even cislunar flight (outside the Earth's radiation belt). The latter is based on certain requirements for evenness in propellant particle size and in the need for a heavy metallic propellant component to insure better propellant focusing on the pusher plate. The rating number 4 given the system on that count is meant more as an expression of lack of knowledge than an absolute rating. Compared to it, the chances to refuel hydrogen (CTR, GCR) have been, tentatively, equally as good. Whereas, the chances to refuel on cesium or mercury (NE) have been rated one point lower, merely on the general grounds that their abundance is lower on Earth than that of heavy metallic propellants for the NP. In any case, the extraterrestrial refueling capability criterion is one of the least certain

in the system. The ambiguity is compounded by the fact that presumably very different worlds such as Mercury and Jupiter moons are included, and by the fact that no differentiation was made between initial conditions and an advanced state of fully developed mining operations. Since mercury and cesium, as well as some of the very heavy metals desired for the NP, constitute far more attractive mining products than hydrogen, extraterrestrial refueling of the NE and NP may eventually be more feasible on a number of bodies than refueling the CTR or GCR.

Aside from the NP, the CTR shows the best performance aspects, whereas the GCR shows the most well-rounded quality pattern, similar to the NP but on a lower level. The NE drive, by comparison, appears less attractive for manned interplanetary flight, primarily because of its greater sensitivity to environmental conditions and because of the principal limitations to low absolute thrust force and low engine thrust/weight ratio which can be overcome only by change from singly charged particles to a plasma and from many conversion steps to direct reaction. These changes lead to the CTR.

SUMMARY AND CONCLUSIONS

Strategic planning for orbital and lunar operations should primarily be mission oriented: manned space station, scientific satellites, application satellites, or Apollo lunar base.

When it comes to the solar system, strategic planning must become capability oriented. This means:

- Science should emphasize the exploration of a multitude of worlds before progressing to detailed experimentation on one (Mars).
- Overall planning should be oriented toward objectives which recognize that beyond scientific objectives, important as these are, lie profounder aspirations: that is, to seek out and to develop the potential usefulness of other worlds.
- Unmanned and manned operations must be taken into long-range consideration, without bias either way, according to mission requirements and necessary lead times.
- Engineering solutions should no longer be based on the marginal performance of a few individual missions. This is particularly true for manned missions.

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Longer lead times are required for this approach, especially so far as manned missions are concerned; but no longer than the lead times available for defining meaningful manned missions. The expenditures involved are applied more efficiently. They are likely to be less in the long *and* in the short run, because this strategy justifies more consistent support, greater steadiness of technological objectives, absence of crash programs and a strategically meaningful sequencing of unmanned and manned missions in accordance with long-range objectives.

The overall objective is the acquisition of the solar system, defined in the first two sections of this paper as exploration, occupation (manned transportation and residence capability), and utilization/exploitation. The core of this objective is the recognition of future human needs for resources beyond Earth. In this context, the solar system region extending from Mercury to Jupiter is recognized as of primary initial interest.

This strategy does not look at the solar system as an extension of a scientific laboratory. It rejects the scientifically unfounded conjecture that man is not useful in solar system exploration or not able to tolerate the rigors of interplanetary flight. The strategy recognizes that every experience so far gives us confidence.

- That man indeed is *useful* in solar system exploration, when assigned the proper missions,
- That man is *needed* for solar system acquisition,
- That man is *able* to go anywhere from Mercury to Pluto, or beyond for that matter, given the appropriate technological armor.

In manned missions, it is of considerable importance to reduce heliocentric transfer times as much as possible, because of the great distances involved. In terms of orbit mechanics, this requires hyperbolic heliocentric transfers.

Why short transfer times? Fundamentally, because the utilization/exploitation potential of a new region is only as good as the means of transportation available. In addition, the overwhelming number of individual effects of hyperbolic transfer is beneficial:

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- Human factors in general: improves the practicality and convenience of human transportation.
- Artificial gravity: Less critical need, if any.
- Psychological effects: Favorable. Less time is spent in heliocentric transfer, the most inactive portion of the mission.
- Solar thermal radiation effects: Favorable. Shorter exposure reduces many problems associated with thermal protection and unavoidable absorption of part of the solar thermal radiation offered.
- Meteoroidal effects: Fewer hits due to shorter exposure time, but greater penetration due to higher speed of vehicle relative to meteoroids. Net effect may be favorable or unfavorable, depending on the effect of increased velocity on meteoroid shield thickness.
- Corpuscular radiation (solar flares): Effects are mildly favorable, because of shorter exposure time; but, proximity to Sun of flight path and level of solar activity are stronger influence factors, within the range of exposure times to be considered, than speed of transfer.
- Missions to Mercury: Particularly effective in reducing overall mission duration. Capture periods can readily be tailored to the particular mission requirements due to the fast orbital motion of Mercury relative to Earth. Capture periods, therefore, are little affected by speediness of transfer. Reduced overall mission duration is, in the case of Mercury, particularly beneficial in terms of thermal and corpuscular radiation effects.
- Missions to Mars: Permits greater flexibility in adjusting capture periods to mission requirements. With elliptic transfer paths, capture periods must either be brief (10 to 30 days) or synodic (layover to the next return launch window). Longer capture periods can be attained if a midcourse maneuver (perihelion maneuver) is executed or when return flight via Venus is feasible. Hyperbolic transfers permit longer capture periods (2 to 4 months) without penalizing transfer times.
- Missions to Jupiter and many asteroids: Particularly effective in reducing outbound and return transfer times.
- Vehicle engineering effects: Favorable. To the extent to which they reduce overall mission time, fast transfers reduce the required mean time before failure (MTBF); or, for given MTBF, failure probabilities are reduced.

Propulsion is of central importance, because the obvious price for attaining hyperbolic transfer capability is the availability of a propulsion system of high specific impulse and relatively high thrust acceleration. The specific impulse should be $I_{sp} \gtrsim 5000$ sec,

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depending on the mission velocity spectrum to be covered; and $I_{sp} \geq 10,000$ sec if the entire region of interest, from Mercury to Jupiter, is taken into consideration. The mission velocity spectrum depends on the desired range of transfer times and requires round-trip mission velocities upwards of 80 km sec. The thrust force should be high enough to permit thrust accelerations of the order of $\geq 10^{-3}$ g. In addition, it is of importance that the propulsion system offers a realistic and significant growth potential in terms of specific impulse to $I_{sp} \geq 40,000$ sec and of high absolute values of thrust force, F.

Why, specifically, are these characteristics important? In addition to the previously mentioned general reason, they offer a number of practical and significant advantages, summarized subsequently in terms of important criteria:

- Development risk (I_{sp}): Reduced sensitivity of propellant factor to mass fraction "slippage" in the course of hardware development (lower development risk than if I_{sp} is marginal to begin with). See Section 8.3.
- Crew survival (I_{sp}): Greater design margin offering higher assurance of crew survival and of mission success in general. The improvement in design margin means also, in effect, greater freedom to lower the mass fraction without too severe penalty in terms of propellant factor, payload fraction or mission velocity capability.
- Crew survival (I_{sp}): Increased flexibility in terms of emergency options which, in solar system missions, generally are associated with an increase in velocity requirements. This velocity margin, therefore, complements the before mentioned design margin to raise significantly the overall safety and success probability margin on account of higher specific impulse.
- Mission (I_{sp}): Wider trade-off range of transfer time versus payload fraction.
- Mission (F): Ability to transport larger payload masses. The initial payload mass for a manned explorer mission is typically of the order of 40 to 100 metric tons. The payload mass of freight carriers should be 4000 to 40,000 tons for economic extraterrestrial mining.
- Mission (F): Improved capability to utilize effectively the higher specific impulse for faster transfers.
- Mission (I_{sp}): Broader mission velocity flexibility (i.e., the product λr stays high over a wider range of mission velocities). See Section 8.3.

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- Mission (I_{sp} , F): Wider transfer windows, because of broader mission velocity flexibility and sufficient thrust to meet faster acceleration requirements where they occur.
- Mission (F): Higher mobility in the vicinity of the giant planets, especially Jupiter.
- Mission (I_{sp} , F): Greater flexibility in the choice of capture orbits at target planets and in terminal Earth capture orbits.
- Economy (I_{sp}): Reduced propellant expenditure per unit mass of payload (reduced transportation cost effectiveness).

The era of manned interplanetary flights will be born in the last two decades of this century. Contemplating the use of any lesser means of propulsion than on the level of kiloseconds and myriaseconds of specific impulse is inconsistent with our nuclear technological capability and equally inconsistent with any strategic approach to interplanetary flight.

The principal propulsion candidates are the nuclear pulse (NP), the controlled thermonuclear reactor (CTR), the nuclear-electric drive (NE), and the gaseous core reactor (GCR). These systems are described and compared in the last section of this paper. It is concluded that the NP offers the greatest promise as manned interplanetary drive, followed by the CTR.

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XVIII

The Human Eye In Space Exploration

Col. James F. Culver*

When space explorers or scientists are asked, "Why do we want to explore space?" the standard answer is usually, "Because it's there," or to "observe what's there," and the best way to make an observation that I know is to look at it. I suppose man's exploration of space began when he first gazed into the heavens and began to look at the Sun and the stars and the Moon—and to wonder. With the development of the telescope, his capability to explore was expanded and now our trained astronauts and cosmonauts have begun first-hand observations.

The majority of the papers presented at this symposium have supported the importance of the human eye. It is always thrilling to see such beautiful photographs as shown by Dr. Lowman that were taken in orbit by the astronauts, and to see the exciting motion pictures of the Sun's activity as shown by Dr. Evans, and to view the telescopic observations by Dr. de Vaucouleurs. Dr. Gilruth has told us of plans to have a telescope in orbit; and on the other end of this telescope in space as well as those on the ground, behind the cameras and other devices, is the human eye—a most reliable, flexible, adaptable and essential sensor.

Prior to actual space flight, some prophets suggested serious problems could be expected regarding man's visual capabilities in space flight. Laboratory investigations had indicated that in the presence of a homogeneous or empty visual field, experimental subjects were unable to completely relax their accommodation. The term *space myopia* was coined to describe this state.¹ Some

*Assistant Director of Research and Development, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas.

advocated that man's visual sense would be confused by illusions.³ Others felt he might be restricted by his perception time, fixation time, and reaction time and later argued that the power of resolution of the eye was too limited.

I am sure that this recalls to mind the controversy over what astronaut Col. Cooper saw and the numerous articles and letters that transpired in the columns of both scientific and lay publications. Many writers and speakers were adamant, and their opinions ranged from absolute denial to total acceptance. Numerous hypotheses flowed, such as possible hallucinations, magnification due to atmospheric conditions, and the possibility of improvement in visual acuity because of weightlessness. Most of these explanations either were insignificant or were not accepted. Considering Col. Cooper's capabilities and the prevailing conditions during his first flight, most authorities concluded that the visual sightings as reported from an orbital altitude of 86 miles had finite probabilities, or in other words, "He saw what he said he saw."^{3, 4} Experimental data from later Gemini flights supported these conclusions.⁴

With impending space flight, many investigators became increasingly concerned about the effects of weightlessness upon the eye. There were suggestions that there would be changes in the shape of the cornea or tilting of the lens with a resulting astigmatic error and change in refraction causing a decrement in visual acuity. There were speculations that in the weightless state the extraocular muscles as well as the ciliary muscles, long accustomed to a 1-G environment, might be affected to produce variations in muscle balance, accommodation, and fusion—and diplopia or double vision would ensue. It was asked, "Would the eye be able to make the necessary adaptation during prolonged weightlessness to provide for safe, accurate, and comfortable visual performance?" and "Could the eyes rapidly readapt to the positive gravity state upon reentry into the Earth's atmosphere?"

During the Third International Symposium on Bioastronautics and the Exploration of Space in 1964, Dr. Clark and I discussed some of the considered important stresses of space flight, among them, *weightlessness* and its effect on vision.

It was our opinion that weightlessness was not necessarily a stress on the visual system but, rather, a relief from stress. We

felt that there was nothing physical, physiological, psychological, or neurological to indicate weightlessness would be a particular problem for the eyes.⁵ Our optimism has been supported by the successful completion of the Mercury and Gemini programs, which have provided us with approximately 2,000 man-hours of weightless exposure, and the experiences of the Soviet cosmonauts, which have provided an additional 533 hours.⁵

Experience to date has revealed none of these detrimental occurrences that some had considered. Careful preflight and postflight examinations have indicated no significant changes in the visual system of any of our astronauts as a result of space flight. There were two inflight incidents of somewhat severe eye irritation: one as the result of exposure to lithium hydroxide in the suit circuit, and, in the other, the precise cause was undetermined. Immediately postflight, we have noted some mild conjunctival injection that cleared within a few hours. We felt this injection was primarily due to the drying effect of the rich oxygen environment. This had been anticipated, so a small vial containing 1% methyl cellulose ophthalmic solution was provided in the onboard medical kit for such purposes which proved to be useful. Such occurrences were not uncommon in chamber simulations or as the result of leakage around the nosepiece of faulty oxygen masks during aerial flights.

We also anticipated the possibility of some decrease postflight in fusional amplitudes (often referred to as vergence amplitudes). This was found in a few instances, primarily after the longer missions and was probably the result of some fatigue. These measurements returned to normal after a few hours of rest. Some colleagues suggested that a possible cosmic ray strike could be detected should the lens of the eye be involved. Slit lamp examinations performed postflight on all astronauts have revealed no evidence of any lens damage. To date, there have been no significant changes noted in the visual capability of any American astronaut or Soviet cosmonaut to my knowledge from weightlessness. This has borne out the main point of our presentation at the Third International Symposium in 1964 when we then stated that the visual system was more than adequate for all planned space flight missions and that no operational plans should be slowed down or suspended for lack of information about the eyes. We see no reason to change our minds for future planned missions as

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long as our men are informed and continue to have adequate life support and protective equipment.

The planners for future space missions, such as Apollo, realize that man will continue to operate in a unique visual environment and know that many of the mission requirements are absolutely dependent upon the astronauts' vision.* They are therefore interested in obtaining important information concerning the visual requirements of these missions to enhance man's effectiveness. Adequate, accurate information is required by engineers who must design guidance systems, display panels, and protective and support equipment. Available information, as shown in Table I regarding parameters of the space environment which could directly affect vision, is being catalogued by NASA scientists.

Table I. Primary Parameters of the Visual Environment of Space*

	90° Solar Illumination	Surface Reflectance	Mean Atm. Transmission
Earth (Night illumination with full Moon = 0.04 ft-c)	10,800 ft-c	Ocean .03 Ground .15 Snow .80	.70-.80
EVA (Earth Orbit)	12,700 ft-c	Aluminum .55 Dark Paint .10 White Paint .80	1.00
Moon (Full Earth = 1.25 ft-c; 30° phase = 0.80 ft-c; 90° phase = 0.26 ft-c)	12,700 ft-c	Maria .07 Crater Wall .20	1.00
Mars	7,600 ft-c	Maria .17 Continents .18	.80

*From the article, "Advanced Vision Research for Extended Spaceflight," by Walton L. Jones, M.D., William H. Allen, and James F. Parker, Jr., Ph.D., *Aerospace Medicine*, Vol. 38, pp. 475-8, 1967. Reproduced by permission of Aerospace Medicine.

This table presents the primary variables which determine levels of useful visible radiation. It indicates that the level of illumination above the atmosphere during daylight is about one-fifth higher than that on Earth. This will be attenuated to some extent by spacecraft windows, visors, etc. It is also of interest that night illumination on the Moon may be as much as 60 times higher than that which the astronaut is accustomed to on Earth. This, of course, will work to his advantage since it will allow operating under mesopic rather than scotopic conditions. Such practical information is necessary not only in the design of flight equipment but also in developing realistic simulators for the training of astronauts in anticipation of what they will see on the lunar surface. It is realized that this data is not finalized but is constantly being updated as new information becomes available. This pool of information will be available to engineers as well as to investigators in the biomedical fields.⁶

Specific tasks for each mission must also be anticipated and delineated in defining operational visual requirements. There are a number of tasks on the Apollo mission in which vision of the astronauts is a primary factor. Some of these tasks are listed in Table II which describes the types of visual performance anticipated in the environment.⁶

Table II. Apollo Mission Tasks With Critical Visual Performances

Mission Tasks	Visual Tasks
Navigation	Locate and identify navigation stars, using IX, 60° scanning telescope and 28X, 1.8° sextant.
Docking	Angular rate discrimination in a range up to 3°/sec.
Lunar Landing	Discrimination of texture based on contrasts from 2.6 to -0.7 in illumination levels from 1500 to 4300 ft-c (alt. of sun 7° to 20°).
Extravehicular Maintenance	Discriminate brightness and color contrast under high glare with direct illumination to 12,700 ft-c.
Lunar Exploration	Observe terrain in absence of shadow gradients—shadowed areas completely dark.

From the article, "Advanced Vision Research for Extended Spaceflight," by Walton L. Jones, M.D., William H. Allen, and James F. Parker, Jr., Ph.D., *Aerospace Medicine*, Vol. 38, pp. 475-8, 1967. Reproduced by permission of *Aerospace Medicine*.

Researchers at the Ames Research Center are concerned with the expected visual environment of Mars⁷ and with the possible problems created by high luminances. They are studying visual processes associated with extreme light adaptation and glare and are concerned with the phenomenon called "retinal irradiance" in which a bright object appears larger than the angle it physically subtends. Since several navigation systems require measurements that involve luminous objects in the night sky, they feel the subjective expansion might lead to errors in measurement that could be of concern. Should these investigations prove the existence of significant errors, designers can consider corrective factors for design into the navigational systems or select appropriate optical filtering. These investigators are also concerned that retinal irradiance can lead to a perceived change in the physical appearance of a glare source under high-luminance conditions. They feel that space activities requiring the visual identification of an object on the basis of its shape may involve serious errors if the object subtends a small visual angle and is highly illuminated.⁸

Thus far, our astronauts have been successful in sighting and rendezvousing with the Agena vehicle or another Gemini capsule with which they were familiar and which they were anticipating, and the Soviet cosmonauts have not reported any apparent problems in their successful missions.

At Texas Christian University, NASA contractors are continuing the study of problems of distance judgment and rate of closure under simulated space conditions by presenting targets at apparent distances of 6 to 6,000 meters (20 to 20,000 ft). The object of this research is to ascertain the distance at which the visual detection of closing conditions is reliable. It is recognized that some of the visual cues utilized in judging distance and in perceiving depth are altered in the space environment, but they apparently have not deterred our astronauts in docking accomplishments thus far. Gemini VIII was our first experience with rendezvous and docking in orbit, and further experience was gained in IX-A, X, XI, and XII, with rendezvous and docking being completed during the initial orbit on Gemini Mission XII.

Man and his visual sensors are highly adaptable and can function well under even unusual circumstances; nevertheless, it

is to his advantage that he be as well informed as possible regarding what he will encounter. Experience with realistic simulators should enhance his confidence.

Reports indicate that the Lunar Excursion Module is to land on the Moon in sunshine conditions with the altitude of the Sun at between 7° and 20° . This provides less than a two Earth-day period in which optimal landing conditions can be met. It is entirely possible, because of unforeseen circumstances, that a landing may have to be accomplished during earthshine rather than sunshine. Therefore, a project has been underway at the Manned Spacecraft Center to study the minimum illumination requirements to perform successful lunar landings. This investigation utilized a helicopter equipped with a modified lunar module window to simulate lunar module flight trajectories from 30 meters (1,000 ft) of altitude to the surface. The trajectory, the window visibility requirements, and the ability of the pilot to select and commit to a landing site were thus evaluated under various lunar brightness levels. This investigation indicated that a surface brightness level of 0.04 ft-L is required. The Apollo schedule calls for a landing in daylight, but circumstances could change at the last minute and data on the astronauts' ability to land on the lunar surface under all conditions is therefore essential.

A number of reports are available regarding lunar environment. We find that daytime illumination at the Moon's surface exceeds that on Earth by about 25% and the nighttime illumination facing the Earth is approximately 60 times that of the Earth due to Earth's reflectance. This advantageous earthshine will illuminate the Moon's surface with a brightness which is sufficient to read a newspaper. It is noted that many of the visual cues which we ordinarily use will not be available or may be modified on the lunar surface, and certain cues such as aerial perspective and familiar reference objects for judging distance and size will be lacking. Harsh luminance contrasts will provide the astronaut with an unusual picture, and, because of the lack of atmospheric scattering, the deepest shadows will approach zero luminance.^{8,9} Due to a lack of scattered light to illuminate areas directly shaded from the Sun, auxiliary light sources will be needed. Well-designed reflectors and even small fingertip lights similar to the ones developed by astronauts on early Mercury flights could be most useful.

Since the sky will appear essentially black above the lunar horizon, the Sun will present a definite glare source, and, due to the need for thermal regulation, vehicles and fixed installations which may be highly reflective will contribute other glare sources.⁹ The time necessary to cause a possible solar retinitis by viewing the sun will also be shortened due to the lack of protective atmosphere, but the use of visors which also attenuate glare will obviate this possibility.¹⁰

The precise thresholds for an actinic keratoconjunctivitis from ultraviolet radiation have not yet been verified. Again, due to lack of atmosphere on the Moon's surface, ultraviolet radiation will be more intense than on Earth. The NASA has requested investigators at the USAF School of Aerospace Medicine to ascertain these threshold levels. This up-to-date information will provide data for proper visor and window design.

Filters will remain a necessity, and, should the state-of-the-art permit, a variable density feature that will automatically change with ambient illumination would be a welcome addition.

Some presently available materials can provide advantageous properties such as added strength or photochromic properties, but they still may contain some flaws that present-day technology has not yet alleviated. Consequently, some trade-offs may have to be considered. For example, should it be necessary to accept a less than perfect helmet or visor because of superior structural properties or other advantages, it becomes necessary that we know how much distortion can be tolerated by man's visual system without a serious performance decrement. Norma Miller at Technology, Inc., under contract with NASA, has been investigating visors, helmets, and transparencies with this problem in mind.

The visual capability of potential astronauts requires accurate assessment. The ophthalmologist-flight surgeon's function in the space program has been as examiner, consultant, and advisor. In the selection process, it has been his responsibility to ascertain that the astronaut-pilot's visual capabilities are excellent and will continue to be so on a long-term basis. His examination must rule out active subclinical diseases, early asymptomatic dystrophies, potential glaucomatous processes, abnormal accommodation, etc., and be designed to predict possible future incapacity of the visual system.¹¹

In the pre-launch examination, he must ascertain that there are no impending defects that could compromise the primary mission or interfere with prescribed onboard experiments. Upon the astronaut's return, the immediate functional ability of his eyes must be evaluated; any possible injurious effects must be detected; and, if it should be necessary, treatment rendered. This requires the utmost cooperation of each astronaut in undergoing not only the numerous ordinary examination procedures but also specific examinations designed to define physiological capacity from stress. This system has worked well, and our selected astronauts' performances in the Mercury and Gemini programs have been first-rate and appreciated.¹¹

We are firmly convinced that excellent visual function must remain one of the prime requirements for space crewmen. To allow anyone to explore these new environments without an optimum visual capability would be an unjustifiable waste of investment and constitute a significant risk of failure.

CONCLUSION

During the next phase of space exploration and landing on the Moon, the changes in lighting and the decrease in clues for distance judgment is evident, but the astronaut can and will compensate for these. Two inputs are needed: the absolute size of the viewed object and the rate of closure. If both or either is known, and by proper training they can and will, judgment of distance utilizing other available cues can be sufficiently accurate to assure success. As we have previously said, it is possible the visual sense can be tricked, but this is not likely in a highly trained astronaut.

Man is an adaptable and highly sophisticated computer that cannot be mechanically reproduced, but he does depend upon his eyes to provide the major input. These sensors are without parallel and are constantly tuned to receive data. As with any sensor, the human eye could be defective, but proper selection procedures can assure quality control.

As Professor Strughold so aptly stated in 1959, "Under the condition of weightlessness, vision is the only sensory means for orientation in space,"^{12, 14} and this soon after was confirmed by John Glenn during our first orbital flight.¹⁵

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These sensors are still without parallel and will not fail, provided our support systems are maintained and available knowledge is utilized. The human eye has proved to be a most reliable, unsurpassable, and indispensable sensor in the exploration of space.

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XIX

Biodynamic Environments in Spaceflight

Lt. Col. Neville P. Clarke*

INTRODUCTION

When the effects on crewmen of mechanical forces associated with aerospaceflight are evaluated, two sets of boundary conditions are pertinent: (1) those which establish the mechanical force environments (biodynamic environments), and (2) those which establish man limits to survive and perform adequately in these environments.

In the first case, the velocity change required to achieve orbital or escape velocity of Earth and other planets is obviously a boundary condition. However, the more important considerations are the engineering performance characteristics of the space system because these functional characteristics determine how the velocity change, either acceleration or deceleration, is achieved. Further, the system produces vibration and noise environments whose effect on crewmen must be considered. Previous experience has shown that space systems can be designed to perform under *nominal conditions* within the stated limits of safe exposure of crewmen and within limits which permit man to function as a useful part of the system. The area of more concern involves the effect of *non-nominal* or *emergency* conditions which can occur during spaceflight.

The second set of boundary conditions, those dealing with man, is interrelated to system function in that the limits imposed on the design of the system depend on the degree or level of performance required of the crewmen. Under nominal conditions,

*Chief, Plans and Operations Division, Directorate of Research and Development, Headquarters Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas.

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crewmembers may be expected to perform complex control tasks during exposure to, for instance, boost and reentry accelerations. On the other hand, under emergency conditions, they may only be expected to survive the forces associated with, for instance, an abort on the launch pad. These two extremes of required performance level are separated by a continuum when the multiplicity of in-flight conditions associated with the nominal and non-nominal function of a complex manned space system is considered. For example, if future spacecraft include an orbital escape system,¹ crewmembers may be called upon to effect a manually controlled reentry in a ballistic vehicle which exposes them to high acceleration forces, vibration, and unusually high temperatures.

Somewhat in contrast to the hardware system, man's response to the environment is not the same during all stages of flight but is dependent upon antecedent exposures to the conditions of spaceflight, including weightlessness. His response to biodynamic environments is also affected by concurrent exposure to other environmental extremes.

The relation between man and the space system he operates is, then, a complex one. The design of a manned space system involves estimating crew capability as a function of time and previous exposures versus engineering trade-offs in the functional characteristics of the system to optimize the usefulness of man.

In this paper, attention will be focused on two major aspects of effects of biodynamic environments of spaceflight on crewmembers: (1) the effect of increasing duration of exposure to weightlessness and other environments associated with spaceflight on subsequent response to mechanical force environments, with particular reference to (2) the effects of extremes of sustained acceleration, vibration, and impact forces which occur under emergency conditions.

MATHEMATICAL MODEL OF THE HUMAN BODY

The injurious effects of mechanical forces on the human body result from their producing relative displacement of one tissue or segment of the body with respect to another. For this reason, models which have been most useful in predicting effects of these

forces are those which consider the body as a mechanical system. One such model is shown in Figure 1.² This lumped parameter model provides a useful representation of the response of the body to vibration, impact, external pressures, and blast. Such models allow one to calculate curves of equal tissue stress as a function of amplitude and frequency of vibration or of amplitude and pulse duration of impact loads. These, in turn, form the basis for estimating curves of equal injury potential. The whole body mechanical impedance is defined by such a model and can also be measured under experimental conditions. Impedance is defined as the complex ratio of the force applied to the resulting velocity.

MECHANICAL MODEL FOR THE HUMAN BODY FOR G_z VIBRATION AND IMPACT LOADS AND EXTERNAL PRESSURE LOADS (ACOUSTIC, BLAST, DECOMPRESSION LOADS).

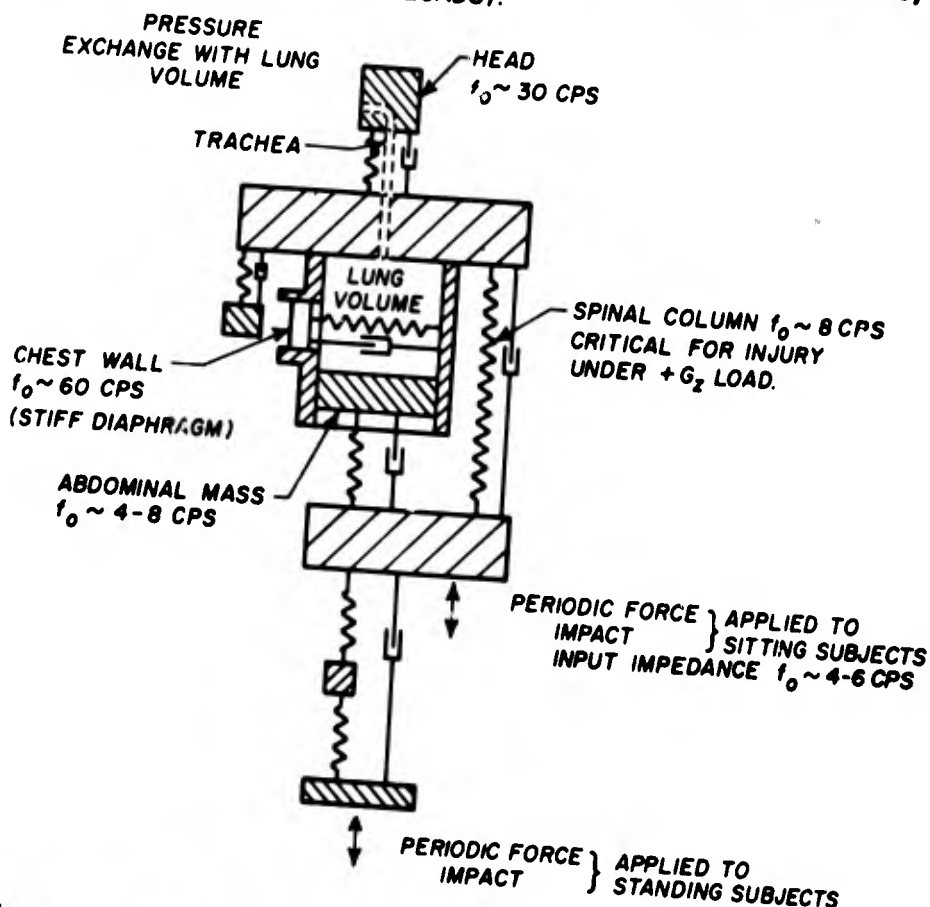


Figure 1. Mechanical model for the human body for G_z vibration and impact loads and external pressure loads (acoustic, blast, decompression). From Von Gierke (2).

In studies of the effects of vibration on man, the force is measured at the seat surface and constitutes an estimate of energy transmitted to the man. The function reflects the body's main resonances as shown in Figure 2.³ Whole body impedance changes considerably if the body is exposed to more than one g of sustained acceleration. This is important, for instance, if boost accelerations and booster induced vibration of the spacecraft occur concurrently, since effects of sustained g on vibration response characteristics are increased stiffness, reduced damping, and higher energy transmission to internal organs.⁴ As will be shown in a subsequent section, models related to this general analogue can be used to accurately assay the effects of G_z impact forces on man.

EFFECTS OF VIBRATION ON MAN

Figure 3 shows man's voluntary exposure tolerance to vibration as a function of frequency and duration.^{5, 6} This shows that the

THE MECHANICAL IMPEDANCE OF ONE SUBJECT SITTING AND STANDING IN VARIED POSTURES

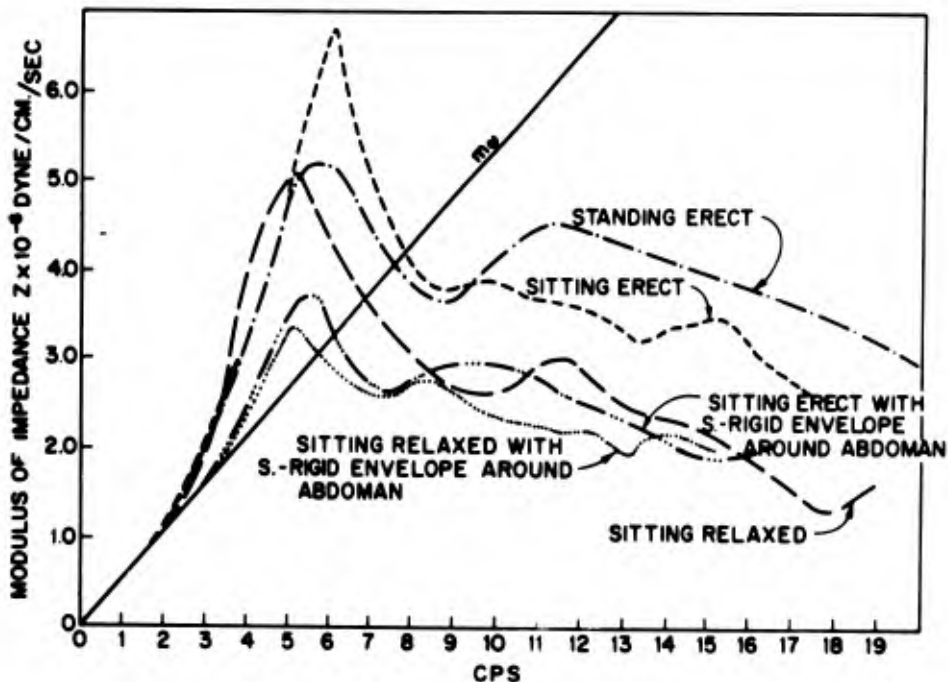


Figure 2. The mechanical impedance of one subject sitting and standing in varied postures. From Coermann, et al. (3).

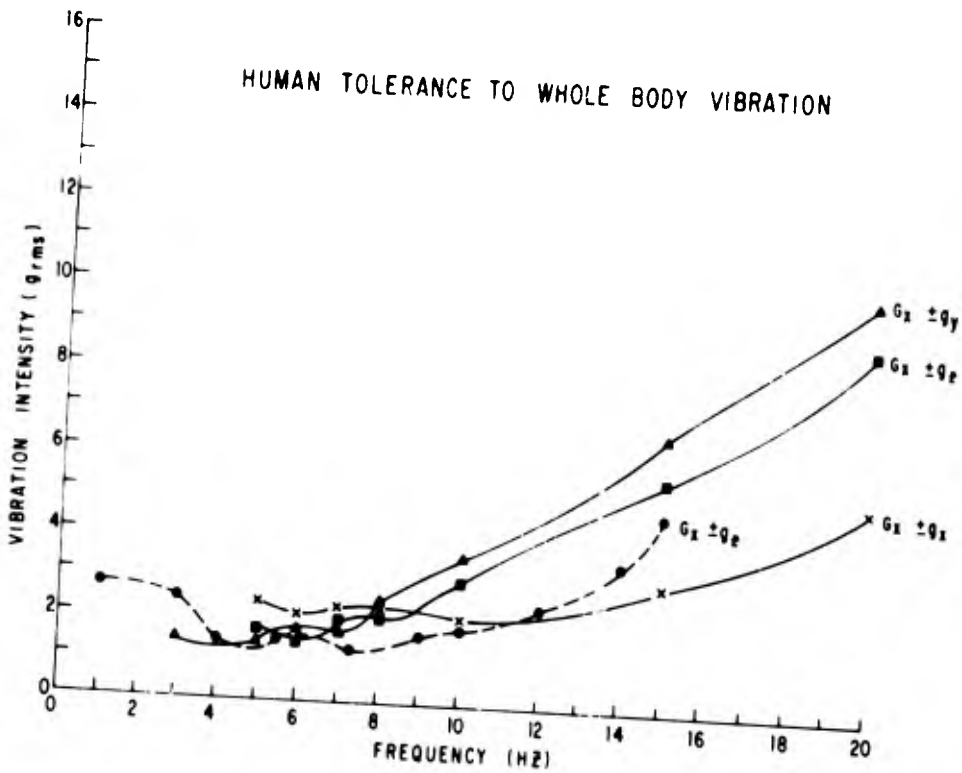


Figure 3. Human tolerance to whole body vibration in various axes. From Magid, et al. (5) and Temple, et al. (6).

minimum acceptable acceleration levels for vibration occur within the same broad frequency band of 2 to 12 Hz as the frequency range where the peaks in the curve for whole body impedance occur. In other words, man's tolerance limits to vibration exposure correlate well with the whole body mechanical characteristics which were discussed previously. Figure 4 shows mean arterial blood pressure, cardiac index, and heart rate in human subjects as functions of the amplitude and frequency during x-axis vibration.⁷ Again, the same frequency dependency as was seen for whole body impedance and voluntary human tolerance limits is evident in these physiological measurements. Minute volume is also increased during vibration, with the largest changes occurring in this same 2- to 12-Hz frequency range. Part of the increase in respiratory volume can be attributed to the oscillating volume of air resulting from the involuntary movement of viscera into and out of the thorax with each cycle of vibration. This volume is in part

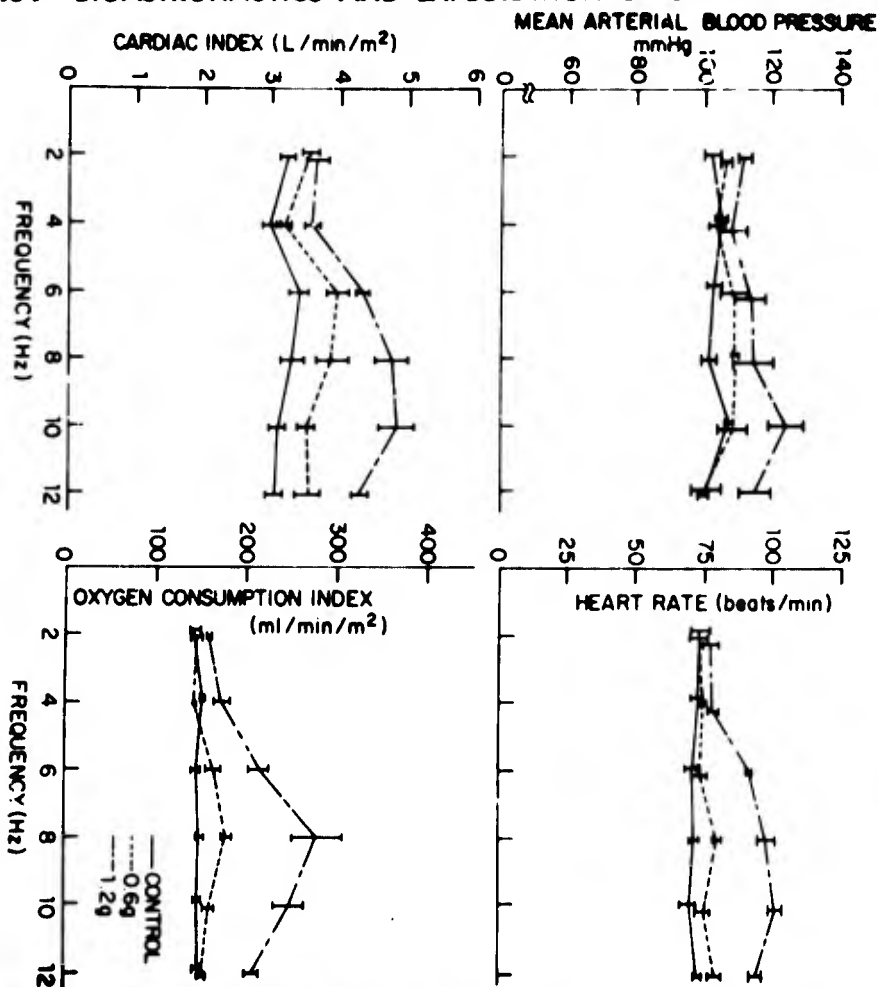


Figure 4. Effect of amplitude and frequency of $G_x \pm g_x$ sinusoidal whole body vibration on mean arterial pressure, cardiac index, heart rate and oxygen consumption. From Hood, et al. (7).

nonfunctional in that only the physiological dead space is ventilated. In some cases, the pCO_2 is decreased, and clinical signs of hypocapnia are observed. This suggests that such exposures produce some degree of hyperventilation. Blood levels of corticosteroids and catecholamines are increased in animals during prolonged or severe vibration, indicating that this environment elicits the generalized response which has been shown to exist for other stressors.⁸ The combined cardiopulmonary response to vibration in the 2- to 12-Hz range is one which resembles the response to exercise. The increased effort in bracing against the vibration and possibly the increased work of breathing may account for some of the response, but apparently not all of it for the same trends

are seen in anesthetized animals. Several researchers have proposed that the stimulation of various mechanoreceptors in the skeletal muscle, cardiovascular tree, or pulmonary system may contribute to the observed changes.

Maximum voluntary exposures to vibration are frequently limited by the appearance of a substernal chest pain. There has been considerable concern that this pain might be cardiac in origin. However, recent studies⁹ have shown that blocking of the intercostal nerves with local anesthetic either abolishes or greatly reduces the severity of the chest pain. This indicates that the pain originates by stretching of the perichondrium, periosteum, or the joint ligaments at the costochondral and/or costosternal junctions.

At frequencies of vibration in excess of 10 to 12 Hz, the symptoms limiting voluntary exposure shift from the thorax to symptoms associated with the head and neck. In the range of 25 to 30 Hz, resonance of the head with respect to the shoulder girdle occurs. At frequencies in the range of 60 to 90 Hz, resonance of the eyeball occurs. Both of these tend to limit visual capability in the respective frequency ranges.

Motor performance is, in general, limited by the involuntary displacement of the extremities: either by passively induced motions of the torso or by relative motions of the extremities with respect to the torso. As would be expected, maximum motions of the extremities are related to the basic mechanical properties of the body which were previously described. At very low frequency vibrations, man attempts to correct for the individual oscillations passively induced in the extremities. In some cases, his efforts to correct for these involuntary displacements produce even further errors in control (referred to as pilot-induced oscillations).¹⁰ As indicated above, decrements in visual capability are related to relative displacement of the eye with respect to the instrument panel. In the frequency range of 2 to 12 Hz, visual decrements are related primarily to passively induced movements of the head, resulting from torso motions. In the higher frequency range, i.e., 25- to 30-Hz, torso motions are relatively small, but resonance of the head tends to produce further visual decrement. The effect of duration of exposures to vibratory environments is not generally a problem with manned spacecraft systems, since the duration of booster burning, reentry, and other operational situations potentially capable of producing vibration are relatively

short. However, in situations where exposures last for the order of minutes or hours rather than seconds, the overall factor of fatigue and its effect on performance are of concern. There is no clear-cut indication that vibratory environments, *per se*, influence man's intellectual capability.

Most of the potentially severe vibratory environments predicted for manned space systems occur during boost or reentry. This means that the vibrations which do occur will be superimposed on varying levels of long-duration, linear acceleration. Very little data exist concerning the effect of the combination of these two environments on the crewmen's ability to perform. The limited studies which are available suggest that the linear acceleration may provide an improved coupling of the body and head to the support system, with the result being that the performance, particularly in terms of visual ability, may be slightly enhanced by the combination of the two environments.¹¹ There is at least no indication that the combination of sustained acceleration and vibration is any worse than the equivalent vibratory environment in the absence of sustained acceleration.

Protection against vibratory environments can be approached in basically two ways: First, the restraint and support systems employed can couple the man as rigidly to the system as possible. Secondly, the protection system can provide isolation from the environment where possible. Under ideal conditions, the optimal protection system would employ the latter approach, but this frequently proves impractical in the case of very low frequency vibration because of the requirements for displacement and the limited space available to provide this within the spacecraft.

One example of an isolation system currently in use is the nonlinear seat cushion which is used to attenuate high frequency (low displacement) vibration while at the same time providing more or less rigid coupling of the man to the system where large displacements are encountered with low frequency vibration. A second, more recent development under consideration involves an active mechanohydraulic isolation system which is interposed between man and the seat of the vehicle.¹² This system senses the acceleration environment and adjusts the degree of damping imposed between the system and the seat in such a way as to optimize the acceleration force delivered to the man. One of the

overall problems in providing vibration protection, either to prevent injury or to enhance performance, lies in the fact that the same hardware utilized for this purpose must also function during the imposition of high-amplitude acceleration forces which may be associated with emergency escape or abort. In this case, "bottoming out" is the matter of major concern and must be prevented by nonlinear characteristics of the system.

EFFECTS OF IMPACT ON CREWMEN

Short-duration transient accelerations or impact accelerations occur either during ground-landing impact of vehicles which descend to Earth by parachute or during emergency escape conditions. As previously indicated, in this condition, the requirement for performance of crewmen is generally regarded as minimal and consists at most of monitoring critical instruments to make further decisions about deployment of emergency equipment. The use of mathematical models of the human body has been particularly fruitful in describing the probability of injury associated with arbitrary G_x impact acceleration environments.¹³ The model employed uses the load applied to the vertebral bodies as the critical factor. Vertebral injuries have been the most common failure mode in G_x impact accelerations. In this orientation, then, knowledge of human responses to impact have been sufficiently refined so that it is possible to predict the probability of injury based on what has been called the dynamic response index. Knowledge of maximum exposure limits and failure modes for lateral or transverse acceleration (G_y and G_z) are less refined, so that a mathematical model to predict the probability of injury for acceleration vectors directed in other than the $+G_x$ orientation does not presently exist. Design criteria for these modes of acceleration are then more empirical in nature and are based primarily on operational experience and on empirical test data which demonstrate survival without injury of impact accelerations with varying durations, amplitudes, and rates of onset.¹⁴ The maximum safe exposure to impact accelerations may well be a function of the duration of antecedent weightlessness. The reasons for concern over this situation in long-duration, manned spaceflight will be discussed in the next section.

EFFECTS OF SPACEFLIGHT DECONDITIONING

Spaceflight deconditioning, as considered in this paper, refers to the physiologic and biomechanical alterations in the body which

occur as a result of the combination of environmental stressors which are associated with spaceflight. It is assumed that the major factors at play are the physiologic effects of weightlessness. Previous operational experience has involved variations in performance of environmental control systems, so that it has not been possible to attribute the observed deconditioning solely to the effects of weightlessness but, rather, to the concurrent effects of thermal extremes, i.e., possible dehydration. Weightlessness is generally presumed to affect mainly the cardiovascular and musculoskeletal systems. Ground-based simulations of weightlessness to study these two systems consist of evaluating the effects of bed rest, immobilization, or immersion of the body in water. Results of both operational and experimental studies of cardiovascular effects of space flight deconditioning and possible countermeasures are discussed elsewhere in this book (Ref: Swan, Berry).

EFFECTS OF BONE DEMINERALIZATION FROM WEIGHTLESSNESS ON ACCELERATION TOLERANCE

It has been known for over a century that mechanical stresses such as those produced by weight bearing and muscle tension are necessary for the maintenance of normal skeletal mass.¹⁵ In the absence of these stimuli, bone becomes spongy and porous (osteoporotic), its density diminishes, and it becomes susceptible to fractures. Whole body immobilization and bed rest, to some extent, without immobilization result in an increased excretion of calcium in human subjects and a gradual loss of bone density.^{16, 17} The similarity between these experimental conditions and those encountered during weightlessness in spaceflight led to the postulation that similar changes in bone composition and morphology might be expected during protracted orbital or interplanetary flights. These predictions were at least qualitatively confirmed in the recent experience with Gemini flights.¹⁸ In Gemini V, for instance, a 10% to 20% reduction in bone density of the calcanei and metacarpals was estimated for both the command pilot and the pilot after this 8-day mission. Although less quantitative measures were obtained in Gemini VII, this 14-day mission also led to a distinct tendency for bone loss and increased calcium excretion.¹⁹ Whole body immobilization of human subjects by casting is associated with a reduction of between 1 and 2% of total body calcium per month.¹⁵ This calcium loss persists for many

months at approximately the same rate. Clinicians estimate that a loss of 30% to 50% of the specific bone volume can produce "spontaneous" fractures associated with normal activity.²⁰ The basic question at issue is, therefore: Will a prolonged 0-g environment alter human bone structure and strength to such an extent that reentry profiles and other acceleration stresses must be regulated in consideration of a possible decrease in acceleration tolerance? Under extreme conditions, one must question also whether the normal 1 g of Earth's gravity will represent, for at least some period of time, a potential danger to the weakened skeleton.

To investigate these questions, rhesus monkeys, whose distribution of mass about the bony skeleton and whose general morphology are reasonably analogous to man, were immobilized in whole body casts for periods of 60 days.²¹ Both the control animals (allowed freedom of motion in standard cages) and the experimental animals were maintained under similar controlled environmental conditions. The animals restrained in whole body casts were fed a standard diet twice daily and offered water, at regular intervals, sixteen times daily. Some animals were subsequently exposed to short-duration high-amplitude impact accelerations in the G_x orientation. Others were sacrificed, and the musculoskeletal systems were examined to determine changes in the gross appearance and dynamic structural characteristics of the bone, muscle, and ligamentous and tendinous attachments of muscle to bone.

Figure 5 shows a sagittal section of a lumbar vertebra from a control animal (left) and a monkey immobilized for 60 days. The striking feature observed is a thinning of the trabecular structure, particularly in the area of the lamina terminalis. This thinning of the trabecular structure is associated with a decrease in red marrow, along with a replacement by fatty infiltration. This change, along with the decreased trabecular structure, produces a less effective damping mechanism for hydraulic energy dissipation. The force required to produce a failure when such vertebrae are loaded in compression is approximately two to three times less than that required to deform a normal, average vertebra (Fig. 6). Also observed was a slightly increased vertebral concavity in the central portion of the lamina terminalis. When two vertebrae are loaded in compression, the intervertebral disk erupts into the lamina terminalis of the adjacent vertebra body, with a shattering of the end plate.

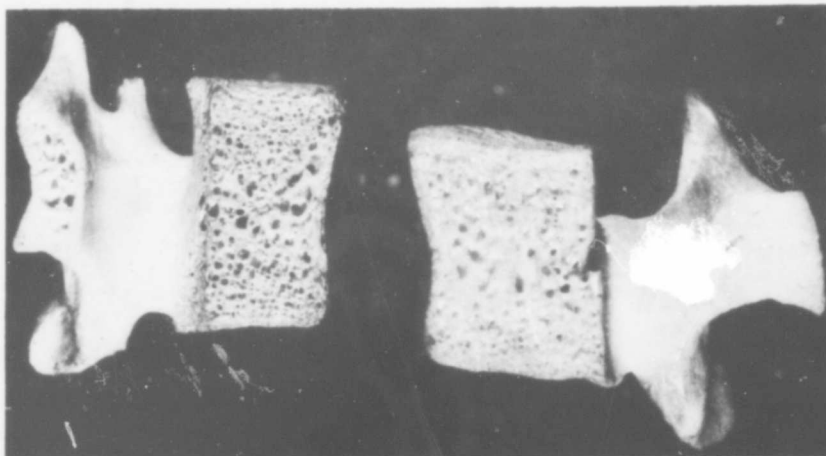


Figure 5. Effect of immobilization on architectural changes of lumbar vertebra in the monkey. On the left sagittal section of a vertebra from an animal immobilized for 60 days in comparison to the vertebra of a control animal on the right. From Kazarian (21).

Figure 7 shows the external appearance of lumbar vertebrae from a normal rhesus monkey. In contrast to this, Figure 8 shows a similar vertebra from an animal immobilized for 60 days. The most notable feature is the marked resorption of cortical bone—particularly at the sites of muscle and ligamentous attachment. Notice also what appear to be numerous resorption channels which have formed over the external surface of the cortex. Disuse atrophy of the skeletal muscles was also demonstrated by using a technique which estimated the volume of corresponding control and experimental muscle masses. There was approximately a 30% reduction in the energy required to separate tendons from the periosteum overlying these areas of porous cortical bone. In animals exposed to $+G_z$ impact following immobilization, compression fractures of the thoracic vertebrae occurred at energies which were also approximately 30% lower than those required to produce similar injury in control animals.

Figure 9 shows similar osteoporotic changes in the head of the femur in comparison to control animals (shown on the left). Note that the trabecular structure, as well as the cortex, is reduced in volume.

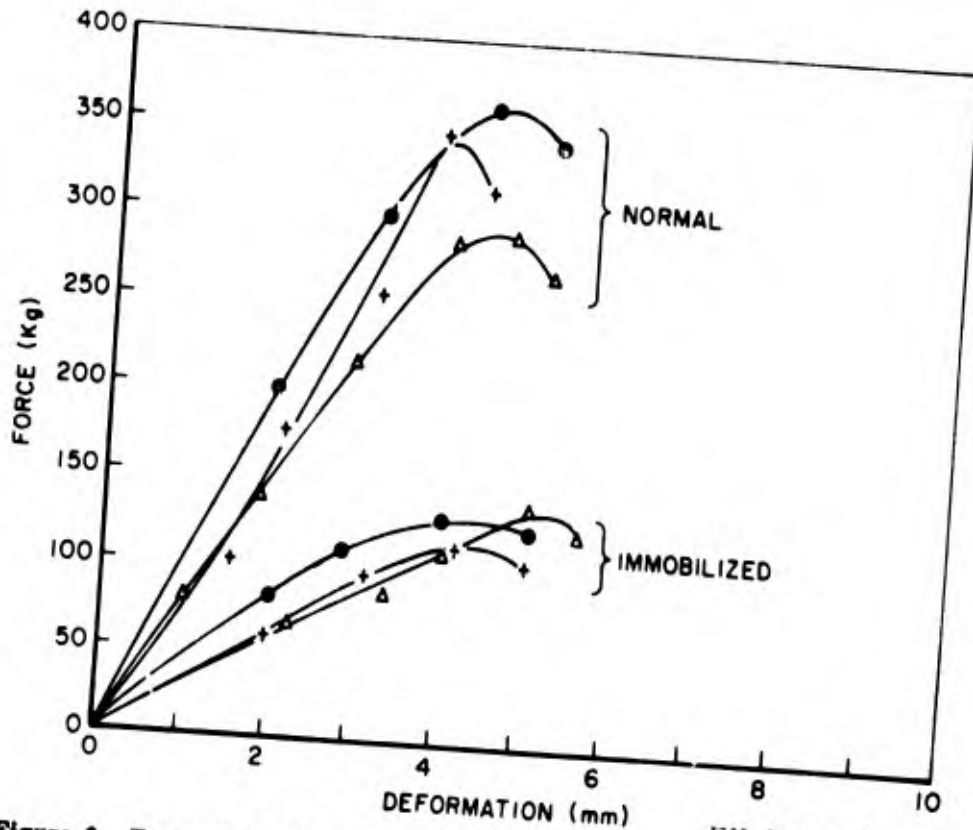


Figure 6. Force deflection curve for vertebra of normal and immobilized rhesus monkeys. Note the reduction in force required to compress and to cause failure of the vertebra from immobilized animals is much lower than that for a normal animal. From Kazarian (21).

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The mechanism by which normal skeletal architecture is maintained under normal conditions is unknown. However, it appears that the dynamic forces imposed on the bone by weight bearing and by contracting muscle activity are a necessary stimulus to the maintenance of normal bone architecture. It has been demonstrated that bone has a piezoelectric property such that strain produces an electrical potential.²² It may be that the electrical potential so generated is a necessary stimulus required to maintain normal bone metabolism and geometry. Immobilization produces a general picture as though remodeling occurs to the point which is minimally necessary to maintain the static structural integrity of the bone. The remainder of the trabecular structure tends to be resorbed. Muscular atrophy combined with the reduction in strength of muscle attachments to bone not only favors soft tissue injury during exposure to abrupt acceleration but also

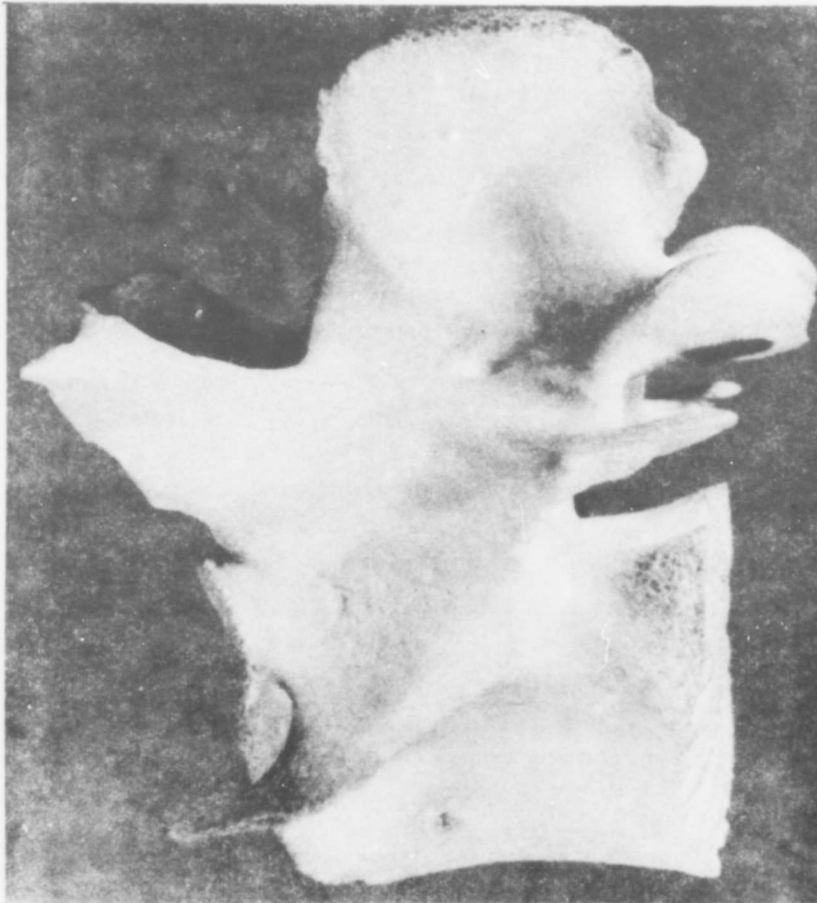


Figure 7. External surface of the vertebra from a normal rhesus monkey. From Kazarian (21).

increases the probability of bony injury due to loss of the support that normally would be provided by the muscles.

Although the rhesus monkey, a subhuman primate who is fairly analogous to man, is a useful experimental animal for these studies, it is apparent that the growth and maturation rates of this animal, as well as other dissimilarities between this species and man, make it necessary to evaluate the quantitative results of these data with

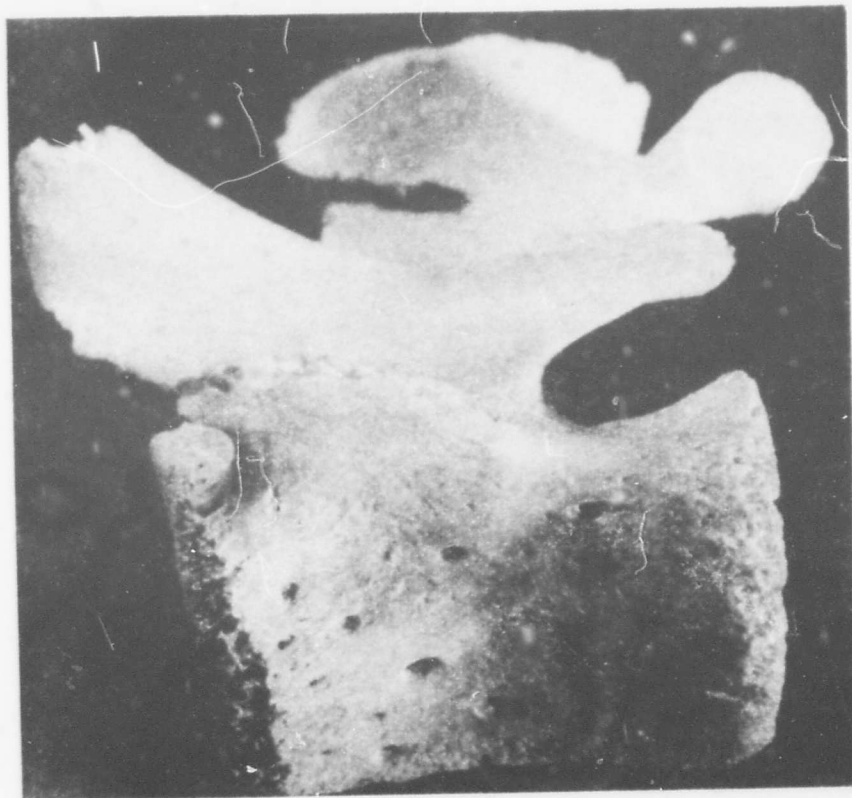


Figure 8. External surface of the vertebra from a monkey immobilized for 60 days. Note the resorption of bony material particularly at the site of insertion of vertebral muscles. From Kazarian (21).

some caution. The similarity of whole body immobilization to that of the situation encountered in weightlessness is also subject to reservation, although the similarity of general pattern observed in man between bed rest and the limited observations of astronauts under operational conditions leads one to believe that the qualitative results of these experiments can be accepted as being likely analogues to the operational situation.

It seems reasonable to conclude, therefore, that considerable attention must be devoted in future ground-based experiments, as well as in longer duration spaceflight missions to the factors which lead to the altered structure and metabolic changes in bone which are associated with weightlessness. It is difficult to propose an effective countermeasure against this phenomenon in the absence



Figure 9. Sagittal section of the head of the femur from (left) normal and (right) from an animal immobilized for 90 days. Kazarian (21).

of definitive knowledge of the mechanisms which are involved in maintaining normal bone geometry. Preventive measures which come to mind are artificial gravity, hormone therapy, and physical exercise—although, to date, none of these have been validated. Tailoring of reentry acceleration profiles, as previously indicated, and optimization of support and restraint systems to reduce the bending and loading of bony structures can also be considered. Adequate methods for impact attenuation to reduce the effect of the accelerations associated with post-reentry ejection and escape, as well as with ground landing impact, will need consideration in future manned space missions of increasing duration.

BEHAVIORAL LOSS AND OTOCONIA DISPLACEMENT IN GUINEA PIGS FOLLOWING LINEAR ACCELERATION

The pathophysiological effects of sustained acceleration have traditionally been cited as being primarily related to the cardio-pulmonary system.²³ Performance limitations are usually regarded

as those restricted by incapacitation of the motor and visual systems.²⁴

Recent experiments have revealed still another potential pathophysiological effect of this environment as it may occur under operational conditions. This was the demonstration of mechanical damage in guinea pigs to the saccular and utricular maculae; sensors which detect static gravitational forces.²⁵ Histological evidence of this damage was significantly correlated with loss of swimming ability and righting reflex in these animals. Figure 10 shows a dissection through saccule of a guinea pig exposed to 25 g for a period of 195 seconds. Detachment of the crystalline maculae from the otoconia and dispersion of the granules in the endolymph is clearly evident. Figure 11 shows a similar, although less severe, detachment of the same structure produced by an acceleration of 25 g for 95 seconds. The minimum acceleration intensity for loss of the righting reflex and swimming ability was approximately 50 g, lasting for a duration of 60 seconds. Evidence of loss of the



Figure 10. View through a dissection microscope of the saccule of a guinea pig exposed to 25 g for 195 seconds. From Parker, et al. (25).



Figure 11. View through a dissection microscope of the middle ear of a guinea pig exposed to 25 g for 195 seconds. From Parker, et al. (25).

otoconia from the maculae, without demonstrable behavioral changes, may be produced by acceleration as low as 12 to 25 g for durations of 195 to 330 seconds. Acceleration at 100 g for 30 seconds results in severe loss of otoconia from all maculae. Recovery of swimming ability and righting reflex may take place in from 1 to 64 days following exposure of accelerations of up to 300 g for 15 seconds. However, exposures at 400 g for 15 to 20 seconds result in an irreversible loss of the righting reflex and a severe disturbance of swimming ability. No histological evidence was observed for otoconia reformation during postexposure periods. However, the possibility for replenishment of the gelatinous layer of the otoconia was suggested. Similar deficits in righting reflex and swimming ability were also observed following severe exposures to vibratory environments. Although the nominal operational accelerations predicted for launch and reentry are less than those required to produce functional and anatomic evidence of injury to this system in the guinea pig, this potential mechanism of injury and its resulting behavioral deficits must

be considered in the definition of acceptable upper limits of acceleration exposure which may occur during non-nominal or emergency conditions.

CONCLUSIONS AND SUMMARY

The biodynamic environments which are predicted for nominal performance of systems for future, long-duration, manned spaceflight are not necessarily any more severe than those which have been successfully tolerated in previous operational experience. Design of future manned spacecraft will need to consider the upper limits of maximum safe exposure, as well as decrement in performance as a function of severity of the environment for non-nominal or emergency conditions. The major unknown factor in biodynamics which must be evaluated in the consideration of very long-duration missions, such as might be encountered in manned orbital space stations or in interplanetary travel, are related to the potential effects of confinement and weightlessness on the cardiovascular and musculoskeletal systems. It would appear that the concern over these effects is not so much related to man's ability to survive and to perform useful functions during weightlessness, but, rather, the effects of subsequent reentry emergency escape and landing impact forces on an astronaut whose cardiovascular and musculoskeletal systems have been deconditioned as a result of antecedent weightlessness to the point where his ability to withstand these forces is restricted. Countermeasures against both cardiovascular and skeletal deconditioning have been proposed and will be evaluated as the duration of spaceflight missions is gradually increased. However, obtaining techniques or equipment for preventing this form of spaceflight deconditioning requires an objective determination of the basic control or regulatory mechanisms whose functions are altered by this environment.

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Nutrition for Long Space Voyages

Dr. John E. Vanderveen*

Experience with the short-term flights of Mercury and Gemini has demonstrated the need to carefully plan the space pilot's diet on an individual basis. It became evident that personal preferences in food significantly influenced food consumption. Total food consumption was insufficient to provide body needs for nutrients, and, although complete direct measurements were not made, actual tissues losses were evident¹. These nutrient deficiencies may have been partly responsible for the biochemical and physiological changes observed in these flights. For long space voyages, losses in body tissues cannot be tolerated. Continued losses will eventually result in decrements in physical performance and in mental acuity.

PLANNING SPACE DIETS ON AN INDIVIDUAL BASIS

The fact that variations exist in nutritional requirements is well established. Such factors as body size, level of activity, age, and environment are among the many factors which influence nutrient requirements. In most cases, the important consideration is to provide sufficient quantities of each nutrient to meet individual requirements. Moderate excesses of each nutrient generally present no hazard since the body can control tissue levels through absorption, storage, catabolism, and excretion. Energy requirements, however, are an exception. Insufficient energy in the diet results in the catabolism of body tissues which include not only fat but protein and other organic constituents. Excess energy (in the diet), however, is stored only as fat or glycogen.

*Chief, Metabolic Factors Function, Physiology Branch, Environmental Physiology Division, USAF School of Aerospace Medicine, Brooks Air Force Base, Texas 78235.

Planning diets to meet the individual energy requirements of each astronaut is a cumbersome task. Ideally, each astronaut would undergo a metabolic balance study to define his individual requirements. The demanding training schedule of the flight crews has made such a study impossible; therefore individual energy needs will have to be established on a less rigorous basis. During the past 75 years, extensive research has been conducted to establish the factors associated with energy requirements². This research has resulted in the establishment of several systems for predicting individual energy needs. However, even the most consistent methods were not reliable for predicting the caloric requirements of men having extremes in body composition. As a result, the Physiology Branch of the USAF School of Aerospace Medicine (AMD), Brooks Air Force Base, Texas, undertook a study to measure the nutrient requirements of man while living in a simulated space environment. These studies were carried out using a low pressure chamber to provide an atmosphere comparable to that planned for future space vehicles. Subjects were selected from volunteer airmen on the basis of medical records, results of aptitude tests, and personal interviews. Metabolic balance studies were performed for energy, nitrogen, calcium, potassium, sodium, phosphorus, magnesium, and manganese. Prior to and immediately following each study, body composition measurements were calculated for each subject using data on total body water, body volume, and body weight³.

The results of these studies show that lean body weight measurements are very reliable for estimating human caloric requirements. In Figure 1, the body weight changes for forty subjects are plotted versus the kilocalories consumed per kilogram of lean body weight. A level of 41 kilocalories/kilogram of lean body weight/day was sufficient to maintain body weight for periods of at least 60 days. In Figure 2, the lean body weight changes are plotted versus the caloric levels consumed. These data reveal that lean mass is lost when insufficient energy is consumed to maintain body composition. In Figure 3, the fat body weight changes are plotted versus the caloric intake, and these data show no correlation of losses when insufficient calories are consumed. However, excess caloric intake is expected to show a corresponding increase in body fat. For long space voyages, it is now possible to estimate each astronaut's caloric requirement and thereby permit him to consume the correct amount of food to maintain his body composition throughout the flight.

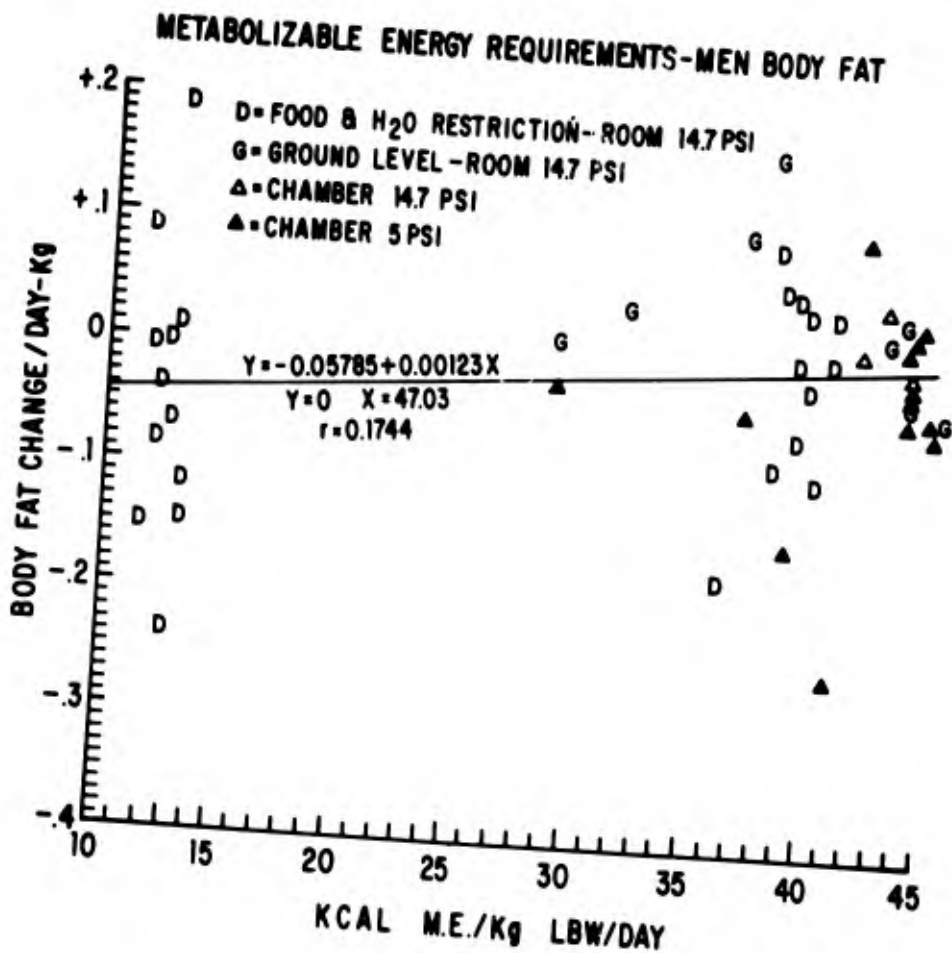


Figure 1

Allergies and biochemical insufficiencies must also be considered when planning an astronaut's diet for long space voyages. The effects of food allergies are well established and need no further discussion here. It is sufficient to say that each astronaut should be examined for specific food allergies, and those foods should be eliminated from his diet. Similarly, astronauts should be examined for evidence of enzyme or other insufficiencies which will influence his digestion of nutrients. An example of this is found in lactase deficiency which affects large segments of adult male populations. These individuals have an inability to utilize lactose which is found in whole milk. In some individuals, the consumption of whole milk causes a gastrointestinal syndrome characterized by the production of gas, discomfort, and frequent defecations. For these individuals, milk or milk products should

METABOLIZABLE ENERGY REQUIREMENTS-MEN BODY WT.

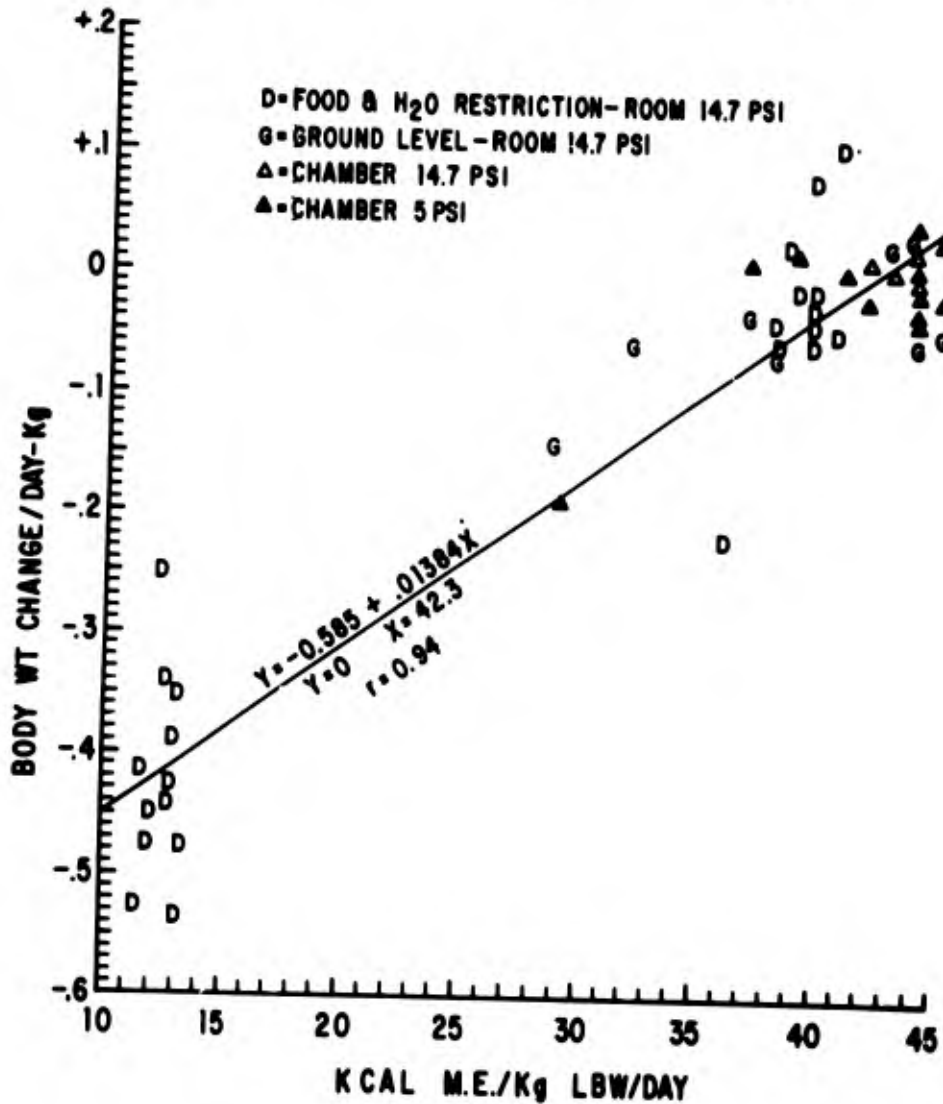


Figure 2

be eliminated from their diet. The existence of other enzyme deficiencies has been postulated; however, further research will be required for verification.

VITAMIN AND TRACE ELEMENTS

During long-term space voyages, greater attention must be given to the vitamin and trace element requirements of man. Requirements for these nutrients are ill-defined for man largely

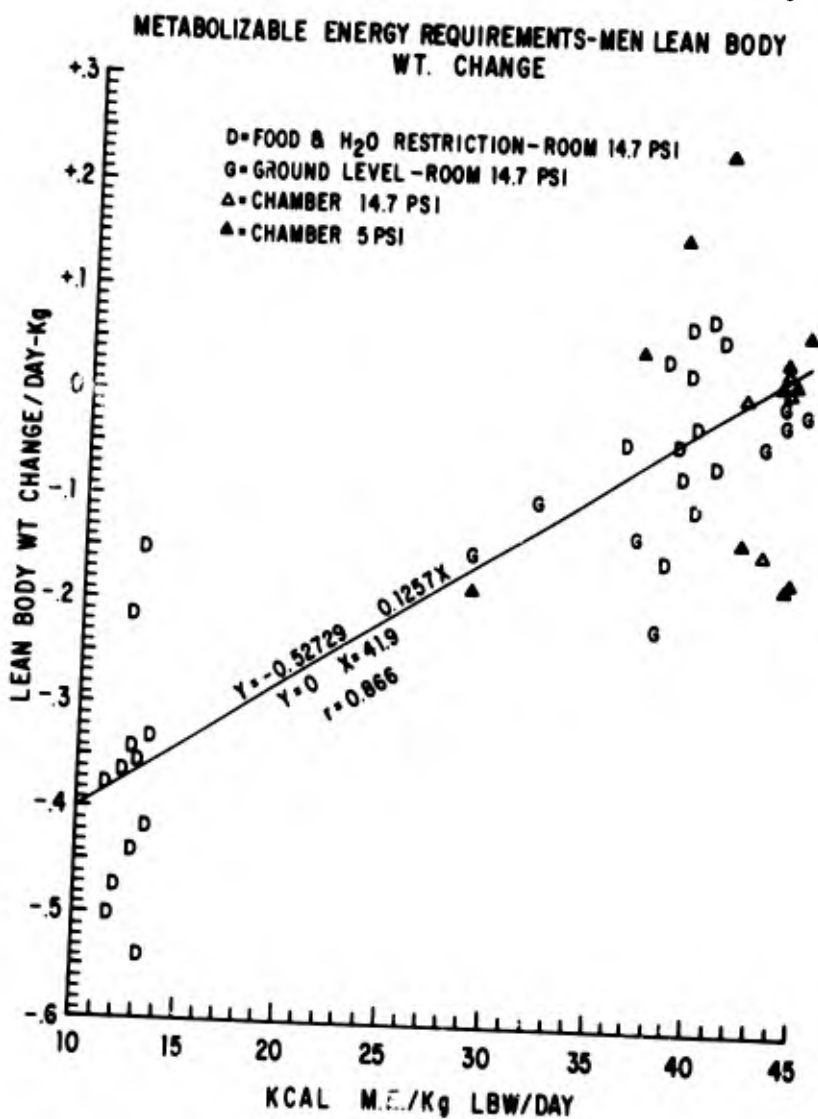


Figure 3

because most Americans eat a varied diet which provides sufficient quantities. Space diets by contrast are limited in the variety of foods, due to the demanding specifications imposed for space flight qualification^{4, 5}. It is therefore conceivable that present space diets require fortification to meet the astronaut's needs. There are some indications that astronauts may require additional vitamin allowances over those prescribed for Earth habitation. It has been postulated that Vitamin E and Vitamin C are both destroyed at a rapid rate in the high-oxygen atmosphere of spacecrafts¹. There is also a growing concern that vitamins,

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which are suspected of being produced by bacteria in the lower gastrointestinal tract, may become in short supply because of alterations in the bacterial population as a result of the environment and diet aboard the spacecraft. Although the body usually stores sufficient quantities of vitamins for use in periods of low intake, these supplies are expected to be depleted in a period from 30 to 60 days. A solution to the problem would be the use of daily vitamin supplements.

Trace element nutrition will be more difficult. There are elements which may be required in very small amounts which are as yet unrecognized as nutrients. In the last ten years, zinc has been identified as an essential element for growth, and it appears that selenium may also be required in trace amounts. Perhaps what is more important in trace element nutrition is the delicate balance which is necessary among the elements. The existence of interrelationships of copper, molybdenum, and sulfate are well known. Similar interrelationships are suspected for other elements. Several researchers have drawn correlations between trace elements imbalances and heart disease. Further investigation is required before such a relationship can be proven, but the importance of not adding trace elements to the diet indiscriminately is clearly emphasized.

IMPORTANCE OF FOOD ACCEPTANCE IN LONG SPACE VOYAGES

The importance of food acceptance has been well established in the short-term space missions completed to date. Indications are that the astronaut's food likes and dislikes influenced both what he ate and his total food consumption. In future flights, consumption of adequate nutrients will be vital to mission success. This does not mean that the astronaut will have to eat precisely the same amount of food each day, but rather that his daily average must meet his needs.

Research in the area of food acceptance and voluntary food consumption⁶ has confirmed several facts; (1) Individuals tend to select foods with which they have had previous experience. In general, they must acquire taste for entirely new foods. (2) Foods differ in the frequency with which they can be fed. Such foods as bread and potatoes can be consumed more frequently than other items, without the individual tiring of the item. (3) Any food

can lose acceptance if fed too frequently. (4) The acceptance of a food item is sometimes influenced by other food items available for consumption.

These four facts tend to encourage the development of more food items which have a closer likeness to those foods which are consumed by the average person. They also demand that the astronaut be given greater opportunity to gain experience with flight qualified foods before his flight. In addition, each astronaut's food preference must be taken into consideration when his menu is planned, and his menus must be arranged to limit repetitious patterns. The value of computers to accomplish this task has already been demonstrated⁷. It is anticipated that long-term space voyages will tend to increase the occurrence of food monotony; every effort will therefore have to be made to insure adequate food consumption. Food which is not consumed cannot provide nourishment.

FOODS FOR LONG SPACE VOYAGES

For missions up to 120 days, it is most probable that dehydrated foods, similar in composition to those presently being used in the Apollo program, will be used. These foods provide the maximum in economical use of available space and weight. They require no power for preservation, and they are high in food acceptance and nutrition⁸. Present production technics insure stability of the dehydrated foods for periods of up to a year in a spacecraft environment, and future development is expected to increase the stability severalfold. The processing of these foods is also advantageous to consumption. Many dehydrated foods can be consumed with no preparation, while others require only the addition of hot or cold water. It is anticipated that further refinement by compressing these foods into hard bars or bites will add further to the efficient use of space.

As space voyages become longer, the importance of considering the interaction of foods with medical science will increase. The food technologist and the dental scientist are already cooperating to develop specifications on the types of foods which will promote optimum dental health and reduce chances of creating a dental hazard in space. The importance of such planning can be seen in a recent simulator study in which a subject broke a restored tooth

chewing a piece of bite-size food. The dental scientists are also investigating the effects of space environments and space diets on the maintenance of both hard and soft tissues of the oral cavity. Data obtained from these studies will be used as criteria for future food development.

Further, packaging of dehydrated foods is expected to undergo drastic changes. Packaging presently accounts for over 40% of the weight of space feeding systems⁹. Recent developments in bulk storage dispensing devices hold promise for revolutionary changes in packaging methods for the future. The bite-size food dispenser shown in Figure 4 has many advantages over present feeding systems. This device can be used to hold over 14 man-days of food, and requires less weight and volume than the polylaminated film presently in use. In addition, the system provides greater crew selection, requires less eating time, and requires fewer storage

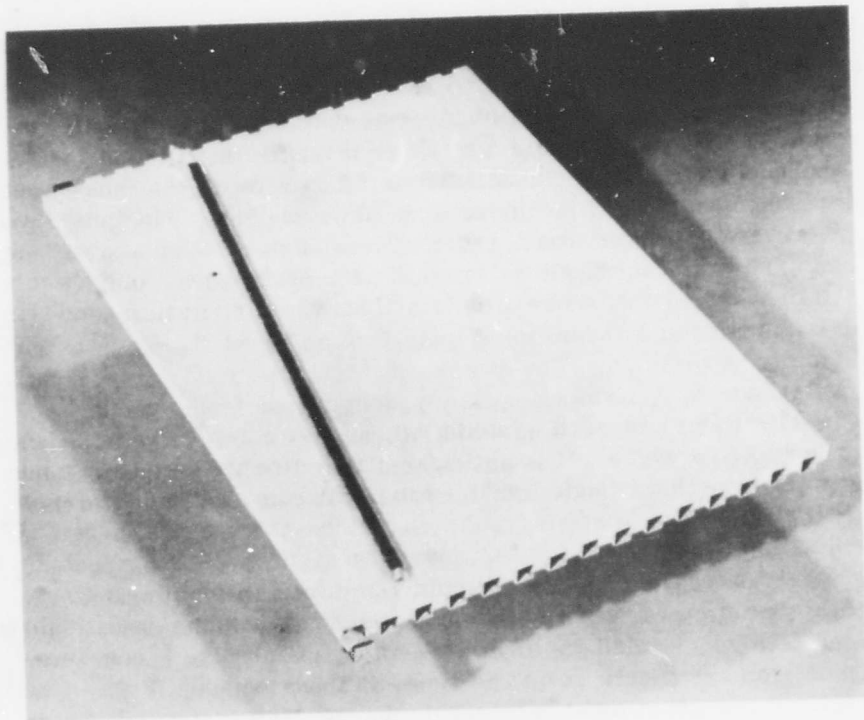


Figure 4

problems. This device can also increase the efficiency of available weight by being used as a structural partition within future spacecraft.

Similar devices are expected to be developed for storing and dispensing rehydratable foods. Storage dispensers will allow the crewman to vary his menu, to select different food combinations, and to eliminate waste storage problems. Recent investigations on food preparation and consumption in a weightless environment have revealed that moist or liquid foods can be consumed readily with conventional eating utensils. This will permit the use of a simplified fixable food container for rehydratable foods. Such a container will require less weight and volume and retain more food texture than the zero-g feeders presently in use.

FOODS FROM CHEMICAL AND BIOREGENERATION SYSTEMS

For space missions longer than 120 days, it is anticipated that chemical and bioregeneration systems may have greater efficiency than carry-aboard foods. The feasibility of such systems which provide part of the nutritional requirements of man has been widely demonstrated. Presently, however, both chemical and bioregeneration systems require extensive modification and further refinement. Such systems are still in a stage where only highly trained professionals can maintain them in an operating condition for any length of time.

The weight of such systems is still not competitive with the weight of carry-aboard foods, but no real attempt has been made to develop a lightweight system for flight use. Perhaps the most serious problem requiring solution before these systems can be used in space is that of the development of processing techniques which render food products acceptable for long-term space voyages. Most products from current systems have strange undesirable tastes which would tend to become monotonous, if not completely unacceptable, over a period of time. Extensive application of research and developmental efforts in food technology will be required to convert these products into foods which an astronaut will consume during a long-term space voyage.

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XXI

Space Chemistry in the 1970's

Dr. Willard F. Libby*

INTRODUCTION

The role of the chemist in the space program as it develops during the next decade probably will be important even though the main thrust of the program may not be chemical. It will be more than just furnishing rocket fuels since the spread of knowledge of materials and the fundamental nature of matter make the chemist an indispensable participant.

It also seems very likely that as he becomes better aware of space, he will use the opportunity afforded by the space environment for his own purposes. For example, the inexhaustible vacuum of the spaceship might make many chemical reactions much easier. So we hope to find that chemicals which are easily damaged by oxygen may be prepared better in a spaceship in orbit or in one of the large vacuum chambers used for testing spaceships in the aerospace laboratories than in any chemical plant yet built.

But, perhaps, more important than any of these chemical applications of his space afforded opportunities may be his leadership in understanding the evolution of the planetary atmospheres and of the chemical processes which lead to the formation and the evolution of the planets themselves. His role in working out the very important steps in the chemical evolution of the atmospheres may help lead to a better understanding and piecing together that would be otherwise nearly impossible.

*Department of Chemistry and Institute of Geophysics and Planetary Physics, U.C.L.A.

**THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
PROGRAM IN SPACE CHEMISTRY AT UCLA**

To illustrate a possible direction of development of space chemistry of the next decade, I will describe our UCLA program.

For 6 years, the Air Force Office of Scientific Research has supported the chemical researchers in my group at the University of California at Los Angeles, and the National Aeronautics and Space Administration has supported us in the areas of geophysics and planetary physics. In the borderline regions between these two fields, funds from both agencies have been applied. We're very grateful to both NASA and the Air Force.

I wish to speak this morning mainly about our work in five principal areas; four pertain to the study of chemistry in the space environment; high temperature, radiation, high pressure, vacuum chemistry; and the fifth: the chemical aspects of the evolution and nature of the planetary atmospheres, particularly those of Jupiter and Venus.

Chemistry of High Pressures

The chemistry of high pressures is still largely unknown, but we know that certain general principles must apply—atoms are squeezed together by high pressures, and solids and liquids which have vacancies or holes in their structures are compressed to eliminate these vacancies. For example, as Bridgman first showed, ice with its very open tetrahedral lattice (considering the oxygen atoms only) collapses progressively through seven different forms as pressures are applied up to 100,000 atmospheres. The chemical consequences of such structural collapsing may be substantial.

For instance, if a Group IV element which normally has a tetrahedral diamond type lattice corresponding to four nearest neighbors is compressed until it has more neighbors, it is clear that the number of chemical bonds which are possible in the denser phase is less than the number of neighbors because the maximum number of bonds to a fourth group atom is four, and this leads to a fundamental change in chemical properties. Just

as in the case of the molecule benzene where two alternative atomic arrangements are conceivable (Kekulé structures), a new structure intermediate in nature arises which assures that the bonding electrons belong to the whole molecule in a kind of metallic state so one is inclined to associate the excess of neighbors over the number of valence bonds possible with the occurrence of the metallic state, at least, for Group IV elements. In fact, it has been shown that, in the case of all of the Group IV elements except carbon, compression to a denser structure causes the formation of a metal. These metals produced by the application of pressure may be called *Metallic Diamonds*, even though metallic diamond itself has not yet been made.¹ Other than tin, the metal indium antimonide in its compressed phase was the first of the family. Indium antimonide, InSb, in its normal low-pressure form is tetrahedral with a diamond lattice; but, at pressures of 23,000 atmospheres, it is converted into the tin-like six-neighbor lattice and becomes metallic.² The technique used to recover the material was chilling of the press with liquid nitrogen before release of pressure.³ In this manner, the metal was obtained free of the press, and its properties below about -60°C were studied. If warmed above -60°C , it explodes to form the normal diamond-lattice solid in powder form releasing heat. It is a particularly hard material as compared to its sister metal. Tin, indium, and antimony are neighbors in the periodic table, so it was no surprise when we discovered that metallic indium antimonide forms tin alloys in all proportions which are strictly indistinguishable from tin with X-rays (Table I). The extra hardness of the indium antimonide metal might be understood in terms of the fact that the valence average of four, which is characteristic of tin, must be obtained in indium antimonide only by indium and antimony averaging together. Therefore, there may be some tendency to allow only those movements of atoms which preserve the proper averaging. In any case, it is quite clear that indium antimonide metal is harder than tin and that the alloys rich in indium antimonide also are harder. Figure 1 shows these data. It is interesting that this is also true for the diamond form. Nonmetallic indium antimonide has been found to be harder than nonmetallic tin. We are led to speculate from this that perhaps nonmetallic boron nitride, in the diamond lattice form, will prove to be harder than diamond. This seems to be a logical consequence—and it may encourage the production of cubic boron nitride as a super-hard material.

Table I. Lattice Spacings for Sn(β), InSb(II), and for Metallic Alloys InSbSn₁, InSbSn₂ and InSbSn₄.

kkl	Sn(β)	InSbSn ₄	InSbSn ₂	InSbSn	InSb(II)	Sn(β)
	25° C	25° C	25° C	-197° C	-197° C	-197° C
	d (Å)	d (Å)	d (Å)	d (Å)	d (Å)	d (Å)
200	2.912	2.918	2.921	2.897	2.910	2.907
101	2.789	2.793	2.794	2.776	2.788	2.778
220	2.062	2.062	2.064	2.057	2.062	2.055
211	2.015	2.015	2.017	2.012	2.030	2.007
301	1.658	1.658	1.660	1.654	1.654	1.651
112	1.483	1.484	1.487	1.476	1.474	1.474
400	1.458	1.458	1.457	—	1.452	1.453
321	1.442	1.442	1.440	1.438	—	1.436
420	1.304	1.304	1.303	1.301	—	1.300
411	1.292	1.294	1.294	1.290	—	1.287
312	1.205	1.205	1.206	1.201	—	1.198
501	1.0950	1.096	1.096	—	—	1.091
103	1.0437	—	—	—	—	1.037
332	1.0405	1.041	—	—	—	1.035
440	1.039	1.032	—	—	—	1.028
521	1.0251	1.025	—	—	—	1.022
a ₀	5.8309	5.8356	5.8337	5.8219	5.833	5.8181
(Å)	±0.006	±0.0007	±0.0027	±0.0024	±0.019	±0.0007
c ₀	3.1824	3.1810	3.1873	3.1665	3.170	3.1634
(Å)	±0.0005	±0.0013	±0.0029	±0.0022	±0.014	±0.0007
c ₀ /a ₀	0.54578	0.54510	0.54636	0.54389	0.5435	0.54372

A regularity comes out of the work on *Metallic Diamonds* which is very useful in estimating the pressure for the metallic transition in diamond itself.^{3,4} This relation is that the free energy of the transition (pressure \times volume change) is a constant fraction (close to one-half) of the energy required to lift the

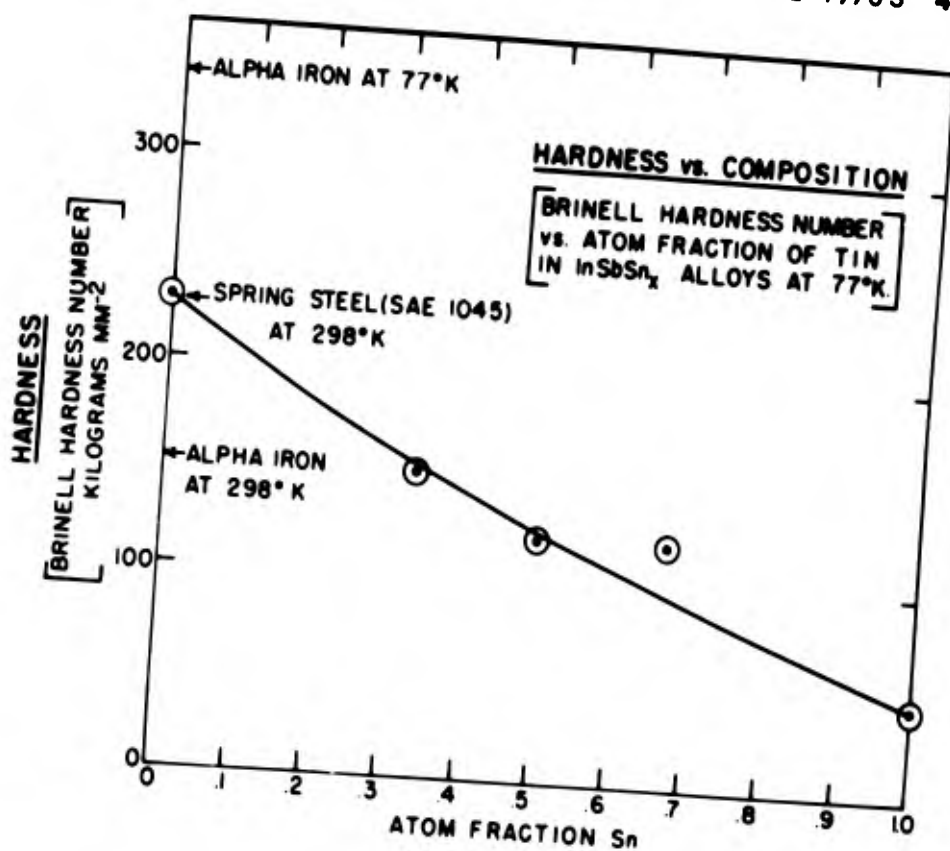


Figure 1

highest valence electron in the diamond lattice into the lowest metallic conducting state in that lattice. This is called the electronic energy gap. Table II gives these data. The volume change can be calculated for diamond (except for any atomic squeezing to change the atom radius which probably is small) to be 21% of the volume of the diamond solid. We can therefore estimate the pressure at which diamond will be converted into the metal. Diamond's molal volume is 3.24 cc; therefore, since its energy gap is known to be 5.6 eV, we calculate that its pressure for conversion to metal will be about 3.7 million atmospheres. Therefore, we conclude with considerable confidence that diamond probably is the ideal material for high-pressure apparatus to attain the highest pressure, since it will not suffer a phase collapse under pressures as high as 3 million atmospheres. The pressure inside the Earth is slightly in excess of 3 million atmospheres at the center. We believe that structural collapse (i.e., the transformation of low coordination number lattices into close-packed lattices)

Table II. Comparison of the $P\Delta V$ Work for the Semiconducting \rightarrow Metallic Transition with E_g of the Semiconductor

Substance	Transition Pressure (kilobars)	ΔV ($\text{cm}^{-3}/\text{mole}$)	$P\Delta V/\text{atom}$ (ev)	$\Delta E_g/2$ (ev)
Sn	-0.7	4.3	0.003	0.03
InSb	+22	7.59	0.09	0.09
Ge	120	2.85	0.32	0.32
Si	200	2.73	0.56	0.54
GaAs	240	5.52	0.69	0.69
C	—	0.72	—	2.80
GaSb	90	5.19	0.22	0.35
AlSb	125	4.97	0.32	0.75
InAs	102	5.82	0.31	0.18
InP	133	5.45	0.38	0.60

will occur in nearly all other cases below these pressures. Therefore, we expect that all materials (except, possibly, diamond) at the pressure at the center of the Earth will be in the twelve-neighbor, close-packed lattices and that many nonmetallic materials will thus have become metallic.

It is interesting that all metallic diamonds tested so far have proved to be superconductors. Figure 2 shows the data for InSb (II) and its alloys with tin. There are many possible metals of this type, for it isn't necessary to work just with Group IV elements; III-V combinations, as in indium antimonide, and even II-VI or I-VII will work also. Thus, many new metals can be made by the technique of compression and freezing.

During the past year, we have discovered new metals with the following properties:

- (1) Cadmium Arsenide II (Cd_3As_2): stable at atmospheric pressure to 150°K , crystallizing in the $D5_2$ structure with $a = 430 \text{ \AA}$, $c = 6.87 \text{ \AA}$ and $c/a = 1.60 \text{ \AA}$. This high-pressure metallic polymorph is not superconducting down to 1.1°K (Ref. 5).

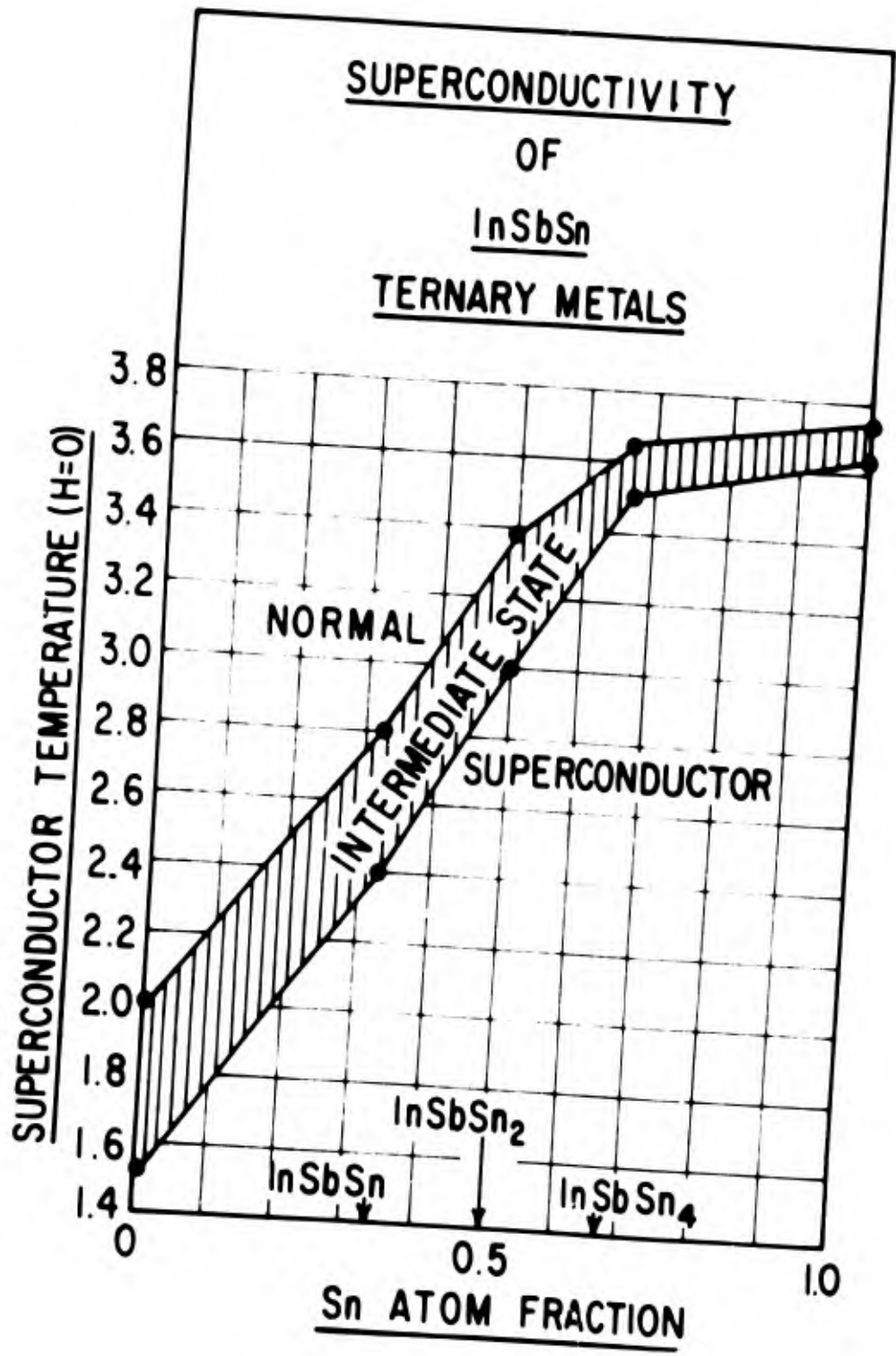


Figure 2

(2) Cadmium Tin Arsenide II (CdSn As_2): stable at atmospheric pressure to 300°C , crystallizing in the NaCl (B1) structure. Its superconducting properties are now being investigated.

It is our hope and plan at UCLA to try to build a megabar (1 million atmospheres) press at UCLA. Prof. George C. Kennedy of the Institute of Geophysics is seeking support from the National Science Foundation and the Advanced Research Project Agency of the Department of Defense for the construction and operation of such a facility. At present, our maximum capability statically is in the diamond anvil presses of Prof. H. Drickamer of the University of Illinois which uses milligram samples, but takes them to about half of one megabar. Dynamic techniques using high explosives in a number of laboratories here and abroad—but particularly at the Stanford Research Institute and the Lawrence Radiation Laboratory at Livermore—have given several megabars, but for only a few millionths of a second, so measurements of many important properties are extremely difficult.

The problem of building a static press of appreciable volume (half of 1 cu cm of sample, or so) that would reach into the elusive megabar region appears to consist primarily of the problem of bonding diamond powder as a particulate aggregate, much as tungsten carbide is bonded by metallic cobalt in the material commonly used in most static presses whose present usage is in the range of up to 100,000 (atmospheres). This problem probably is in part the matter of wetting the diamond surface with a material of compatible compressibility and thermal expansion coefficients—although this is not completely clear. A great deal of work here lies ahead, but at least this is the direction towards the static megabar press.

A megabar press would be just as revolutionary to geophysics and planetary science, and possibly to chemical industry, as was the original Bridgman work (up to 100,000 atmospheres) which resulted in the present process for the manufacture of synthetic diamonds." Such a press would open up the science of the planetary interiors to more direct laboratory attack.

Beyond structural collapse to the densest twelve-neighbors lattices, high pressures eventually collapse even the atomic structures themselves. After structural collapse has proceeded to the

ultimate twelve neighbors' closest possible packing, further compression raises the electrons to higher momentum states in order to squeeze them into smaller volumes at higher densities. In this state, the electrons cease to belong to a single atom—they move into a type of superstate which is metallic. We see stars whose interiors seem to be in this state. The star Sirius is really a double star, and its companion star is a white dwarf whose density averages about 10^6 gm/cc. Other such cases are also known.

We can thus expect that, at pressures of the order of one megabar, many atoms will have collapsed into the superstate envisaged whose properties are essentially unknown to us. We might reach this wonderful new kind of matter with a megabar press.

The compression of graphite by explosive has produced diamonds in yields of several percent by weight.^{7,8} The diamonds are small but still recognizable as diamonds by X-rays. So we see that at least several million carbon atoms can be made to react in the very brief interval of a few millionths of a second. Our group is inclined to believe that this very remarkable reaction may in itself be kinetic evidence for the superstate. We have suggested⁹ that, as the shock wave compresses the graphite, it transforms into this state from which it reverts immediately, as the shock passes, and some of the newly reformed carbon atoms are caught in the metastable diamond lattice on the way back to graphite.

Radiation Chemistry

Our second area of work in space chemistry is the general field of the chemical effects of ionizing radiation. Ionizing ultraviolet sunlight and cosmic rays both produce ions in matter as well as in excited neutral atoms and molecules; ions are produced when one or more electrons are removed or added to a neutral atom or molecule. When ionized, atoms and molecules represent different chemical species with most remarkable chemical properties, most of which have been discovered in the last 15 years, although the pioneer S. C. Lind, in the first decade of this century, published many papers on the chemical effects of ionizing radiation. We concentrate on ionic chemistry with the hope and in the belief that ions last longer, are more reactive, and thus may dominate over

excited states in the chemical effects of ionizing radiation. Experimentation seems to bear out this presumption in many systems.

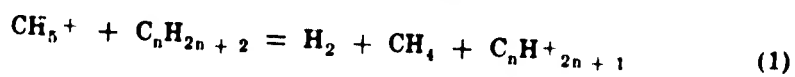
1. **General Principles.**¹⁰ One would expect to find some suggestion of the chemical properties of ions in those ions of analogous electronic structures in neutral atoms and molecules. For example, knowing that argon with its eighteen electrons is a chemically inactive species, we would immediately predict that chloride ions and potassium ions as well as calcium and scandium ions (Cl^- , K^+ , Ca^{++} , Sc^{+++}) all with their eighteen electrons would also be chemically inactive, although it is clear that the charges polarize molecules and thereby attract them to contact and react, if reaction is possible. This *Principle of Analogy*—that electron structures which differ only in nuclear charge will behave similarly—appears to be sound and helps us to understand some chemical properties of ions.

We should expect that an ion with one electron (i.e., He^+) would be hydrogenic; and we should expect, if it were possible for He^+ to react without catching electrons because of its high electron affinity, that it would form molecules like those formed by ordinary hydrogen atoms. A better case is the argon ion, Ar^+ , which by our principle should behave as does a chlorine atom. So, we should expect that the chlorine-like properties would show by Ar^+ attacking hydrogen molecules to form HA^+ and release atomic hydrogen just as chlorine forms hydrogen chloride and hydrogen. HA^+ should be a very stable molecule as long as its positive charge is not neutralized by an electron or by some other negative-charged species.

In fact, it's quite clear that the extra positive charge on the nucleus of this chlorine-like Ar^+ ion makes its levels all lie below those of ordinary chlorine atoms and that it should therefore have a higher ionization potential and form stronger chemical bonds. In other words, the dissociation energy of HA^+ should be greater than that of hydrogen chloride. Lampe¹¹ has used this reaction to catalyze the production of atomic hydrogen by ionizing radiation. Using argon's large cross section to absorb gamma rays, he was able to increase the yield of atomic hydrogen and thus of ethane by adding argon to a mixture of hydrogen and ethylene. On neutralization, the HA^+ gives another atomic hydrogen, so the net result is that the argon catalyzes the dissociation of the hydrogen molecule into two atomic hydrogens.

2. **Aliphatic Hydrocarbon Positive Ions.** The hydrocarbon positive ions have been studied extensively, beginning with the discovery of the very famous reaction of CH_4^+ with methane to form CH_5^+ and methyl radical. Tal'roze, et al., discovered in 1952 that in mass spectrometers CH_5^+ appeared when methane was introduced at relatively high pressures.¹² It appeared to be the product of a reaction of second order. Following our *Principle of Analogy*, we would say that CH_4^+ has seven valence electrons and should therefore behave as atomic fluorine (neglect the disturbing fact that the four protons are not in the center of the electronic assemblages as they are in the case of fluorine). Therefore, there is a considerable tendency for CH_4^+ to capture another electron. This, of course, would make methane, and there is a good affinity for this, some 13.7 ev. However, there is another way in which it can do it and that is by capturing an atomic hydrogen. This is the basis of the reaction. It proceeds in analogy to the reaction of atomic fluorine with methane which forms hydrofluoric acid, HF, and methyl radical. So we think of CH_5^+ as being a Bronsted-type acid, like hydrofluoric acid, and that the reaction of CH_4^+ with methane to form CH_5^+ and methyl radical is quite analogous to the reaction of atomic fluorine with methane to form hydrofluoric acid and methyl radical.

The acid properties are so strong—according to the observations of Munsen and Field¹³—that CH_5^+ treats all hydrocarbons except methane as bases and is able to abstract hydride from them to make hydrogen molecule, methane, and the positive ion of the hydrocarbon with one hydrogen ion missing:



This reaction is very important as it accomplishes the ionization of even the heaviest hydrocarbons without serious fragmentation. We will later discuss and consider why this is so, but the essential present point is that CH_5^+ is a very powerful Bronsted-type acid.

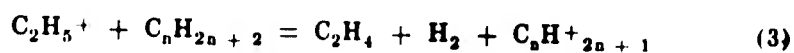
Another ion obtained in major yield in ionizing methane is CH_3^+ . In fact, in the methane mass spectrum with 70-volt electrons ionizing, CH_3^+ and CH_4^+ are about equally abundant. As will readily be seen, CH_3^+ is a very different species chemically, being similar to boron trifluoride or sulfur trioxide, a Lewis-type acid characterized by a missing electron pair. Being positively

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charged, it again is a much more powerful Lewis acid than any neutral species, and it, too, is able to treat ordinary hydrocarbon molecules as bases with surprising ease. For example, it even reacts with methane itself to form hydrogen and $C_2H_5^+$, another Lewis acid:



This type of reaction might be expected to continue to add CH_4 , but it has been observed¹³ to stop in the gas at $C_2H_5^+$. The two ions, $C_2H_5^+$ and CH_3^+ , are the main products of the initial reactions, and both are chemically active as Lewis and Bronsted acids in keeping with the *Principle of Analogy*. $C_2H_5^+$ attacks higher hydrocarbons too, of course:



In pure methane, which is not a strong enough base to react with either of these acids, the reaction stops, and the result is simply the production of CH_3^+ and $C_2H_5^+$, which of course are eventually neutralized. This act may lead to further reaction through fragmentation and subsequent reaction of the fragments, but all of this is delayed for some appreciable time such as a fraction of a millisecond. And, as Munsen and Field¹³ suggest, if another organic gas is added to the methane in small amounts up to 1%, these acid ions can attack it and produce a spectrum of ions, with the main ion being the original molecule less one hydrogen atom. This greatly simplifies mass spectrometry and is a powerful tool for studying the ionic chemistry itself.

3. Aromatic Hydrocarbon Positive Ions. Aromatic systems differ from aliphatic systems in that their ions probably are of the π electron type (i.e., the electron which is most easily removed in aromatic systems usually is a π electron which belongs essentially to the whole molecule). This means that the charge or electron deficiency is distributed over the entire system, and, as a consequence, the chemical effects of the ionization should be much weaker than with the saturated aliphatic hydrocarbons. Evidence from experiments confirms this prediction that the aromatic ion is much less active than the aliphatics. In fact, one type of atomic power reactor (the Organic Moderated Reactor) uses terphenyl (three benzene rings together) as the

working fluid. The fact that the charge in aromatic ions is distributed over the whole molecule reduces the ability of the ion to attract neutral molecules by polarization forces and further reduces its reactivity.

4. **Negative Ions.** Negative ions, in general, have more widely spaced levels and, therefore, form weaker bonds than neutral molecules, just as positive ions form stronger bonds. For example, hydride ion should be chemically inactive, being an analogic helium atom; and chloride ion, as we have said previously, should be like argon, thus chemically inactive.

Free radicals, in general, will have an electron affinity and form negative ions. Methyl radical will take an electron to form CH_3^- , and other free radicals may similarly form negative ions. The negative ions so formed can play important chemical roles although they are in general chemically inert. Their main role is expected to be in the neutralization reaction, for every positive ion must be neutralized eventually.

5. **Electronic Franck-Condon Principle.** An important point in connection with the formation reactions for ions is the *Electronic Franck-Condon Principle*.¹ This principle is that electrons can never move slowly enough to allow appreciable movement of atoms. Therefore, ions produced by electron removal (which is the normal process with ionizing radiation) are formed initially in essentially the same geometrical shape as the parent neutral molecules. Also, they possess the same or similar internal momenta initially. This means that electronic ionization processes (processes which remove electrons by electron collisions, as well as photon ionization process) cause ions to be formed in highly excited vibrational states, depending on the nature of the ground state of the ion. For instance, with methane, there will be an ion formed in the geometry of methane and it is quite natural that the geometry of the ground state of CH_4^+ , though not well known, will be different from the tetrahedral geometry of methane. In fact, certain indications from quantum mechanical calculations are that the CH_4^+ ion in the ground state is far from being tetrahedral. So ionization causes a kind of distortion or vibrational excitation.

We must expect, therefore, that methane ions formed in this condition will occasionally destroy themselves. In fact, about half

of the ions formed by 70-ev electrons bombarding methane are CH_3^+ , corresponding to the elimination of a hydrogen atom. Now, of course, it is true that the appearance potential of CH_3^+ will be above the appearance potential of CH_4^+ because only those CH_4^+ ions which are sufficiently excited to eliminate an atomic hydrogen and form CH_3^+ can do so. And so the yield of CH_4^+ ions at the onset of CH_4^+ is less than the total ion yield at the onset of CH_3^+ because more molecules can be ionized by the electrons at the higher energy. Similarly, at higher electron bombarding energies, the methane will eventually form CH_2^+ and CH^+ and C^+ . Of course, it is possible to produce the CH_4^+ ion in a state excited electronically as well as vibrationally, but it seems very likely that most of the destruction of the parent ions which occur in polyatomic systems is due to the vibrational excitation caused by the great speed of the ionization act itself as induced by fast electrons or photons, the electronic *Franck-Condon Principle*.

This raises the question as to whether it is possible or not to ionize in a slow manner. The answer is yes, as Munsen and Field¹³ have shown (as described above), by using the Lewis acid C_2H_5^+ or the Bronsted acid CH_5^+ . A hydride ion is removed relatively slowly because its mass is so much larger ($1840\times$) than that of the electron with a minimum of destruction. The ionization act in this case, according to the *Franck-Condon Principle*, allows time for the ion to relax, at least in part, to its proper geometry as it is produced.

6. Destructive and Nondestructive Neutralization. The electronic *Franck-Condon Principle* appears to be very general in its applicability to all neutralization processes, and the fragmentation theories of the excited ions appear to apply very well to the molecules made from freshly neutralized ions if electrons do the neutralizing.

Thus, we expect that (1) neutralization by electrons will be destructive, and that (2) neutralization by anions will be less destructive.

In most systems subjected to ionizing radiation, anions can form (air impurity is particularly effective in this regard since oxygen rapidly captures free electrons) and can thus be provided the means of slow neutralization by heavy anions. In the case

of aliphatic hydrocarbons, for example, the free radicals formed in the normal course can capture electrons; CH_3^- is a well-known example found in the mass spectrum, and this might well be important in neutralization processes. Electron scavengers such as SF_6 can be added purposely to arrest destructive electron neutralization. Conclusive evidence for this type of influence is now at hand, particularly in the benzene system.¹⁴

7. Electron Transfer. It is well known that electron transfer reactions are very rapid, providing the *Franck-Condon Principle* does not block them.¹⁵ The electron-transfer cross sections for gaseous species are known to be of the order of the gas kinetic cross sections for the neutral molecules or sometimes even larger, and, in the case of aqueous systems, solvent polarization around the ions bring in the electronic *Franck-Condon Principle* in a serious way, so that electron transfer is blocked in media such as water which are highly polarizable. The electron is unable to move because both the donor and receptor sites are improperly polarized for the charge distribution after transfer. In less polarizable media, the blockage is less serious. So in many systems, and in particular in gaseous systems, and systems of low dielectric constant, the transfer of electrons from one species to another is a very probable process.

This brings in our next principle of the *Chemistry of Gaseous Ions*; i.e., the species of lowest ionization potential will be formed by electron transfer. In other words, if one ionizes a mixture of methane and ethane, the methane ions will be neutralized by electron transfer from the ethane, since the ionization potential of ethane is lower, 11.7 eV versus 13.0 eV. The electron will be transferred to the methane ion, and ethane will be preferentially ionized. *In this manner, it is possible to concentrate the radiation energy on minor species.* This is a very important principle for it allows an enormous selectivity and efficiency gain to occur.

We pointed out previously how the ionization of argon could lead to the dissociation of molecular hydrogen through ionic reactions.¹¹ Similarly, it is true that the ionization of xenon in a mixture of methane and xenon would lead to preferential ionization of the methane. For example, on Jupiter, which is thought to be largely hydrogen and helium with small amounts of methane and other gases, it is very likely that a large part of the ionizing

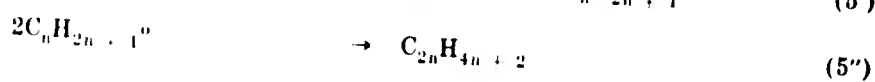
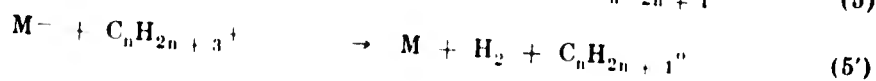
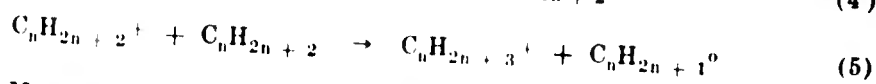
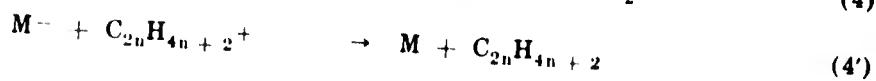
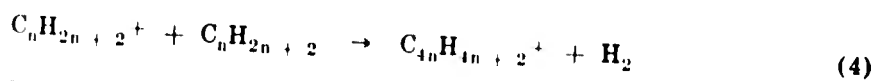
radiation is effective in ionizing methane and the other minor constituents of lower ionization potential, with the result that ionic chemistry probably is very effective in the Jovian atmosphere. It seems likely, therefore, that a very large population of free radicals and complicated organic molecules exist in the atmosphere of that planet for this reason. The strong colors which are seen there seem to indicate that this is true, and we believe that the strong radio signals from Jupiter may be due to abundant organic free radicals.¹⁶

The general principle of electron transfer under conditions of no electronic *Franck-Condon Principle* blockage is an important one in the chemistry of ions, and there is no doubt that the phenomenon occurs. The question is, "How important is it in a given situation?" A solution of normal hexane dissolved in liquid xenon irradiated with Co^{60} gamma rays was found¹⁷ to yield radiation products in the dilute solution of 4% hexane in xenon (molal percent) at just as high a rate as if pure hexane had been used. In other words, electron transfer to the Xe^+ ions was completely effective in transferring the radiation energy into ionizing hexane in this system: In fact, a higher yield was found in the solutions because the stopping power of the xenon for the cobalt-60 gamma rays is larger than for n-hexane. It is interesting that the distribution of the products was not greatly different indicating that the degree of excitation that the hexane ion received was similar to that received from direct gamma-ray ionization by secondary electrons.

It should be pointed out that electron transfer is to be thought of as being a fast process in the sense of our previous discussion. The electron jumps instantaneously, probably by tunneling through the potential barriers of the intervening xenon atoms, and fragmentation effects similar to those for electronic bombardment should be expected.

8. Heavy-Ion Transfer. Perhaps the most important heavy ion found to transfer is the hydride ion, though proton transfer also occurs. Heavy-ion transfers are to be thought of as processes occurring relatively slowly in contrast to electron transfer processes. Thus hydride-ion transfer from heavy hydrocarbons to the Lewis and Bronsted acids, C_2H_5^+ and CH_3^+ , gives the new Munsen and Field¹³ technique for nondestructive formation of the positive ions of heavy hydrocarbons.

9. **The Cross Linkage of Hydrocarbon Polymers.** In the solid, it is known that polymers such as polyethylene cross link when subjected to ionizing radiation. It is our suggestion¹⁸ that this reaction is ionic in nature and that the energy of excitation that is left as a result of ionization can be used to drive the reaction in which two polymer chains, lying neighbors, split out hydrogen and form a cross-linked molecule via a cross-linked cation which is neutralized anionically or nondestructively, possibly with H⁻. Another possible mechanism is that the initial positive ion takes a hydrogen from its neighbor as CH₄⁺ forms CH₅⁺, leaving a radical to react with the radical formed when the cation is neutralized. The equations would be:



The very general nature of the cross-linkage reaction induced by ionizing radiation leads us to suggest this is so. The fact that it occurs in the crystalline solid indicates that nonionic mechanisms are not too likely, and studies on crystalline n-hexane¹⁹ have indicated in some detail that the mechanism probably is ionic.

10. **Polymer Production by Inner Shell Ionization (Auger Electron Effect).** Gamma radiolysis of solid methane at 77° K yields a highly branched polymer [G(-CH₄ to polymer) = 0.3] with a dose-independent average formula of C₂₀H₄₀.²⁰ Since there is very efficient energy transfer to a hydrocarbon dissolved in a liquid rare gas,^{17, 21} we have irradiated dilute and concentrated solutions of methane in liquid argon to look for effects on polymer formation.

Experimental results are shown in Table III. The polymer looks just like that shown in the previous paper on solid methane.²⁰ Drawing arbitrary divisions for C₂₂H₄₂ one gets 55% methyl protons and 45% CH₂ and CH protons (divided about three to

Table III: Data on Polymer from Methane-Argon Solutions

Dose (Megarads)	Mole % CH ₄	G --CH ₄ to polymer	Average Molec. Wt.	Average Formula†	NMR Protons %CH ₃ - %CH + CH ₂
14*	0.15**	—	304	C ₂₂ H ₄₂	53 — 47
11*	0.15	1.3	310	C ₂₂ H ₄₂	
16*	0.63**	—	316	C ₂₂ H ₄₂	55 — 45
11*	1.4	1.3	309	C ₂₂ H ₄₂	
8.5*	3.2	1.3	306	C ₂₂ H ₄₂	56 — 44
10*	4.9	1.3	311	C ₂₂ H ₄₂	
11*	11.0	1.4	315	C ₂₂ H ₄₂	
39	16	1.2	309	C ₂₂ H ₄₂	59 — 41
9	15	1.0	304	C ₂₂ H ₄₂	
21	20	1.1	314	C ₂₂ H ₄₂	55 — 45
10	20	1.0	364	C ₂₆ H ₅₀	
10	29	0.95	381	C ₂₇ H ₅₂	
20.5	30	0.94	351	C ₂₅ H ₄₈	59 — 41
38	31	0.96	321	C ₂₃ H ₄₄	60 — 40
39	37	0.66	348	C ₂₅ H ₄₈	61 — 39
9	37	0.65	394	C ₂₈ H ₅₄	
10.5	39	0.68	391	C ₂₈ H ₅₄	
21.5	42	0.55	378	C ₂₇ H ₅₂	
21.5	50	0.50	387	C ₂₈ H ₅₄	63 — 37
33	46	0.58	369	C ₂₆ H ₅₀	
17*	68	0.32	513†	C ₃₇ H ₇₂	
18*	78	0.20	503†	C ₃₆ H ₇₀	

*Irradiated under liquid argon (87° K), others irradiated at 77° K.

†May be too high if polymer is not completely soluble in benzene.

‡To nearest whole C, based on molecular weight and C, H analysis.

**Irradiated at 0.6 megarad/hour.

two). This distribution means about eight methyl, six CH_2 , and eight CH carbons. Preliminary analysis of the chemical ionization mass spectra shows alkanes, single ring naphthenes, and double ring naphthenes in a ratio of roughly 1:3:5. There is insufficient information on fragmentation of such large branched molecules to determine the molecular weight spread, but the spectra are not inconsistent with the osmometer average molecular weights.

The average formula of the polymer made in the most dilute solution of methane (0.15-mole percent) is $\text{C}_{22}\text{H}_{42}$, and the size does not change much as the methane concentration is increased to 15-mole percent. A gradual increase in size then ensues with further methane enrichment: The average formula $\text{C}_{28}\text{H}_{54}$ results from a 50-mole-percent methane run, and a 78-mole-percent methane polymer came out $\text{C}_{36}\text{H}_{70}$. Hydrocarbons larger than about C_4 are not soluble in liquid argon, so the polymer precipitates and floats to the top of the dense liquid. Growth processes by secondary reactions in solution are thus prohibited.

The $G(-\text{CH}_4 \text{ to polymer})$ values increase from $G = 0.20$ in 78-mole-percent methane to $G = 1.3$ on 0.15-mole-percent methane. In terms of polymer molecules (which are larger at high methane concentration), there is an eleven fold increase in yield going from high CH_4 to high argon concentration. Since these values are based on the total energy absorbed by the mixture, complete energy transfer from argon to methane would result in no change in G , everything else being equal.

These data pose the question: How can a heavy hydrocarbon be made in a primary event from 0.15-mole-percent methane in argon with a G value eleven times that for 78-mole-percent methane? Indeed, in the dilute solutions, almost as much methane is lost to polymer as goes to ethane, the only other major product:

$$[G(-\text{CH}_4 \text{ to ethane}) = 2.0]^{21}$$

The ethane yield can be explained in terms of energy transfer to methane followed by reaction of individual ions or neutral fragments.^{17, 21} However, at such low methane concentrations, single isolated species made by the efficient energy transfer to methane could not produce polymer. Neutral methane fragments could not hold the 9 eV of energy required,²⁰ and ions could not gather

enough methane before electron recombination. *Therefore, the polymer must come from combination of a number of methane fragments produced in a small region.* The NMR data require that about equal quantities of CH_3 , CH_2 , and CH be involved.

We suggest that *such a high local concentration of fragments could be produced by an Auger electron emitted following inner shell ionization.* A 206-ev Auger electron and an Ar^{++} are the major products from ionization of the 245-7-ev L levels of argon.²² K ionization of argon requires 3200 ev and yields a variety of Auger electrons and positive ions up to Ar^{+7} .²³ Carbon K ionization gives a 246-ev Auger.²⁴ The low-energy electrons thus made will be scattered in a short, random, walk path and will produce a small sphere containing a number of ions and excited neutrals. (Since no decrease in polymer size is seen at 0.15-mole-percent methane, the sphere must be at least large enough to contain twenty methanes, i.e., about 100 Å in diameter).

In the low methane concentration runs, the initial species produced will be made from argon by argon Augers, but rapid charge and excitation transfer reactions to methane will occur just as they do for isolated species. (Methane has a lower ionization potential.) Electron recombination with likely methane ions such as CH_4^+ and CH_3^+ could give²⁵ $\text{CH}_2 + \text{H}_2$ and $\text{CH} + \text{H}_2$. Excitation transfer to CH_4 is known to give $\text{CH}_3 + \text{H}$ and $\text{CH}_2 + \text{H}_2$.²⁶ Hydrogen atoms might interfere with condensation of fragments to polymer, but molecular hydrogen could not

At high-methane concentrations, carbon K Augers will be operating directly on methane, and this different excitation process plus the greater availability of methane could account for the increased size of the polymer produced.

11. Application to Radiobiology. It is very likely that as we become better acquainted with the chemical properties of ions, we will be able to understand better and better the implications for radiobiology of their formation in biological tissue. Their great reactivity and their extraordinary properties indicate that it is in this area that many of the explanations of the miraculous phenomena observed may lie. Perhaps in the not too distant future as we come to understand more thoroughly the general properties of ions, especially such highly stripped ions as CH_2^+ , we shall be

able to see how remarkably effective ionization is as a chemical agent, and we may see that the *principle of localization of attack to the group of lowest ionization potential by electron transfer* is important to radiobiology.

The significance of Auger-ionization processes to radiobiology is not clear at the present, but it seems to carry a number of very substantial possibilities.

12. Application to Chemical Industry. It is likely that if we understood the chemical properties of ions thoroughly, we might be able to put the enormous amount of atomic radiation now going to waste to work as a chemical reagent. We have already seen that in food sterilization and in the cross linkage of polymers for the production of desirable products such as hardwood from irradiated soft wood soaked in plastic monomer before irradiation the results are most promising. It seems possible that once an understanding of the basic processes has been obtained we might be able to use atomic radiation as a chemical reagent and make use of atomic power plants as chemical factories.

13. Application to Cosmology. Radiation chemistry is much more important in reducing atmospheres than in oxidizing ones, possibly because oxygen and nitrogen and carbon dioxide are pi systems and make relatively inert ions.

It is very clear that in the beginning of the Solar System all gases were of a reducing nature. Thus, methane was present rather than carbon dioxide, water rather than oxygen, and ammonia rather than nitrogen. Under these conditions, the famous Miller-Urey¹⁹ reactions would occur in the presence of ionizing radiations, i.e., the production of amino acids and other large molecules, the building blocks of living matter. It is very possible that ion chemistry is responsible for a significant part of the complicated organic compounds found in meteorites which possibly served as food for living systems in the beginning. So, when we get to the Moon, we anticipate that unless the Moon has been reworked by volcanic action we may find organic matter. If we do, it might be possible to use this primeval organic matter to help sustain the Moon base, as a source of food. By combustion carbon dioxide could be made and used to grow plants to eat.

From the well-known fact that bacteria have been found which can convert crude oil (or certain of its physically separable fractions) into amino acids, we can expect that bacteria could be found to convert meteorite organics (or certain separable fractions therefrom) into nutritive amino acids. This may be a major point, for it means that we might be able to live in part from the stuff of the planets and their moons if they are meteoritic in origin and haven't been volcanically cooked too much in the course of time.

In fact, it seems possible that the whole fabric of biochemistry may have sprung in major part from the necessity of selecting from the primeval nutrient organic stuff that we find in the meteorites. We may come to see that, just as our blood resembles seawater in overall composition, our molecular architecture resembles this original food.

High-Temperature Chemistry

The chemistry of high temperatures is largely a question of laboratory technique. It is obviously of very great importance and potential, but the eternal question is the technique for obtaining and controlling the extreme temperatures necessary.

One very satisfactory technique is the plasma torch. It uses a radio-frequency power source which feeds a water-cooled metal coil through which gas is circulated. The gas is ignited by the insertion of a metal wire heated by the absorption of the radio frequency; when the gas is hot enough, it itself becomes ionized and picks up the radio frequency; then a flame is formed. Flames can be made in this way in any gas running at temperatures in the 10,000- to 100,000-degree range. Of course, all molecules are atomized at these temperatures, and, as the matter leaves the flame, it reforms into new molecules which may be both useful and interesting. The reactions are doubly complicated because ions exist in the flame together with the high-temperature atoms and the separation of the effects due to ionic chemistry from those due to atomic reactions is very difficult. However, the plasma torch gives a very hot flame for general use in the laboratory. It can be used to vaporize all known oxides. In this way, sapphires can be grown by dropping aluminum oxide powder through the plasma flame onto a seed crystal of sapphire below the flame. The tip of the sapphire is kept at exactly the right position relative

to the flame during the entire growing process. A slow rate of withdrawal is used to keep the crystal growing.

Another piece of equipment useful for the study of solids and liquids at high temperatures uses molten aluminum oxide resting on solid aluminum oxide in a rotating cylinder; it was developed by Dr. A. V. Grosse of Temple University. Figure 3 shows such

CENTRIFUGAL REACTOR

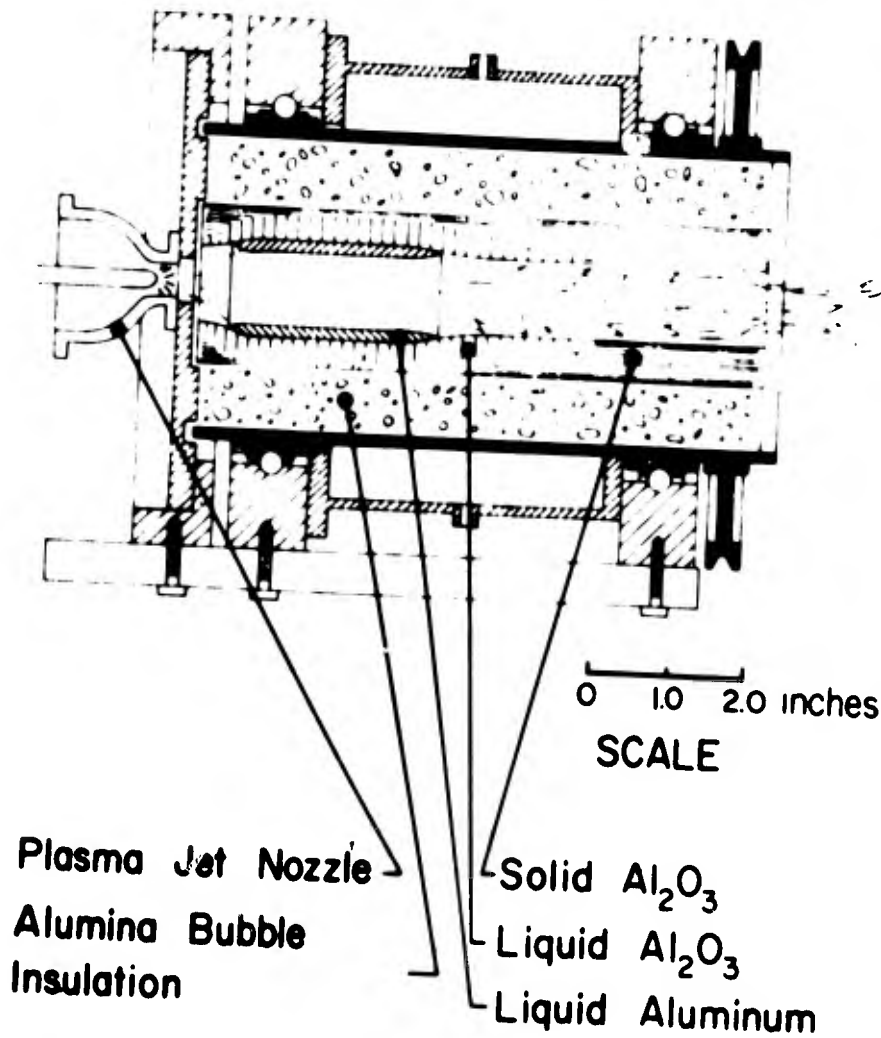


Figure 3

an apparatus. The liquid aluminum oxide is constrained by the centrifugal force to the walls of the cavity, and the material being studied is supported on the liquid, if compatible chemically.

The principal progress in the chemistry of high temperatures in our own laboratory at UCLA to date has been with carbon vapor which we have studied in its reactions with solid benzene²⁷ at 77° K. Similar studies have been made by Skell and co-workers²⁸ on olefins. The best technique here is laser evaporation from a thin filament of graphite suspended in the bulb containing benzene. This technique shows very great promise.

Vacuum Chemistry

The chemistry of high vacuum is essentially the chemistry of uncontaminated surfaces. This is a very promising area; we have never been able to work with clean surfaces on Earth because of the air contamination, and it seems very likely that it would be possible to do air-free chemistry in a spaceship without introducing oxide or nitride contamination into the product. It is very likely that such oxide-free materials would have very different properties. Many crystals probably could be grown under such conditions—so a budding field of chemistry may exist in this application of the inexhaustible vacuum of space to the preparation of pure materials in bulk which are free of oxides and nitrides and other constituents of the atmosphere.

It is almost impossible to produce, in the laboratory on Earth, a vacuum pump of sufficient capacity to rival that available on a spaceship in orbit—so we see that there may be possibilities of using spaceships as chemical laboratories and factories for the production of materials, such as diamond, by the evaporation of carbon. At present, the technique of testing the possibility of making diamonds from carbon vapor is well under way. It is an old problem, and it seems likely that the atmospheric contamination of the surfaces has been in large part responsible for past failures and the use of high vacuum of the levels available in outer space may solve the most difficult problem and lead us to success. In any case, the possibilities of using the high vacuum as a chemical aid appear to be large.

We are attempting the growth of diamond from carbon vapor (Section C, High Temperature Chemistry) using the LEED (Low

Energy Electron Diffraction) apparatus as a monitor. Another application also being attempted is the production of ductile beryllium by air-free distillation. This most important structural material for spaceships and airplanes may be producible in economical form in this way. At least, this is our hope.

Planetary Atmospheres

1. **Jupiter.** The planet Jupiter emits strong bursts of megacycle radio waves. One of our group, Dr. Fred Aldridge, has suggested that the pulsers are indeed a binary system somewhat similar to Jupiter and its Moon, Io, in that a mechanism similar to that by which Jupiter's moon Io triggers the radio emission from Jupiter is operating on a close binary, like the Sun and the Earth. But the star has been condensed by exhaustion to a radius of a few hundred kilometers, and the planet plows around in its orbit with a rotation period of, instead of 1 year, perhaps $1\frac{1}{2}$ second or so. This then, causes emission by the same type of mechanism, making Io active on Jupiter: for which we have previously suggested one possibility (*Nature*, Vol. 214, 126; 1967) to be that of the turbulence caused by Io plowing through a Van Allen belt plasma.

Our explanation of the Jupiter radio signals being controlled by Io was that Io was plowing through a Van Allen-type radiation belt and magneto hydrodynamic disturbances were then impinging on the polar areas of the ionosphere and causing it to emit plasma, electron spinflip, and organic radical magnetic dipole frequencies. In fact, we suggest that the strong radio signals from Jupiter may in part be due to the rich variety of organic radicals which may be present in the reducing atmosphere (Section B, Radiation Chemistry.)

2. **Venus.** Our concern and interest in applying chemical and physical chemical information and techniques to the analysis of planetary atmospheres have been extended to Venus, and we are now deep in a Venus program. Our analysis of the Russian and Mariner V data of last October has convinced us that there is a good chance of temperate regions on Venus in which plant life may exist. (*Science*, Vol. 159, 1097; 1968).

We find that the most telling evidence is the Russian identification of oxygen on the planet. This, when taken together with the

absence of any appreciable amount of carbon monoxide (the actual amount of carbon monoxide is reliably reported to be 45 parts per million), shows that the one-tenth to two-tenths atmosphere of oxygen reported probably could not have been derived from the photolysis of carbon dioxide nor from that of water. There is no inanimate way in which carbon monoxide can react with the surface of the planet, so the carbon dioxide photolysis would have to produce carbon monoxide in twice the oxygen yield. The photolysis of water has been well demonstrated by Urey and by Marshall and Berkner to be unable to explain the oxygen on Earth, and, it would seem, it therefore cannot explain the oxygen on Venus.

On this basis, we conclude that it is likely that oxygen on Venus is derived from plants. Of course it's possible that the Russian detection of oxygen is in error, in which case the evidence for life disappears.

However, an additional argument makes it even more likely that there are temperature regions on Venus: It's the argument of chemical similarity. Venus and Earth have, on the whole, very nearly the same density and very nearly the same size. It seems, therefore, likely that their overall chemical compositions and volcanic histories would be similar. The main differences between these two planets will be the slower rate of rotation of Venus and its closer position to the sun. This leads us to argue that the 18 or more atm of carbon dioxide found on Venus (which, incidentally, compares well with the total limestone on Earth, if it were converted to carbon dioxide) was accumulated because oceans were not present. A similar argument was made years ago by Mentzel and Whipple²⁹ who suggested that the entire surface of the planet was covered with oceans. Of course the high temperature of 280° C found by the Russian probe in the Venus equatorial region rules out oceans. Therefore, we are forced to ask where the water may be and to suggest that it is present in giant ice caps which may extend to as far as 45° latitude and average some 10 km in thickness.

The question has been raised as to whether such ice caps would actually not flow back too rapidly into the hot equatorial regions and thereby melt. We suggest not for two reasons: (1) one reason is that the ice on Venus may not be pure ordinary ice, but may be in part a carbon dioxide hydrate ($\text{CO}_2 \cdot 5\text{-}\frac{3}{4} \text{H}_2\text{O}$) whose physical

properties may be quite different. In particular, it is known that the melting point of the carbon dioxide hydrate rises with pressure. It seems to us that the precipitation will probably be ordinary ice (the rate of reaction of carbon dioxide with water and ice is very small), but that the glacier may be case hardened, so to speak, by the gradual formation of hydrate. We are studying this reaction at the present time. (2) The second reason is that snow, rainfall, and precipitation in the equatorial regions is impossible because the air is too hot for the water to survive the journey downward; therefore the only areas of the planet that can receive precipitation are the polar areas. And it may indeed be snowing continuously in these regions; if so, sunlight may never reach the surface.

We know that sunlight does reach the surface in the equatorial regions, for we find that the surface is the hottest part of the planet in these regions and the air progressively cools as one rises up to the maximum height at which measurements have been made and that the rate of rise agrees well with the air being carbon dioxide and not absorbing any of the heating radiation for that part of the atmosphere covered by the Russian probe Venera 4 which fell apparently 26 km or so, from about the level for 1 atmosphere pressure. In other words, sunlight appears to pass straight through the equatorial atmosphere to the ground. We believe this would not happen in the polar regions; there, sunlight would be scattered by the snow and would eventually be absorbed in the air thus making a layer of warm air which would overlie the cold air covering and protecting the polar ice caps. Snow could fall through this cover but sunlight could not, and hot equatorial winds would rise over and ride above the cold layers. In this way, we deduce that it is quite reasonable that there is a temperate band on the planet. At the edge of the glacier between the polar ice caps and the hot equatorial belt, a region of moderate temperatures may exist, and plant life may exist in this very temperate region.

We are conducting a program attempting to grow plants in a Venus-like atmosphere. The Venus growth chambers have to stand high pressure, so they must have thick walls, but preliminary assessment from experiments at 1 atm makes us hopeful.

An extensive program of calculations on the wind pattern to be expected on Venus is under way at the National Center for

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Atmospheric Research (Boulder, Colorado) through the cooperation of Dr. Kasahara.

CONCLUSION

It seems that in the Space Program, as in most scientific and technological programs, the chemical properties of matter are important; chemists must therefore play a major role in the future growth. Space Chemistry probably is minor in importance when related to astronomy and astrophysics—but it has its opportunities and offerings which may be substantial.

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XXII

Bionics - Its Role and Future in Support of Astronautics

Henning E. von Gierke*

INTRODUCTION

The exploration of space has been a tremendous challenge to all scientific-technical disciplines. It has stimulated new ideas, approaches, and insight, in the biological and physical sciences, which almost immediately have left the realm of the space effort itself and exerted marked impacts on other technologies and developments in our society. It is probably much too early to assess its overall importance in the history of science of our century, already marked by many revolutionary developments and milestones. However, the space effort is perhaps characterized by the fact that it embraces practically all sciences. This is no wonder if one considers that it involves the technologies necessary to explore the completely new physical environments of space, to make these hostile environments livable for man, and to adapt man to this new man-made environment.

The challenge of an almost self-contained microworld in space has brought forth two related requirements: First, man and the machines to assist him in surviving the space environment had to be more closely coupled and compressed into a smaller volume than ever before. This first requirement led to the second; namely, a far closer cooperation of the biomedical and physical-engineering disciplines than had ever existed before, despite being pioneered in aircraft and submarine development. All of the technical, medical, physiological, psychological, and even some of the social problems which are confronting man on Earth and taxing and

*Chief, Biodynamics and Bionics Division, Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio.

stimulating his ingenuity, must be solved for successful space ventures. In addition, we must solve them quickly, and we are restricted in volume and weight to accommodate any solutions.

To allow man to survive in his microworld in space, we are forced to immediately and simultaneously attack some of the problems to which on Earth we address ourselves leisurely (and, as we all realize, frequently, only too leisurely) such as environmental pollution, toxicology, bioengineering, automation, etc. It is for this reason that the interdisciplinary areas composed of the life sciences, physical sciences, and engineering sciences have been of particular interest in connection with the space effort and have been supported and pioneered by it to an impressive degree. It is obvious that the final long-range importance, extent, and application of these fields goes far beyond the space effort; many efforts in these areas are already today continued and supported for "earthly" reasons overshadowing the original space-oriented interest. However, this does not mean that their necessity for the continuation of a progressive space effort has been lessened in any way.

One of these new interdisciplinary areas combining the life sciences, physical sciences, and engineering sciences is the subject of this paper. The emphasis of this review will be on *Bionics*, although some might question why I do not term it "Bioengineering" or "Biocybernetics." It is futile to spend much time trying to give a sharp definition of fields which overlap to a large degree and which often require the same basic knowledge, differing only in the use and application of this knowledge. An attempt to illustrate the interrelation between these fields is given in Figure 1.

Cybernetics grew as the unifying science, considered by many as the healing counterweight against overspecialization and separation of the disciplines, allowing a new synthesis and unification of the biological, social, physical, and engineering sciences.^{1, 2, 3} Its future is heralded by many as holding the required key to the optimization of man's development in the new technical environments created by him on Earth and in space. It is obvious from many signs in our technological world that, while in the past man's technical endeavors concentrated on extending and multiplying his energetic capabilities, his future depends to an increasing degree on an extension of his intellectual insight. Cybernetics may well be the scientific start in this direction.

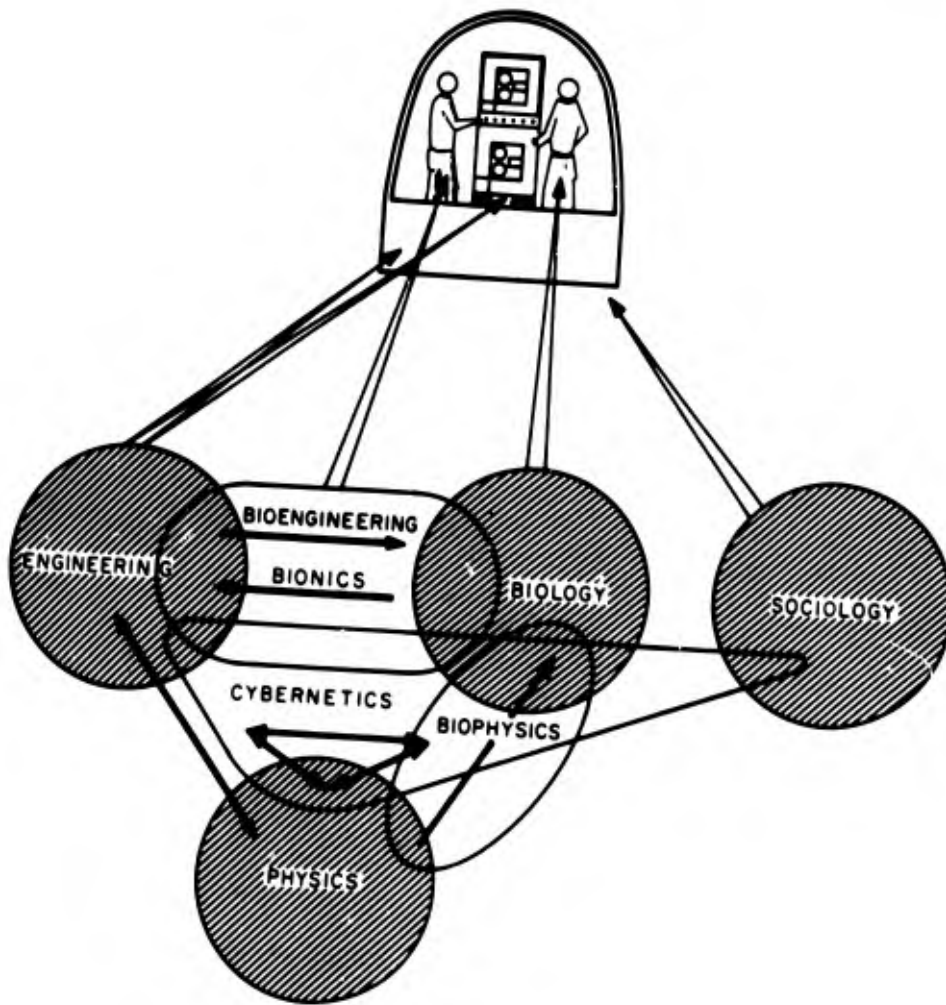


Figure 1. The Interrelation and Overlap of the Various Interdisciplinary Areas Between the Biological, Physical and Engineering Sciences, which Support Man and His Support Equipment in Aerospace Flight.

Biocybernetics, in contrast to engineering and social cybernetics, applies the cybernetics principles and theories to biological systems: helping to understand them, explain them, and model them.⁴

Biophysics is understood primarily to concentrate on the physical basis for life and, to a lesser degree, to include the application of refined physical methods and theories to biology and the action of physical energy on biological systems.⁵

Bionics can be looked at from the biologist's point of view as applied biology or cybernetics;⁸ from the engineering point of view, it is basic research into biological systems with the goal to contribute to the design of better technological systems based on biological prototypes.^{7, 8, 9, 10}

Bioengineering grew from the originally somewhat restricted interphase between the traditionally established schools—of engineering, of medicine, and of biology—to a concept and program of ambitious scope and importance, which is considered by many today to include, at least for academic training, most of the areas shown in figure 1.¹¹

The importance to space research of the areas outlined is obvious. Figure 2 summarizes the main goals: (1) The hostile environments of flight and space posed engineering challenges in life support equipment which could be solved only by the closest cooperation of the life and engineering sciences, and by a more quantitative description of man and his functional reaction to unusual environmental conditions and changes. Man and machine, or better man and his man-selected environment, had to be married. (2) The new environments which man chose for himself required

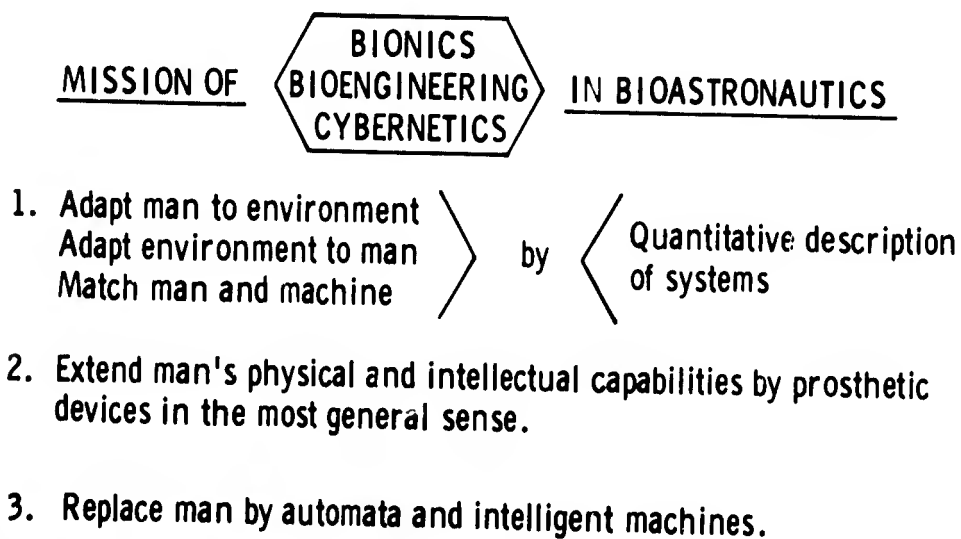


Figure 2. The Three Primary Goals of Bionics/Bioengineering/Cybernetics Efforts in Support of Bioastronautics.

an extension of man's physical capabilities to enable single individuals to control, under the most adverse conditions, engineering systems of unprecedented complexity. This control required the real-time processing of such a tremendous inflow of the most diversified information (from propulsion, navigation, communication and other systems) that its prioritized consumption and correlation, as the necessary base for control decisions, could only be handled by computer systems extending man's intellectual capabilities. (3) Notwithstanding man's basic curiosity and desire to be a direct physical part of any space exploration, there are many space missions which, for some time to come, require man to stay at home. He must restrain himself to explore the universe through man-made "observers," but, for the sake of efficiency, he would like these automated and remote controlled laboratories to be as "intelligent" and as efficient as possible. A glance at the future problems and objectives in aviation, as well as in space exploration, clearly illustrates to what extent progress in aerospace flight will depend on progress in the three areas listed. And, in turn, such progress is directly or indirectly coupled to progress in bioengineering, bionics, and cybernetics, in general.

It is for the latter reason that this paper will discuss some of the bionics-oriented research now under way with emphasis on its possible contribution to space exploration. One of the most important and basic potential contributions of bionics is illustrated in Figure 3: in most of our man-made systems, reliability decreases with systems complexity. Nature, through millions of years of evolution, has developed intelligent, adaptive, self-correcting and self-repairing capabilities in complex biological systems which enable them to perform tasks unmatched by man-made machines. Therefore, it is the purpose of bionics-oriented research to study the superior capabilities of biological systems with the goal to discover and formalize the principles responsible for the specific superiorities and then to apply these principles toward the design of an advanced technology. Needless to say, nobody dreams of rigorously copying biological system; rather, one intends to integrate and to translate the findings made into the state-of-the-art of the existing technology in specific areas. The ultimate hardware will not resemble the biological prototype and, in some areas, might easily exceed the original biological capability which inspired man to imitate it: our flying machines today exceed in many aspects the flying capabilities of birds; and computers can already handle many tasks faster and more reliably than man.

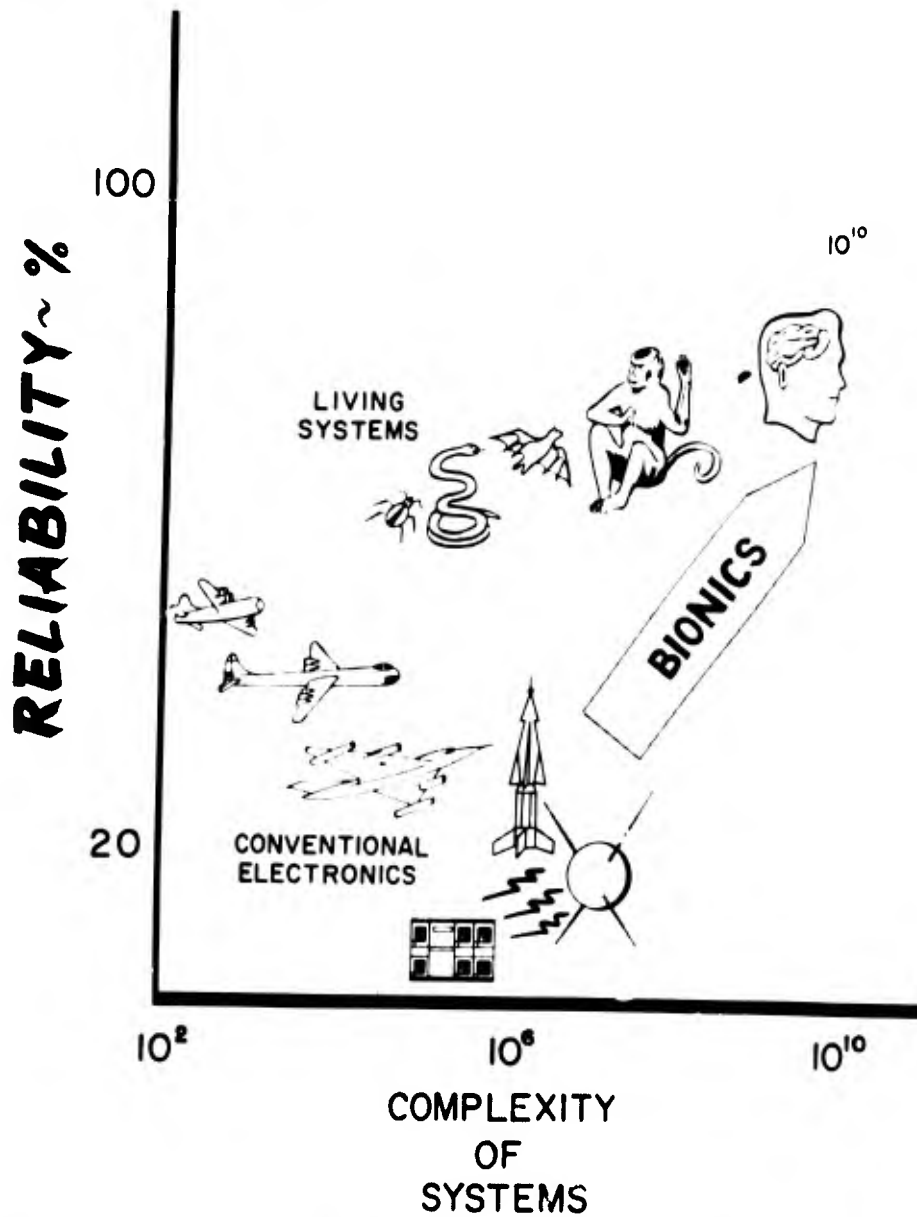


Figure 3. Systems Complexity Vs Reliability of Biological and Electronics Systems.

But in other areas, primarily those related to sophisticated information processing (such as pattern recognition, concept formation, prediction, optimum decision making, learning, self-adaptive control and "intelligent behavior" in general), biological systems are far superior with respect to capability, efficiency, and space

requirement. Those areas where the Bionics/Biocybernetics approach promises to be most rewarding and stimulating to hardware development are listed in Figure 4.^{6, 7, 8, 9, 10} Examples of some specific items being studied in these areas are discussed briefly in the following. The selection is arbitrary to a large degree, and it is primarily intended to show the broad spectrum of these efforts and of their potential applications.

EXAMPLES OF BIONICS EFFORTS

Biological Locomotion

As an example of work in this area, Figures 5 and 6 are taken from the extensive work of Hertel, the airplane designer who

BIONICS / BIOCYBERNETICS AREAS

1. Biological Locomotion
2. Bio-energetics
3. Sensory Mechanisms
4. Information processing, storage and retrieval
5. Pattern recognition and concept formation
6. Communication, Navigation
7. Systems organization, reliability and control
8. Design of Automata, Artificial Intelligence, and Learning Devices
9. Extension of Human Motor and Intelligence capability through Prosthetic Devices

Figure 4. Technical Areas of Bionics/Biocybernetics.

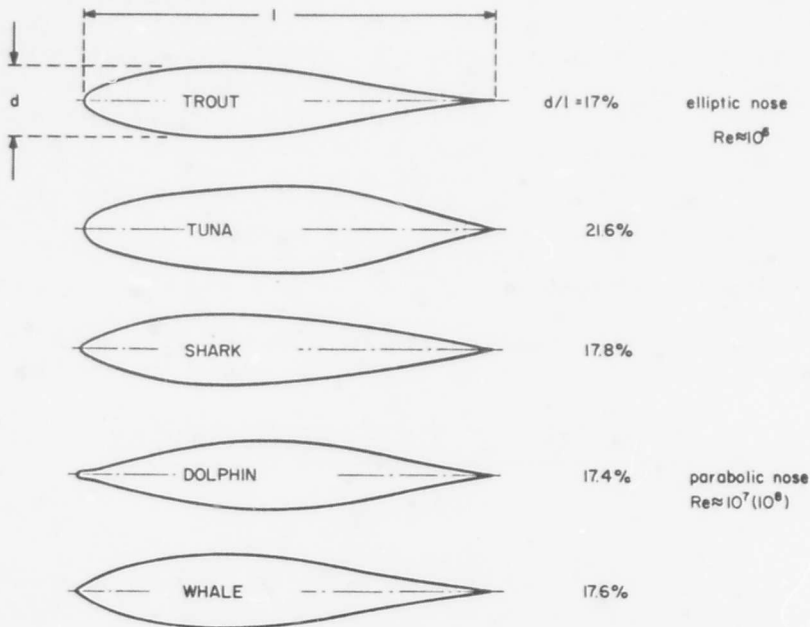


Figure 5. Laminar Profiles of Fish and Whales (from Hertel, Ref. 13).

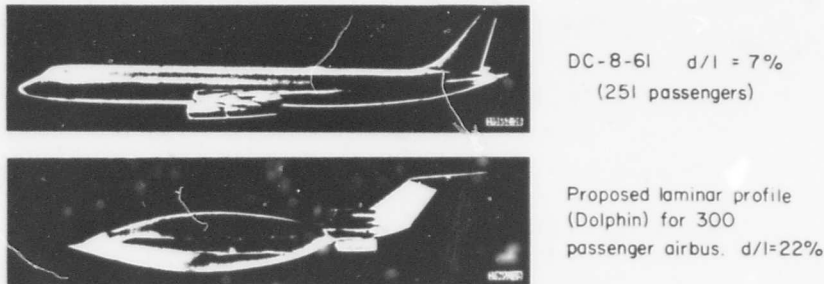


Figure 6. Comparison of Conventional Fuselage (Thickness Ratio 7%) with the Proposed Laminar Profile (Thickness Ratio 22%) Based on Studies of Biological Forms (Fig. 5). Note: The biological prototype has maximum volume for the smallest possible drag in the Reynolds number range for which it is designed. The proposed air bus model shows the application of another principle found in biological propulsion, which has been studied with respect to its superior efficiency: the concentration of the thrust in the area where the main drag occurs (from Hertel, Ref. 13).

studied structure, form, and motion of birds and fish and who translated many of his findings into new design approaches and proposals.¹² In the first figure (Fig. 5), the optimum forms for laminar flow at increasing Reynolds numbers is shown.¹³ These forms are contrasted with conventional present-day airplane profiles. Based on these findings, Hertel proposed the "dolphin" profile of Figure 6 for a modern air bus. The proposed model in Figure 6 not only incorporates the optimum form and nose found in nature for the Reynolds number of the plane but also uses a second principle found in most biological systems: the thrust is concentrated where the drag is, not separated from it. This principle appears to be more effective as borne out by technical tests, and it is hoped that its practical application is also feasible.

Information Processing^{6, 14}

Information processing systems, whether living organisms or machines, can be divided into the four stages shown in Figure 7. The biological receptor mechanisms, primarily eye and ear, as information input devices, have been studied extensively.¹⁵ Studies on the coding and preprocessing in the next stages of the nervous systems are still going on and lead to an increasing understanding

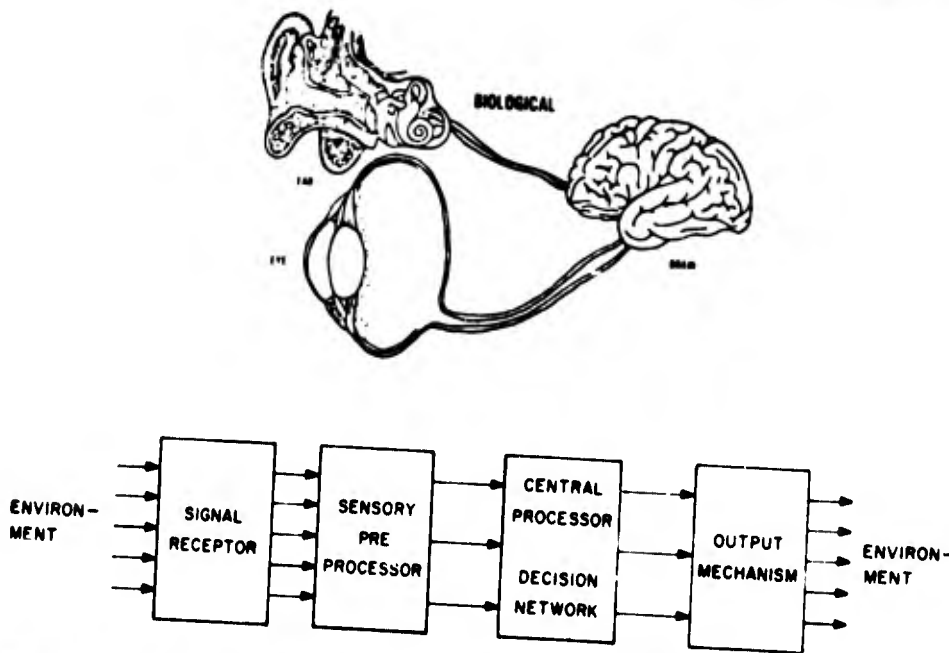


Figure 7. The Four Stages of Biological and Technical Information Processing/Recognition Systems.

of the intricate functions of signal-to-noise enhancement, property filtering, and reliability by redundancy, which lead in turn to a remarkable information compression and reliability at the input of the central processing stage. Figure 8 illustrates this condensation and filtering of the incoming information flow which is selectively filtered at the conscious level by a $1:10^7$ factor.¹⁶ The information content at the output (effector) stage of the biological information processing system increases again sharply, as indicated, due to genetic and learned "programs" and subprograms stored and selected for effective action. It is revealing to compare the capability of the human central processor with that of a large conventional general purpose digital computer (Fig. 9). The special characteristics and the differences between the systems are obvious from the comparison.

Among the most interesting on-going work in analyzing quantitatively and in modeling central nervous system functions is that by McCulloch, Kilmer, and Blum on the concept of the Reticular Formation (RF).^{17, 18} Looking at the RF as the computer with the central command function, new ways to couple and decouple computer systems, depending on the need of the overall systems combination, present themselves. These authors think of the RF as one would think of the commander of a battle fleet

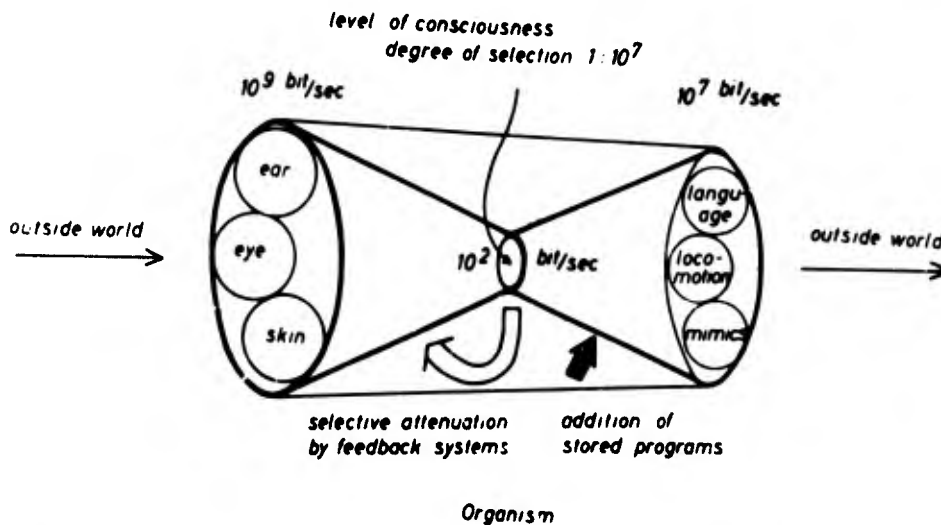


Figure 8. The Flow of Information Through Man (after Keidel, Ref. 16). Note: While the amount of sensory input information is reduced on its way to the conscious level, the number of elements engaged in processing the information increases at the cortex of the brain.

COMPARISON OF:		
	BIOLOGICAL SYSTEM	AND COMPUTER
MODE OF OPERATION	PARALLEL OPERATION, DIGITAL, ANALOG	SEQUENTIAL OPERATION, DIGITAL
INPUT, OUTPUT	~ 25 BITS/SEC	~ 10 ⁸ BITS/SEC
MEMORY:		
A. CAPACITY	10 ¹⁵ -10 ²⁰ BITS	~ 10 ⁶ (HIGH SPEED)
B. TYPE	ASSOCIATIVE	ADDRESS
TIME FOR ONE ELEMENTARY OPERATION	10 ⁻² -10 ⁻¹ SEC.	10 ⁻⁶ -10 ⁻⁸
BASIC COMPONENT:		
A. SIZE	10 ⁻⁶ -10 ⁻⁸ CM ³	10 ⁻² -10 ⁰ CM ³
B. NUMBER	~ 10 ¹⁰	~ 10 ⁵
C. PACKING DENSITY	~ 10 ⁷ CM ⁻³	10 ⁻¹ CM ⁻³
DEVELOPMENT TIME	~ 10 ² YEARS	~ 50 YEARS
WEIGHT	~ 10 ⁰ LBS	~ 10 ⁵ LBS

Figure-9. Comparison of Some Characteristics of Biological and Technological Information Processing Systems (after Oestreicher, Ref. 14).

who depends on his radar, gunnery, navigation, engineering and like inputs, to determine the mode of his fleet: attack by plan 1, 2, etc.; retreat by plan a, b, etc.; reconnoiter and so on. Similarly, the RF relies on the discriminatory, associational, memory, abstracting and programming powers of the cerebrum, but it does not relinquish its command function over the overall organism. Depending on the visual, auditory, and other inputs, it commits the human to an overall behavioral mode such as sleep, eat, drink, work, rest, talk, and commands the associated selection of input information data and associated output bodily movements such as talking, eating, fighting, etc. In simulating the fairly well-known neuroanatomy or wiring diagram of the RF, a set of nonlinear, probabilistic, hybrid computers is stacked in a columnar array resembling the string of modules described in the RF. These are connected not merely from module to adjacent module but also by long jumpers between distant modules (Fig. 10). However, as suggested by the known RF axonal anatomy, modules close together are information-coupled more closely than modules far apart.

SIMPLEST MODEL OF RETICULAR FORMATION

(After Kilmer, McCulloch)

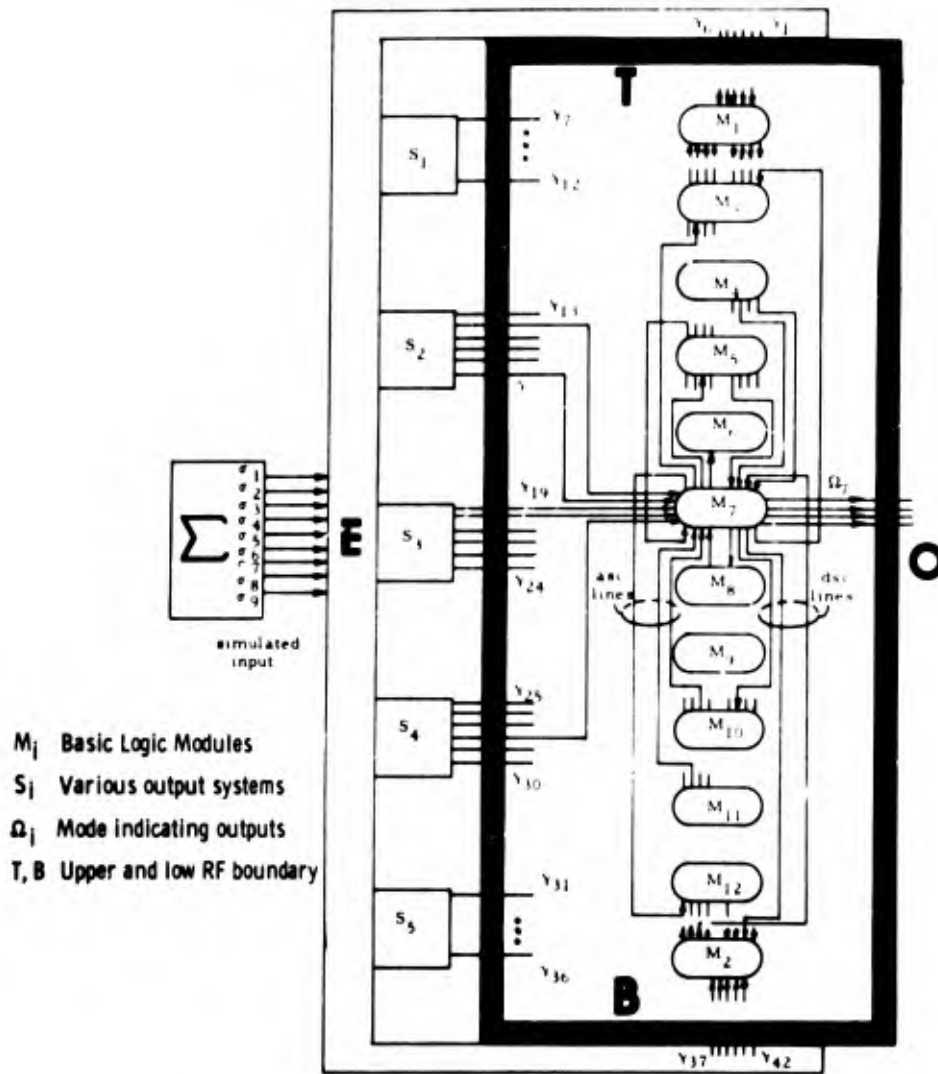


Figure 10. Reduced Schematic of the Model of the Reticular Formation (RF) (after Kilmer, et al., Ref. 17). Note: The M_i 's are the basic logic modules interconnected to a degree and in a way suggested by the known RF axonal anatomy. The S_i 's correspond to the various exteroceptive and interoceptive sensory and internuncial systems which feed into the RF. For the distribution rules for the σ_i and γ_i interconnection lines and other details of the model, see references.

The plasticity of this system achieved by the strategies employed is now very interesting: modules which apparently have

the most information have the most authority, and they express this authority by recruiting other modules with less apparent information. If the input information changes, the modules decouple, and each of them returns to its relative modal preference. Then they again gradually interact with each other and eventually converge on a single output modal consensus. The overall model is thus able to condition, habituate, generalize, discriminate, predict, and generally follow with its behavior a changing environment. The importance of this type of modeling is obvious from a biocybernetics point of view, as well as for the design of adaptive command and control systems.

From the large area of learning networks and learning machines, one important application will be mentioned: the self-organizing and learning control system.¹⁹ The principle of learning taken from the biological prototype implies that the system possesses the capability to change its response to a stimulus depending on the "favorable" or "unfavorable" reaction of the environment to an initial response (reward and punishment). Such control systems are based on the mathematical treatment of self-organization in living systems (Ashby²⁰), of probabilistic logic (von Neumann,²¹ McCulloch and Pitts²²), and probabilistic neuron models. One defines as a learning or adaptive control system a system which acts on-line to improve its performance based on the histories of the controller inputs, outputs, and environmental feedback systems, and on a specified evaluation criterion.

Self-organizing control systems are learning control systems in which internal restructuring takes place as the control system acquires information. Frequently, self-organizing controllers are also defined as systems using small memory retention intervals ($< 0.1\%$ of the plant response time). The self-organizing controller developed during the past 8 years under the Air Force Bionics Program use as its basic element a general purpose statistical decision device, the "probability state variable" system (PSV) for performance assessment (PA) (Fig. 11). Application of statistical detection theory reduces the number of "false alarms" to individual input signals, but discerns only the presence of any bias in the environmental "noise" input. This PSV module has been adapted to a self-organizing flight control system which exhibits many advantages with respect to rapid learning, adaptation to various flight systems, relearning, and other functions

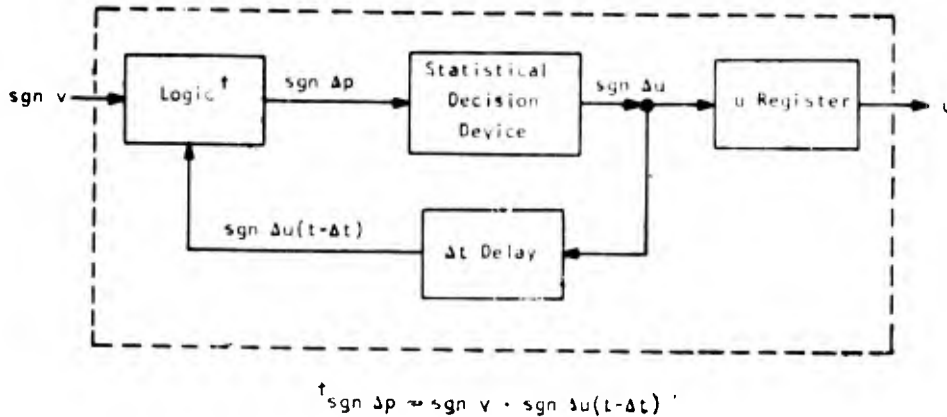


Figure 11. General-Purpose "Probability State Variable" Module for Self-Organizing Controllers (from Barron, Ref. 19, Patent Pending). Note: The input logic accepts binary value signals $\text{sgn } v$ from an external means of performance assessment; $\text{sgn } \Delta p$ is the polarity of an increment to a p-register which is part of the statistical decision device (Fig. 12); $\text{sgn } \Delta u(t-\Delta t)$ is the polarity of the step taken one clock interval earlier. The $\text{sgn } \Delta u$ pulses from the decision device are integrated in the u-register (output register). The output is a function of the input and the probability state.

compared to conventional nonadaptive systems. Components within the PSV system could even fail, with little effect on its learning ability. This self-organizing flight control system has been successfully simulator tested and is programmed to be flight tested on the F-101B within this year (Fig. 12).

The potential of the same system has been demonstrated with considerable success for multiple axis control of a 19,000-lb satellite and appears to be a fairly universal, highly reliable, rapid learning control system with the ability to compensate for unplanned-for eventualities such as being hooked up backward!^{19, 23} Its application to systems with multimoded inputs operating in environments in which we have little *a-priori* knowledge is presently being studied. Here it must learn *on the spot* the environmental characteristic: for example, in a planetary environment about which we have very little detailed information.

Another example studied under contract for the AF Avionics Laboratory uses the same PSV technique to solve energy allocation problems in a varying but unknown environment: for example, as in a satellite. The PSV solutions in this case were several orders of efficiency better than those of preprogrammed computers.

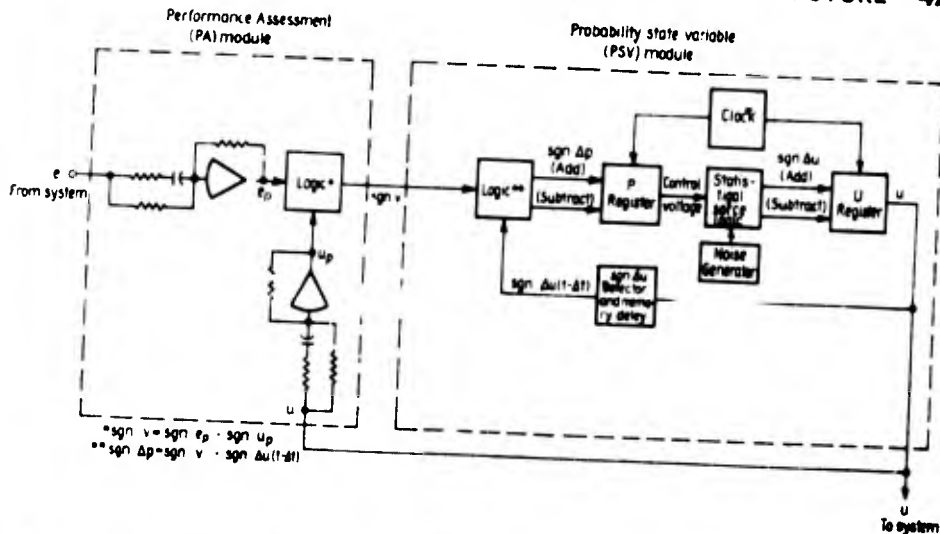


Figure 12. Block Diagram of the Mark III Self-Organizing Controller (from Barron, Ref. 19). Note: e = error, e_p = predicted error, u = control vector, v = assessed performance value. The p -register (bi-directional, reversible binary counter) contains information as to the probability state of the "statistical decision device," which is composed of the p -register, the statistical source logic, and a form of comparator termed statistical source.

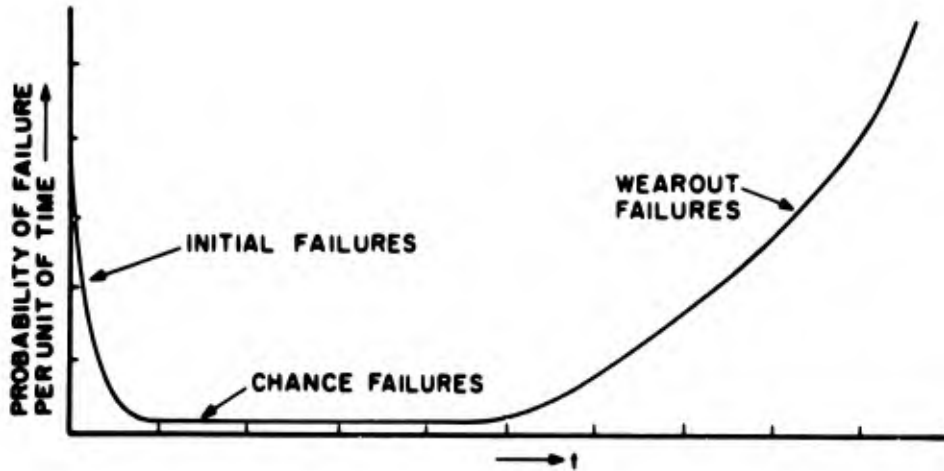
This opens up the potential application of this self-organizing control system to a whole host of allocation problems of high complexity and having an obviously not too well-defined goal structure. It approaches the capability to solve by control systems some of the complex allocation and disposition problems which to date only human beings could solve economically.

An interesting application of control system theory to biological systems is the recently published theory of aging which considers age as the accumulation of uncorrected errors in the various sub-system controls which can be caused by the interference of environmental noise.²⁴ As an example of these considerations, Figure 13 shows the life expectancy of a manufactured article and of man.

Pattern Recognition

One area of particular interest in bionics work is the area of pattern recognition.^{14, 25} It involves the capability which all higher animals have developed to categorize the vast incoming stream of sensory information into classes for further processing, comparison, and recognition. It results in a tremendous information

FAILURE RATE CURVE FOR MANUFACTURED ARTICLES



DEATH RATE PER THOUSAND OF U.S. MALES (1964)

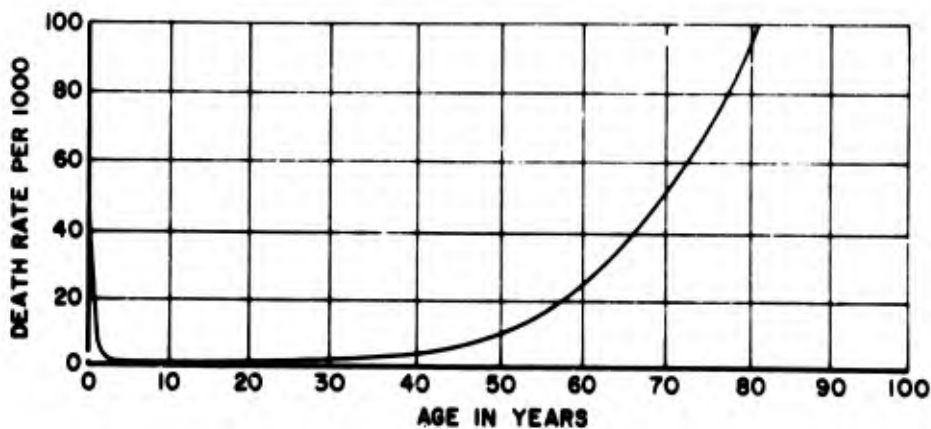


Figure 13. Theory of Aging Based on Accumulation of Uncorrected Errors: Comparison of the Failure Rate Curve for Manufactured Articles with the Death Rate as a Function of Age for a Normal Population (from Goldman, Ref. 24).

compression as indicated on the left-hand side of Figure 7 and in the loss of all sensory information of no direct interest. In higher order biological systems, many preprocessing tasks are delegated to the peripheral level to relieve the central processor and to permit faster response. For this reason, the preprocessing of visual

and auditory information is being extensively studied, and the principles found are being applied to visual pattern recognition machines (reading machines) and to speech recognition devices.

The neurophysiological study of the functional behavior of the pigeon's retina²⁶ revealed classes of ganglion cells responding to specific characteristics of the visual input (Fig. 14). Analysis of the anatomy of the pigeon's eye (Fig. 15) led to a plausible explanation for this behavior on the basis of the connectivity of the horizontal, bipolar, and amacrine cells in the inner nuclear layer. An electronic network with a corresponding wiring diagram (Fig. 16) exhibits the same capability to respond to and recognize the target properties found in the living system as listed in

Ganglion Classification	Functional Performance	
	Response	No Response
Luminosity Detector	Intensity, color	
General Edge Detector (Type I)	Moving spot or edge "ON/OFF" of a spot	Diffuse light Multiple moving edges
General Edge Detector (Type II)	Moving spot or edge "ON/OFF" of a spot	Diffuse light
Convex Edge Detector	Moving spot or convex edge, "ON/OFF" of spot	Diffuse light Long straight edges
Directional Moving Edge Detector	Spot or tongue moving from a specific direction, "ON/OFF" of a spot	Diffuse light Simultaneous spots
Horizontal Edge Detector	Long moving horizontal edge	Diffuse light "ON/OFF" of a spot
Vertical Edge Detector	Long vertical edge (stationary or moving)	Diffuse light "ON/OFF" of a spot
Object Detector	Bug (translated and rotated)	Diffuse light, spots Ellipse, star

Figure 14. Ganglia Neurons in the Pigeon Retina, Classified According to Their Functional Responses (after Maturana, Ref. 26; and Runge, et al., Ref. 27).

Figure 14.²⁷ As shown by other behavioral experiments, recognition of the same type of properties without further specification of the target can lead to immediate response modes of the whole animal.

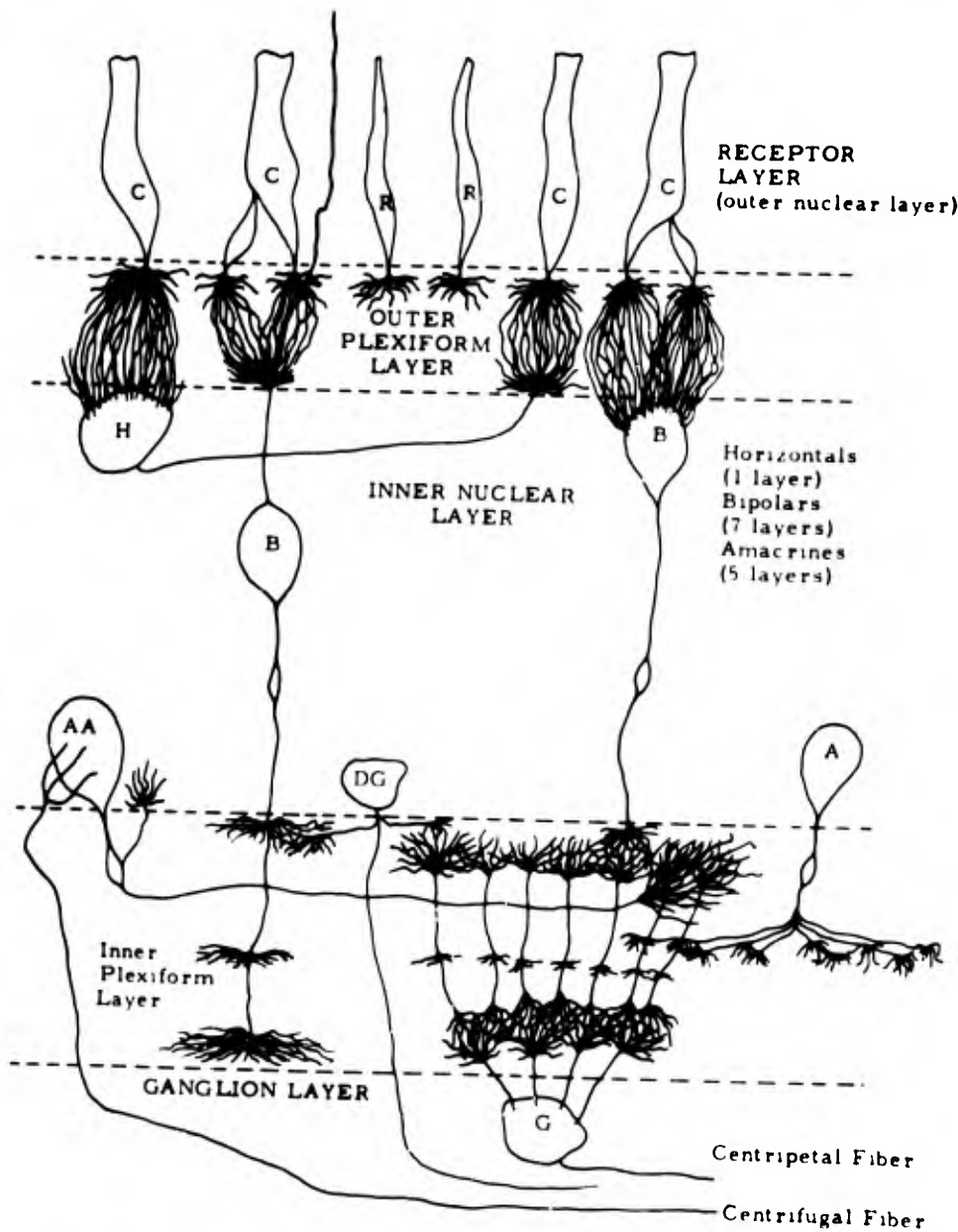
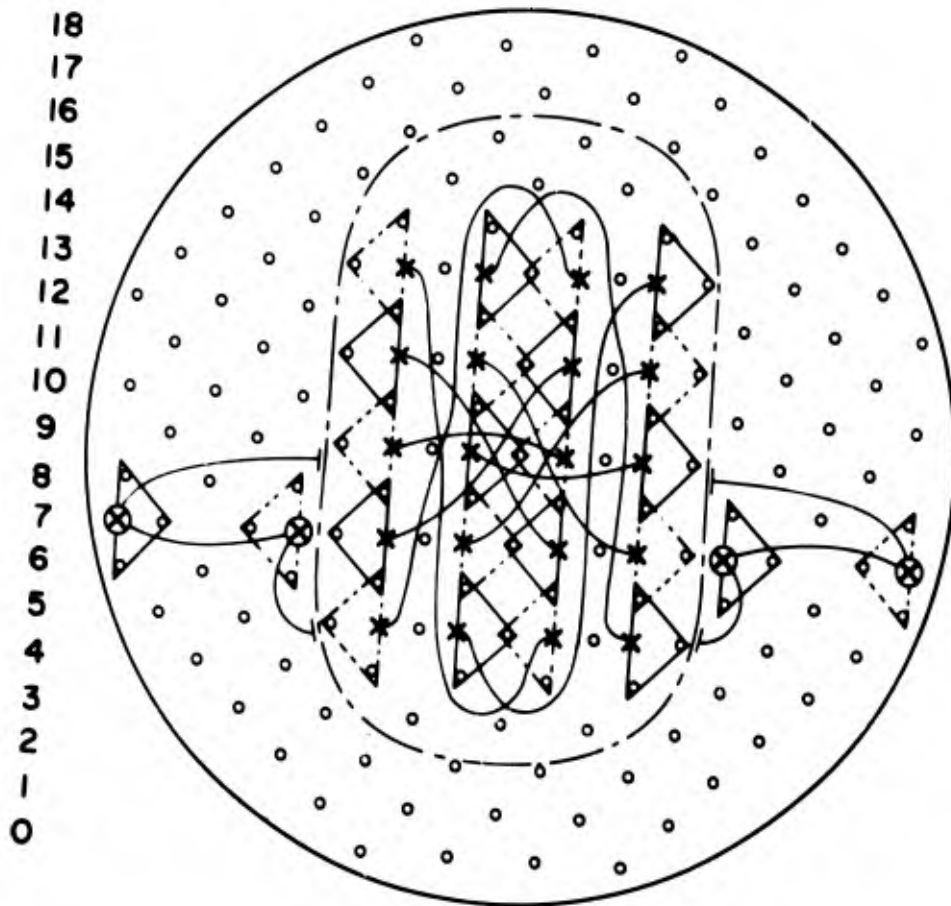


Figure 15. Simplified Diagram of Avian Retinal Anatomy (from Runge, et al., Ref. 27). Note: R = rods, C = Cones, H = Horizontal Cells, B = Bipolars, A = Amacrines, AA = Associative Amacrines, G = Ganglia, DG = Displaced Ganglia.



0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Triangles = receptors inputting to bipolar cells ×
and amacrine cells ⊗

----- = dendritic spread of ganglion input

Figure 16. Electronic Model of the Avian Retina. Note: The sensory array of 145 cone cell analogs is thought of as being equivalent to 2-½ visual degrees of the pigeon retina. The complete model contains 58 horizontals, 80 bipolars, 88 amacrines and 10 ganglion cell analogs. The example of this figure shows the cell connections for the general edge detector ganglion (see Fig. 14). The area enclosed by the broken line represents the ganglion's input dendritic spread. The receptors inputting to each bipolar are contained by the triangles (from Runge, et al., Ref. 27).

A visual pattern recognition problem of considerable practical significance in Earth-bound clinical medicine as well as in space medicine is the electrocardiogram (ECG) analysis. As one specific example from the large literature on pattern classification techniques, the application of the Polynomial Discriminant Method (PDM)²⁸ to the diagnosis of heart abnormalities as evidenced in the vectorcardiogram will be mentioned. The PDM is a non-parametric statistical method by which a pattern is classified as indicating one of several possible states of the natural event based on estimates derived from a learning space of the probability density functions for each of the possible states. The method separates by computer calculation points belonging to different categories as illustrated on Figure 17 for various point distributions (σ represents the "smoothing parameter" for the distribution functions calculated). In applying this method to the vectorcardiographic diagnosis problem,²⁹ samples were taken every 5 msec up to 75 msec after onset of the QRS complex of the electrocardiogram. A separating surface was then calculated for the total set of 46 measurements (15 points on 3 leads plus duration of QRS complex) which would separate points belonging to normal patients from those belonging to abnormal patients. After "training" the classifier with 192 "normal" records and 57 "abnormal" records, the classification accuracy on a testing set of ECG's was 97% correct on normal patients and 90% correct on abnormal patients. This recognition rate of abnormal patients, on the basis of the ECG alone, appeared to be considerably higher than the number of abnormalities detected by clinical diagnosis on the basis of the QRS complex alone. These results by Specht and Toole indicate the potential usefulness of such pattern classification methods. Such a recognition method can certainly be used in space applications for the real-time alerting of any deviation of a crewmember's ECG from an established baseline. The total system can be realized by several ounces of microminiaturized circuitry and can be built as an adaptive element (Fig. 18) so that baseline functions can be established on Earth or during various phases of the space mission. By suppressing all "expected" signals, a method such as the one proposed would yield significant data compression by restricting telemetering to changes from the baseline function.

In auditory pattern recognition, the interest and efforts of many groups have been concentrated for quite some time on automatic speech recognition.³⁰ This area is potentially of great

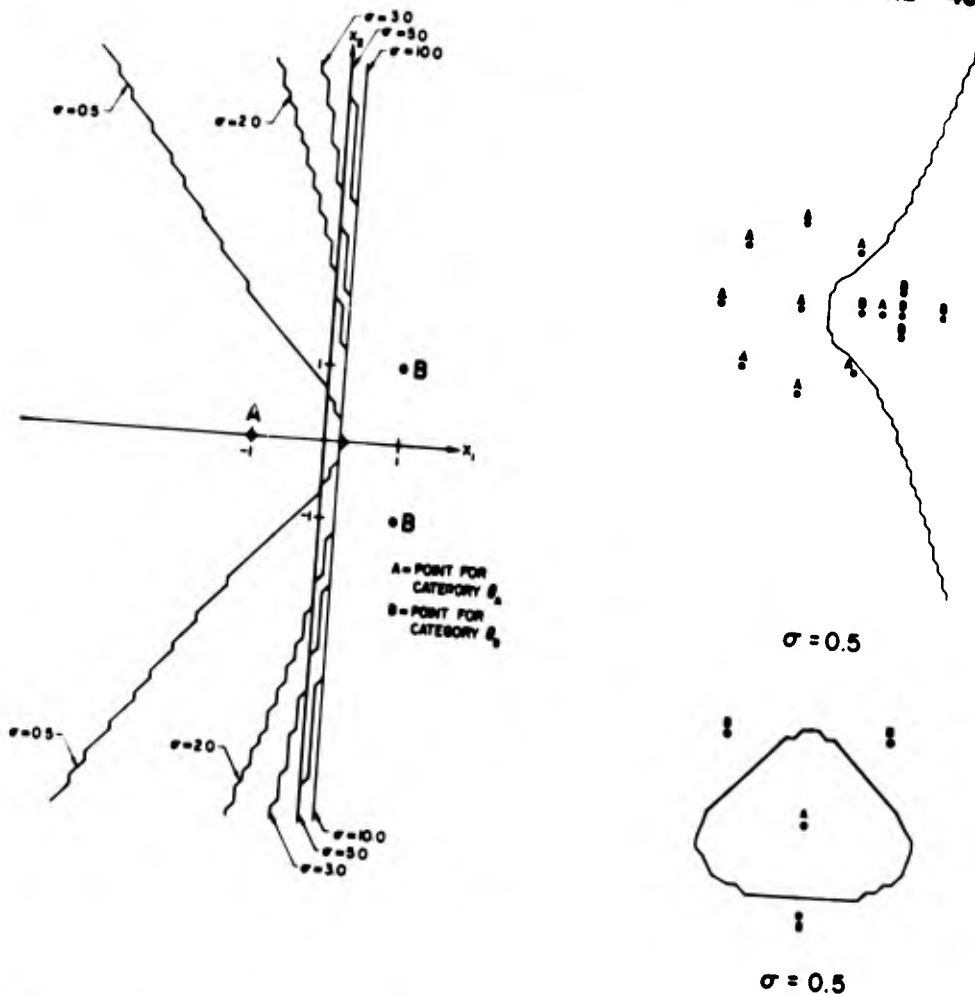


Figure 17. Pattern Recognition by Polynomial Discriminant Method: Calculation of Decision Surfaces to Separate Points in Category θ_A from Points in Category θ_B (from Specht, Ref. 28).

technological usefulness if one thinks of language translation machines, voice actuated typewriters, voice coupling of man to machines and of man to computers, etc. The first step in biological, as well as machine speech recognition is the preprocessing of speech for easier classification. This is accomplished by speech compression to reduce the tremendous redundancy contained in spoken words. Speech compression by itself has been of great concern to communication engineers over the past 30 years, since it leads to more economic use of communication channels by bandwidth compression. Many approaches have been taken for speech compression: for example, the encoding of speech in terms of the

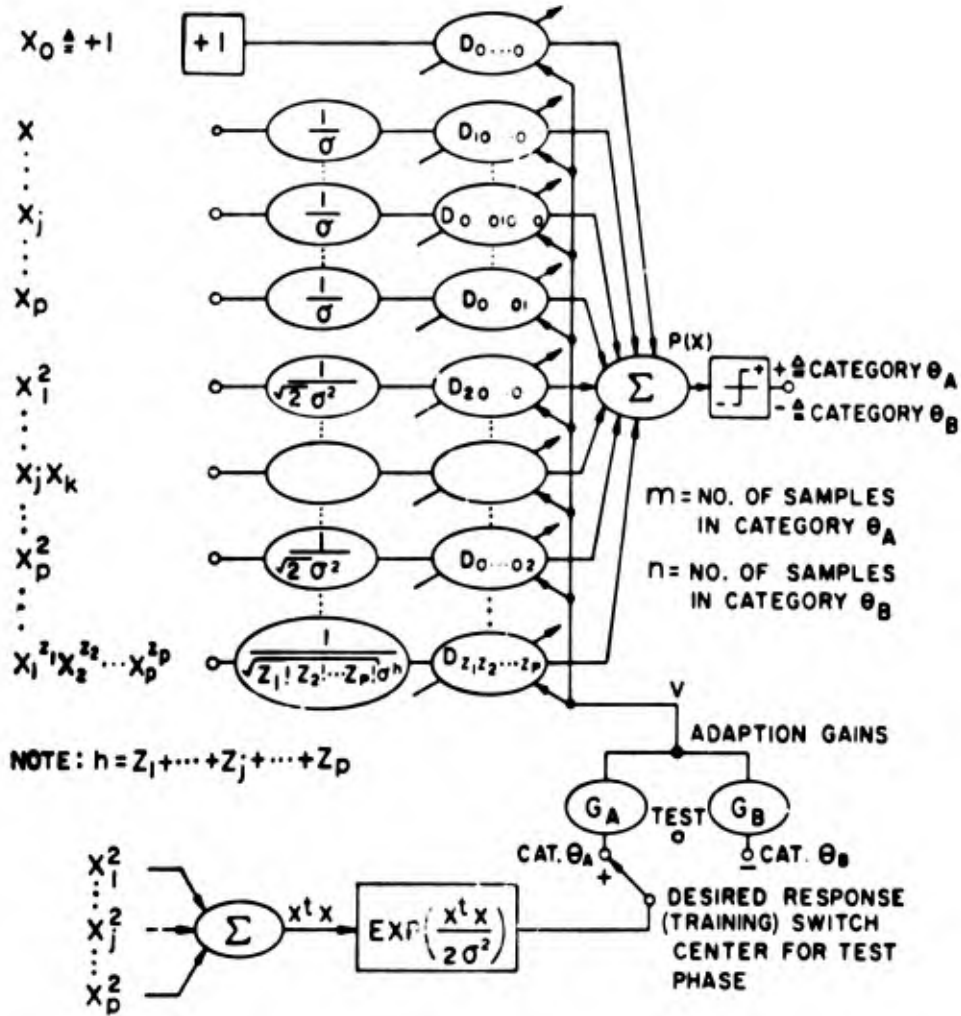


Figure 18. Functional Block Diagram of Adaptive Polynomial Threshold Element (from Specht, Ref. 28). Note: The Polynomial Discriminant Function $F(X)$ is calculated from the input variables X_p and their powers and cross-products. For calculation of the weights D , the normalizing factor $\exp(-X^t X/2\sigma^2)$, etc., see reference. The classifier learns during the training phase (by arriving at the right weights D) the decision surface $P(X) = 0$ separating the two categories to be classified.

properties of the signal-producing mechanism (voice) or the channel vocoder which transmits the short-time amplitude spectrum of various frequency bands and the pitch characteristic of speech. In all these approaches, bandwidth compression of 10 to 1, or more, has been achieved.

The bionics approach to speech compression or speech analysis-synthesis systems is to endeavor to model the biological filtering of the spoken message. This process starts in the mechanical and hydrodynamic filters of the middle and inner ear, is continued in the coding process on the basilar membrane (where the analog motion pattern is transformed into a pulse interval coded electrical signal), and is completed by the selective transmission and filtering of the message as it ascends the auditory pathway. An electronic analog model of the human ear has been developed for this purpose which presents as its output the three-dimensional speech pattern (cochlear position, basilar membrane amplitude and time) as the nervous system sees it at the basilar membrane.^{31, 32} Artificial neurons, modeled after the characteristics of the auditory neurons observed in neurophysiological experiments on the guinea pig, are used for pulse coding, further processing of the spoken messages, and property filtering by neural networks.³³ The results of this approach are interesting with respect to coding, speech compression, and filtering. Speech recognition itself still poses appreciable problems, no matter what method is used.^{30, 34} A main one is the segmentation problem: the cutting of continuous speech into discrete chunks which are then recognized as linguistic units. This capability is difficult to achieve by present-day, real-time machines and is so easily performed by the nervous system. Preprocessed speech, for example, has been presented as visual or tactile signals to human subjects; in general, they were able to learn to recognize these patterns with high reliability. This is accomplished by the nervous system's general ability, regardless of the sensory channel used, to operate on the pattern of the entire word and simultaneously perceive subset patterns. Furthermore, the nervous system must be able to augment or de-emphasize certain pattern features prior to making final recognition decisions. It appears that these are essential features for real-time automatic speech recognizers and that we should be able to improve our understanding of these processes by studying the passing of speech signals through finer and finer distinguishing branches of property filters formed by complex nerve nets.

One specific bionics speech compression system developed by Stewart³¹ will be mentioned here. It uses the human analog cochlea described above and a neural processor inspired by speculations about the neural processing of acoustic information in the grasshopper. It promises to achieve intelligible speech transmission with a bandwidth of approximately 50 Hz—a considerable

improvement over most vocoder systems. It has also some appeal with respect to automatic speech recognition. Each section of the basilar membrane of the analog cochlea used (Fig. 19) is connected to "neural analyzers" which provide a space-time display of the modulation envelope of the various cochlear sections. Examples of patterns obtained with this system for speech sounds are presented in Figure 20.

Speech recognition research is presently at the point where machines are feasible which recognize limited vocabulary speech (10 to 50 words). Learning networks are being used to train the program to increase reliability and allow adaptation to individual speakers or dialects. Although this present capability is still far from continuous speech recognition, some of these research results can be applied immediately to hardware problems. For example, under the Bionics Program of the AF Avionics Laboratory a voice controller for an astronaut maneuvering unit is presently being developed.³⁵ The voice controller is a limited speaker, limited vocabulary speech recognition device (Fig. 21). It is being designed to accept the voices of three different speakers—the size of an Apollo crew—and to recognize fourteen distinct words (Fig. 22). These fourteen commands will be adequate to control the complete functional capability of the dual-maneuvering unit. The voice controller frees the hands of the astronaut, making them available for cargo transfer, maintenance, repair, and assembly operations.

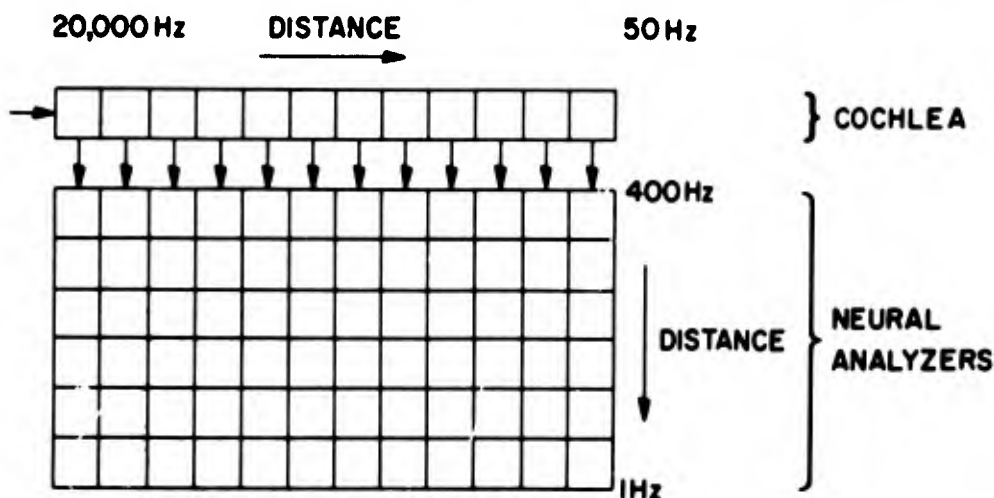


Figure 19. Display Grid for an Analog Cochlea and Neural Analyzing System (from Stewart, Ref. 31).

A second hardware item presently being built for our laboratory is a helium speech processor using the analog cochlea and neural analyzer developed by Stewart to regenerate the distorted speech produced by astronauts in a helium atmosphere, for example, or under other unusual gas conditions, with improved intelligibility and naturalness. This machine recognizes, deletes, and/or corrects the undesired properties of helium speech. Both devices mentioned demonstrate that even today automatic speech recognition research does provide new ideas and solutions to operational problems.

Extension of Human Capabilities through Prosthetic Devices

Any remote control activity, controlled use of power or automation in general, is an extension of human motor or intelligence

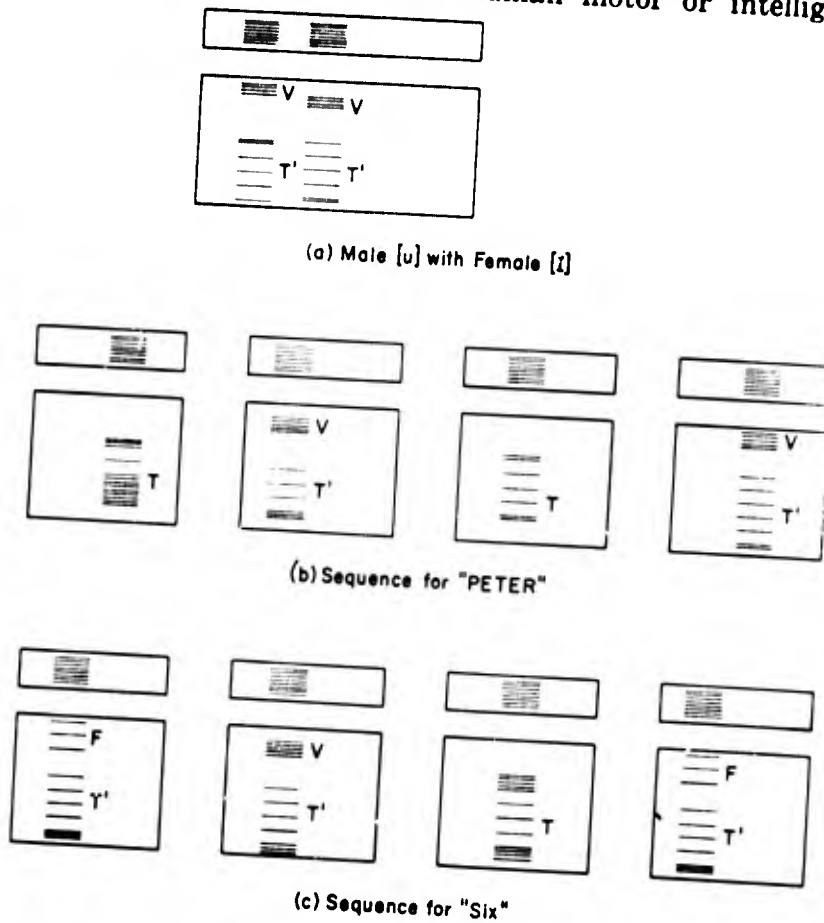


Figure 20. Patterns for Speech Sounds and Words Obtained with the Analog Cochlea and Neural Analyzing System of Figure 19 (from Stewart, Ref. 31).

capacity and is therefore a prosthesis in the broadest sense.³⁶ Despite advances in remote manipulation, control of an artificial hand or arm by biocurrents³⁷ and various robot designs, progress in these areas has been slow due to the lack of appropriate sensory feedback regarding the environment and due to lack of "intelligent" or adaptive behavior of the device.³⁸ The intelligent control of the prosthetic capability, rather than the capability as such, is the problem. In other words, the main problems encountered in the design of such extensions are those of pattern recognition,³⁹ self-organization, adaptation, and control, and any progress in these vital areas will support specific prosthesis design efforts. Whether the problem of interest is automatic screening of cloud pictures taken from a weather satellite or the screening of particles under a microscope and the automatic recognition and counting of certain cells, the task is basically the same: it requires creating some of the functional capabilities of the human visual system and its learning capability. Similar statements are valid with respect to automata expected to perform in complex un-

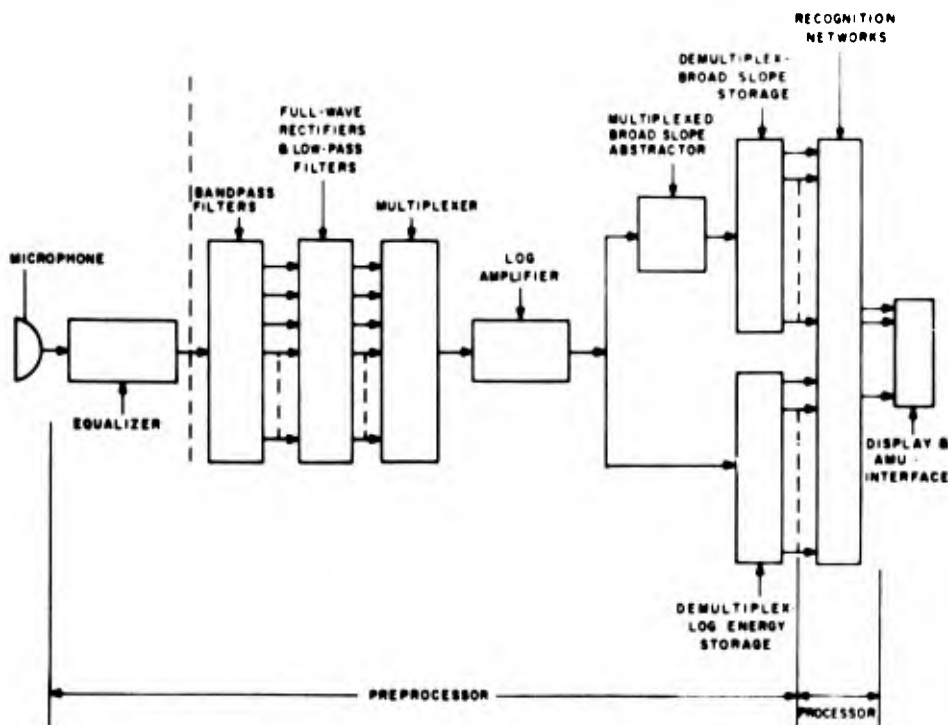


Figure 21. Block Diagram of Voice Controller for Astronaut Maneuvering Unit (from Kelly, et al., Ref. 35).

ISOLATED COMMAND WORDS:

- | | |
|------------|---------------|
| 1. Command | 8. Hold |
| 2. Stop | 9. Open |
| 3. Forward | 10. Pitch |
| 4. Back | 11. Yaw |
| 5. Right | 12. Down |
| 6. Left | 13. Up |
| 7. Roll | 14. Translate |

Command sequences such as "Command Translate Right" or "Command Yaw Left" are possible.

Figure 22. The Command Words Recognized by the Voice Controller for Astronaut Maneuvering Unit of Figure 21; the Voice Controller Frees the Hands of an Astronaut.

known environments: they must be able to adjust their behavior according to the priorities required by the environmental inputs and "learn" the optimum strategy to survive. It appears that biological systems can teach us and guide us how best to design such complex systems and how to control them.

CONCLUSION

This review of the status of bionics/biocybernetics research and its potential contributions to astronautics has aimed at avoiding any overly optimistic predictions and visionary dreams. The applications are almost self-evident once the basic technologies are available. Human recognition capability and human control can be foreseen to be step-by-step replaced by machine recognition devices and self-adaptive computers. The applied physical sciences will be penetrated more and more deeply with biological concepts, ideas, and capabilities. The biological roots of the functional capabilities and of the expressions used to describe them will be

soon forgotten, as its almost already the case today when engineers talk about "adaptive" antenna systems or "learning" flight controllers. The examples of on-going work cited in this paper are neither exhaustive in depth nor in breadth. Time did not permit describing the contributions of biomathematical investigations to the understanding of systems reliability and of control processes in large systems. The potential payoffs of modeling biological chemoreception,⁴⁰ studying biological "fuel cells"⁴¹, or investigating the vestibular system as prototype of a miniature attitude control or short-term inertial guidance system⁴² have not been touched upon.

It was not possible to include in the discussion another hardware item, a radar ground-speed detector which was built according to the principle discovered in the beetle's eye for target speed detection.⁴³ This system, developed for the US Air Force,⁴⁴ is being flight evaluated this year to determine its merits compared to other speed indicating systems. However, it was not the purpose of this review to discuss specific problems or their potential solutions. It was the purpose to discuss the "biologization" of the engineering sciences and the new mission for the biological and medical sciences. Biological research today no longer serves exclusively the direct support of man, but has its potential impact on practically all areas of modern technology. Such efforts to understand and duplicate the functional capabilities of living systems are not to be looked at as separate roads to technological progress leading to solutions completely different from what present-day technology attempts. For this, interdisciplinary communication is already too lively, and it will certainly further improve. But the biological prototypes can stimulate our imagination and provide the living proof that certain capabilities are possible and feasible.

The capabilities and approaches which allowed life to originate, to survive, and to develop on this planet over millions of years are basically the same capabilities needed to assist man and his man-made microenvironment to survive, to explore, and to conquer the new environments of space. The most promising road to success in this venture would be to take full advantage of the biological approaches developed during evolution. No intelligent machine would hesitate to confirm this statement.

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XXIII

Planetary Environmental Medicine (Mars)

Dr. Hubertus Strughold*

In ancient times the *planets* were objects of *divine adoration*.

In the Middle Ages they were, and still are, symbols for *astrological prognostications*.

In modern times, since the invention of the telescope 400 years ago, they have become special attractions for *astronomical observations*.

Some planetary surface features and colorations discovered in these optical astronomical studies during the 19th Century led to *extraterrestrial life speculations*.

In the 20th Century new windows have been opened to earth-based astronomy by *spectrograph, radio, and radar application*.

During the past decade, the fast development in rocketry has made the nearest planets actual targets of space-bound astronomy by means of *instrumented probes, fly-bys, orbiters, and landers* for nearby and *on-the-spot exploration*.

All this has gradually opened the gate for a *manned planetary landing operation*. This has been the dream of the space age prophets, but its realization will be the postlunar goal of the *coming space-enthusiastic generation*.^{1, 2}

Nevertheless, since this Fourth International Symposium on Bioastronautics and the Exploration of Space coincides with the 50th Anniversary of Aero Medicine and the 20th Anniversary of Space Medicine, this is an appropriate time to look into the future,

*Chief Scientist, Aerospace Medical Division (AFSC), Brooks AFB, Texas.

and beyond the moon, to the planets as possible targets for manned landing missions.

In terms of planetary environmental medicine, bioastronautics is faced with the basic questions: Which planets are visitable? (i.e., which are accessible for a landing mission, and which are nonvisitable or inaccessible?). Those which are nonvisitable may be approachable by orbital or fly-by operations. And some may not even be approachable at all. On those accessible, what are the specific hazards en route to and on the planets themselves? How much human life support and protection do they offer naturally? And how much has to be provided artificially in planetary stations to compensate for the deficiencies in order to meet the human physiological requirements and to make the extraterrestrial environments as terrestrial as possible on a confined base?

HOMO SAPIENS TERRESTRIS

The ecophysiological requirements of man can best be demonstrated by the concept *homeostasis* (W. B. Cannon, 1929):³ the tendency of the human body to keep the chemical composition and physical properties (oxygen, carbon dioxide, ion concentrations, temperature, etc.) of the interior milieu (intercellular body fluids) in any exterior milieu *nearly* constant: a precondition for man's health and intact sensorimotoric and mental performance capability. If one of the physical or chemical components of the external environment deviates from normal but is still above the physiologically required minimum or below the permissible maximum, the human body responds effectively with coordinated compensatory and/or defensive respiratory, cardiovascular, muscular, renal, perspiratory, etc., reactions. Deviations beyond these two ecological "cardinal points" lead to pathological effects within cells, particularly brain cells. As a result, the psychophysiological functions deteriorate. Maintenance of a nearly steady state of the body's "fluid matrix" is the function of the autonomic nervous and endocrine systems, governed by control centers in the thalamus and hypothalamus of the diencephalon, or interbrain. These systems and centers make the human body a *self-regulating system*, but only within certain limits.

I have referred to this fundamental physiological phenomenon of homeostasis because it is an ideal departure point for a medical

study of the human body in relation to any environment, or for an ecophysiological analysis of the "fitness of an environment" for man. Homeostasis includes (a) the maintenance of a nearly constant body temperature: *thermostasis*; and (b) the tendency towards a more or less constant circadian cycle of sleep, rest, and activity: *cyclostasis*.⁴ Preservation of this basic homeostatic, thermostatic, and cyclostatic nature of *homo sapiens terrestris* is of vital importance for the success of his extraterrestrial ventures.

This short paper does not permit me to draw a complete picture of the environmental medical aspects of the other planets and their moons. Thus, I shall confine myself to certain environmental factors which significantly determine the prospects and limitations of interplanetary spaceflight.^{5, 6, 7, 8, 9} This will be followed by a brief discussion of the medical problems encountered on a flight to Mars, which is probably the only visitable planet.

MEDICAL ASPECTS OF INTERPLANETARY FLIGHT

One of the ecologically most important environmental factors in our planetary system is *solar electromagnetic radiation*, particularly its thermal section (Table I). At the Earth's orbital

Table 1. Solar Irradiance from Mercury to Pluto

Planet	Mean Orbital Distance from Sun 10 ⁶ km	Intensity Factor	Total Irradiance (cal cm ⁻² min ⁻¹)	Illuminance (lux)
Mercury	57.9	6.67	13.3	935,000
Venus	108.2	1.91	3.82	267,000
Earth	149.6	1.000	2.0	140,000
Mars	227.9	.431	.861	60,300
Jupiter	778.3	.0369	.0739	5,170
Saturn	1428	.01096	.0219	1,530
Uranus	2872	.00271	.00542	380
Neptune	4493	.00111	.00222	155
Pluto	5910	.000640	.00128	90

distance, heat radiation amounts to 2 cal per sq cm and min, known as the terrestrial solar constant. The planet Venus is exposed to a solar thermal irradiance of almost 4, and Mercury to more than 13 cal $\text{cm}^{-2}\text{min}^{-1}$. The Martian solar constant amounts to 0.86; at Jupiter's distance, it drops to 0.074; and, at the distance of Pluto, to 0.0013 cal $\text{cm}^{-2}\text{min}^{-1}$. This factor—heat radiation from the sun, which includes essentially the infrared and visible rays—is ecologically important for manned space operations with regard to the temperature control of the spaceship, the temperature climate on the planets themselves, and the temperature control within planetary stations.

The thermal radiation intensities to which the planets, as a function of their orbital distances, are exposed and to which space ships would be exposed can best be illustrated by an asteroid which comes very close to the Sun and, therefore, has been named "Icarus" by its discoverer, Walter Baade (Mt. Palomar Observatory, 1949), after the legendary Icarus whose wings melted away when he ignored the advice of his father, Daedalus, not to fly too close to the Sun. But this asteroid's very eccentric orbit, with a period of 409 days, also carries it very far from the Sun. The surface temperature of Icarus at its aphelion (283 million km, between Mars and Jupiter), has been estimated to be below the freezing point of water; but, at its perihelion—28 million km from the Sun, within Mercury's orbit—it might rise to some 500 C. At this phase of the orbit, this miniature planetoid (about 1.0 km in diameter) may show temporarily a feeble luminosity of the glowing surface.

This thermal aspect of solar irradiance indicates that there is a heat barrier for interplanetary spaceflight, maybe in the region between the orbits of Mercury and Venus, which would make it difficult or even impossible to keep the temperature in the spaceship's cabin within the range compatible with the thermostasis of its occupants. The decrease of solar irradiation beyond Mars or Jupiter poses problems of its own; for instance, limitation for solar batteries.

As for temperature on the planets themselves as the result of their solar distance, Venus is too hot all around for a manned landing mission, but it may be approachable by a fly-by or orbiting operation. Mercury is too hot on the sunlit side and very cold

on the opposite side. The surfaces of the outer planets are also too cold. Only Mars seems to be accessible to a manned landing mission from a thermoecological point of view.

Before I discuss the medical problems involved in this undertaking, I would like to touch upon another critical factor in interplanetary flight—the *flight duration*. Whereas a flight to the Moon takes only 3 days, a flight to Mars based on a minimum energy trajectory lasts more than 8 months, and to Venus 5 months. This is the simplest and most economic method for instrumented planetary probes, such as Mariner IV and V.

Is such a long duration also acceptable for a *manned* planetary mission? To get a realistic judgment in this respect we must consider the whole complexity of life of the mission crew living in a cramped, closed ecological world with its own economy and autonomy. The activities of this "capsule society" (S. B. Sells)¹⁰ must include power control, navigation, exploration, telecommunication, control of the life-support system, hygiene, etc. Weightlessness complicates some of these activities.

Astronauts, after some 20 hours of flight, should be in a state of "relatively stable adaptation to weightlessness," as has been concluded from the medical observations in orbital flight. Artificial gravity might not be required. Anthropometric comfort, appropriate exercise, and a well-regulated sleep-duty regime might enable them to endure spaceflight in the order of months. Be that as it may, it seems to me a necessary medical requirement to base a flight plan to Mars or Venus on a *high-energy trajectory* to shorten the duration of the minimum energy trajectory by 70% to 80%, which will be achieved by novel methods of propulsion, (nuclear, ion propulsion).¹¹ (See paper of K. Ehricke.)

In addition to the internal cabin environmental complex, the external space environment also must be taken into account. A shorter flight time reduces the possibility of meteoritic incidents and of radiation hazards after solar flares.

In brief, a *minimum in time* and an *optimum in comfort* is the medical prescription to achieve a maximum of success of any manned planetary mission. The opinions of the astronauts with week-long experience in orbital flights and the space medical

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practitioners who have controlled these flights will have a decisive influence in this respect.

In connection with long-range manned spaceflight, suggestions were made some 10 years ago to transform astronauts into *cyborgs*; i.e., to provide them with artificial organs. These suggestions attracted great interest, and they might be revived in these days of the utilization of artificial organs and organ transplantation. This revolutionary, fantastic progress in surgery is certainly of great benefit for man on his own planet, but, for spaceflight of any kind, it would add an additional complication to the already complicated life-support system.

But, preflight *prophylactic surgical measures* must be considered, such as removal of obsolete and semi-obsolete organs which can become the source of illness. For instance, an appendectomy and even a cholecystectomy (gall bladder removal) would certainly be advisable; the latter, of course, only if there is some doubt that the astronaut is completely free of positive and negative gall bladder stones; such a case would require surgery sooner or later, anyhow.

After these general planetary medical remarks, I would like to elaborate in more detail on the medical problems involved in a manned landing mission to Mars, the only known visitable planet. A medical evaluation of the Martian environment can, in addition to the modern ground-based astronomy,^{12, 13, 14} now refer to the exploratory experiments and close-up photos of Mariner IV.

MARS ENVIRONMENTAL MEDICINE

Mars medicine includes selection and medical preparation of the astronauts or areonauts, the medical problems en route to Mars, life support and protection in the Martian environment and safe return to Earth. Some of these points have been discussed elsewhere;¹⁵ the following paragraphs are confined to a medical evaluation of the various environmental spheres of Mars.

NEAR-MARS SPACE

As soon as a spaceship comes closer than one-half million km to the Red Planet, it enters its inner or orbital gravisphere and can

go into a parking orbit for observational tasks and the preparation of the landing maneuver.¹⁶

Fortunately, according to Mariner IV recordings, there are no radiation hazards from a Van Allen-type radiation belt in near-Mars space due to the absence of an effective *magnetosphere*.¹⁷ There are, therefore, no regions "off limits" for parking orbits in contrast to the situation in near-Earth space. Table II shows the orbital periods and velocities at selected altitudes up to 20,000 km, including the mean orbital elements of the two Martian moons, Phobos and Deimos.

The question arises: At what altitude lies the atmosphere related *lower limit* for a useful lifetime of an orbiting vehicle? On Earth, this level is found around 200 km. As the radio occultation experiment in Mariner IV indicates, the surface air pressure on Mars might be as low as 10 to 7 mb. But, because of the lower

Table II. Orbital Characteristics of Vehicles Moving in Circummartian Space (O. Ritter and H. Strughold)

Altitude (km)	Orbital Period		Orbital Velocity (km/sec)
	(hr)	(min)	
0	1	40	3.56
100	1	45	3.51
200	1	49	3.46
300	1	54	3.41
400	1	58	3.36
500	2	01	3.32
600	2	08	3.28
800	2	17	3.20
1,000	2	27	3.13
1,500	2	53	2.96
2,000	3	20	2.82
3,000	4	19	2.59
4,000	5	22	2.41
5,980*	7	39	2.14
8,000	10	15	1.94
10,000	13	03	1.79
15,000	21	01	1.53
17,060†	24	37	1.45
20,000‡	30	18	1.35

*Phobos.

†Syncom Sat.

‡Deimos.

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Martian gravity, the border of the sensible atmosphere might extend just as far as on Earth. A parking orbit at 200 km would certainly provide a revealing perspective for visual observation and for Mars photography. The orbital velocity at this altitude is 3.46 km/sec. From this height the resolving power of the unaided human eye is about 60 m (minimum separable). This would enable the observer to get a detailed view of the darker linear markings ("canali") and to clarify the question as to whether the bluish-green coloration of the dark areas and oases is real or just a visual contrast phenomenon from the reddish surroundings. So far, all indications are that the green color of the larger areas, at least, is *not* an *optical illusion*. And about those earth-based telescopic astronomic observers to whom these areas always look gray, the orbiting areonauts might wonder if *they* ever had their *color vision* examined. From their orbital altitude, they would not be able to determine whether the green coloration is due to vegetation, to chemical reactions of the soil, to variations in humidity, or to fluctuations in radiation. To find the answer requires landing and exploration of the surface *in situ*.

GRAVITATIONAL MILIEU ON MARS

With the beginning of deceleration during the landing maneuver, whatever method is used in the thin Martian atmosphere, *gravity* again enters the life of the areonauts who, after their interplanetary weightless journey of about 2 months, will be completely deconditioned from gravity. If, during this time, an adequate exercise regime and pharmacological therapy had been applied to prevent such symptoms as cardiovascular and muscular hypotonia (hypotension) and bone decalcification, there should be no problem to become conditioned to four-tenths of 1 g, the Martian surface gravity. Certainly this should be easier than the reconditioning after return to Earth from Mars.

In manned orbital flights the astronauts showed a slightly lowered blood pressure.^{18, 19, 20} The interpretation has been that the parasympathetic subdivision of the autonomic nervous system has become somewhat dominant over the sympathetic part during weightlessness. We might expect to some degree also a parasympathictonia (vagotonia) in the gravitational milieu on Mars. Furthermore, the hydrostatic blood pressure pattern might show a smaller difference between the lower and upper part of the

human body when in the upright position on Mars than on Earth.²¹ All of this should be of no consequence for the health of the areonauts.

A man of 75-kg weight, or 75-kilopond, on Earth has a weight of 28.5 kilopond under Mars' gravitational condition of 0.38 g. This should provide sufficient stimulation for the otoliths and the peripheral mechanoreceptors in the skin and muscles for their sensomotoric control of balance and walking on Mars' surface; both should be easier than on the Moon.²²

Because of the lower Martian gravity, the use of a single man propulsion unit would be much more efficient than such use on Earth. All in all, biogravics on Mars should pose no particular problem for terrestrial visitors who, within a few days after arrival, might show a "relatively stable adaptation" to Mars' gravity. But if long-term spaceflights require artificial gravity, the logical level en route to Mars would be four-tenths of 1 g. In this case, aeronauts would feel immediately at home on Mars—gravitationally.

THE ATMOSPHERIC ENVIRONMENT

This is radically different concerning the atmosphere. In this respect, Mars Environmental Medicine has to deal with the following situation: The chemical composition of the Martian atmosphere includes carbon dioxide, nitrogen and argon, but only traces of oxygen, if any. If suddenly exposed to this kind of gaseous sphere terrestrials would experience complete anoxia. Furthermore, if the surface air pressure is in the range of 10 mb, as indicated by Mariner IV,²³ this would be barometrically equivalent to an altitude of about 30 km on Earth and, consequently, would cause boiling of body fluids, or ebullism, which in our atmosphere occurs at 20 km (Armstrong Line). The "time of useful consciousness," or "time reserve," of a man suddenly and completely exposed to the Martian air would be not longer than 15 sec, and the revival time may last 3½ min. In brief, the atmospheric environment on Mars has nothing to offer to terrestrial visitors. They must stay in the closed ecological system of their spaceship which serves them as a Martian Station or Laboratory.

Under Mars' gravitational conditions, the daily metabolic rate of the human body might be in the order of 2400 kcal. This

caloricity requires roughly 500 liters of oxygen per man per Mars' day, which is only 37 min longer than the terrestrial day. This oxygen amount has to be provided in a two-gas atmosphere with nitrogen or helium as the diluent.^{24, 25, 26}

The barometric pressure within the Station could vary from 1000 mb to 500 mb. If the latter is chosen, the oxygen volume content should be 40%, which would provide an oxygen partial pressure of 200 mb to which the areonauts, as oxybiotic creatures, have been accustomed on Earth. Nevertheless, variations in the oxygen partial pressure of plus/minus 50 mb are within the medically permissible limits. The carbon dioxide, one of the end products of the body's oxidation processes, should not exceed 10 mb. Carbon dioxide and water are the base materials for the biologic, i.e., photosynthetic regeneration of oxygen of the station's air. Whether or not the carbon dioxide and nitrogen of the surrounding thin Martian air can be made available for this process is a bio-engineering problem. (Nitrogen, by the way, is required by plants for the buildup of protein.) The intensity of sunlight on Mars during most of the day is within the effective range required for photosynthesis. (For more details concerning life-support, see the chapter "Life Support (Survival) in Space," by A. G. Swan.) I would like to mention only that the pressure suit used in extra-stational excursions should have an oxygen pressure of around 240 mb = 180 mm Hg.

PROTECTION FUNCTION OF THE STATION

The Mars station must also protect the occupants from outside hostile factors such as meteoroids, particle radiation, and the low night temperatures.

The question of meteoritic hazards arises from the low density of the Martian atmosphere which is in the order of 10^{17} molecules per 1 cm^3 near the surface, as compared with 10^{19} molecules per 1 cm^3 in the terrestrial atmosphere. It attracts additional interest because of the neighborhood of the belt of the asteroids. If some 300 million years ago a planet X between Mars and Jupiter disintegrated into many thousands of asteroids, it is reasonable to assume that this catastrophic event or a collision of two smaller planets led also to a population explosion of smaller pieces of matter: macrometeoroids and micrometeoroids. Those iron and

stony-iron meteorites occasionally hitting the Earth's surface are probably of asteroidal origin. But Mars is much closer to the asteroid belt and should attract considerably more of these "bullets from space." Two characteristics might moderate the puncture potential of the macrometeoroids for the Martian station: (1) their velocity is in the same range as the orbital velocity of Mars and, therefore, lower than at the Earth's orbital region; and (2) they might orbit essentially in the same direction as Mars so that hits on Mars should be mostly rear-end collisions, which are not so vicious as head-on collisions. Nevertheless, the wall of the station, as that of the spaceship must include a *meteor bumper* structure (F. Whipple.)²⁷ Micrometeorites might to some extent be absorbed by the Martian atmosphere.

Meteoroids of cometary origin consisting of ice and dust (F. Whipple), too, should pose no hazards when we consider that, even in open circumterrestrial space, so far no meteoritic interference—even during extravehicular activities—has been observed. But we need more astronomical information about the impact rate on the Martian frontside and rearside and, furthermore, about Mars' *penetration dates of meteor streams*.

On Earth we are protected from the *primary energetic particle rays* by the trapping and deflecting effect of the magnetosphere; and those which reach the atmosphere are transformed in collisions with air molecules into less powerful secondary and tertiary rays to which we are daily exposed without ill effects. On Mars, without such a magnetospheric umbrella, all the particle rays in their primary form can reach the atmosphere which in itself, due to its low density, offers a less effective shield than the Earth's atmosphere. It will be essentially a function of the wall of the Mars station to absorb the primary particle rays effectively or, at least, to keep the radiation dose at a level of less than 1 millirad per hour. The pressure suits worn outside the station must offer sufficient protection for a few hours' excursion; but if Mars should be hit by a proton outburst after a solar flare, extrastationary activities are prohibited.

All in all, the life-support system inside a Martian station and the shielding power of the wall from outside hazardous factors have to be more or less equivalent to the respective functions of the Earth's atmosphere. A Mars' station, therefore, is actually an Earth station on Mars—a Terra-island, on the Red Planet.

LOCATION OF MARS STATION

Where should this station be located? Environmental and exploratory considerations suggest the dark areas in the lower latitude regions in which springtime has just begun. This offers for the spring and summer season, lasting more than 300 days, a relatively mild climate during the daytime. Solar illuminance at noon at ground level may attain an intensity of 40,000 lux (lumen per m²), adequate for the photosynthetic regeneration system. The dark-light cycle is practically the same as on Earth and poses, therefore, no problems for the circadian sleep and activity cycle or for the physiological clock of the areonauts. Thermal solar irradiance may reach up to 0.6 cal/cm²/min, which facilitates especially extrastational excursions. From the viewpoint of thermoeology of the landing place, it might not be too far-fetched to look on the Martian surface for *warm spots* of the kind on Earth: for instance, on Mt. Wrangell, Alaska, where the Aerospace Medical Division, Brooks AFB, Texas, in 1964 constructed a laboratory on a perennially warm, snow-free, volcanic sand area surrounded by snow and glaciers, 4211 m high.²⁸ This installation does not require any heating at any time. It utilizes thermal output of an inactive volcano. Knowledge in advance of similar permawarm spots on Mars might be obtained by scanning its surface by means of infrared (or far infrared) sensors carried on Martian orbiters.

So far, I have not mentioned the material resources for the Mars station possibly obtainable from the lithospheric surface. Data in this respect are offered in the chapter of E. Steinhoff. I would like to mention only a hypothesis concerning the possible existence of a water source in the form of an ice layer some 100 m below the lithospheric surface, as suggested by A. Baumann Zurich,²⁹ 1910, and supported by H. E. Suess,³⁰ and V. D. Davydov,³¹ Moscow. It is logical to assume that this *hydrocryosphere*, a remnant of the ancient Martian ocean, may be located below the dark areas and oases; below this ice table, some 500 m below the ground, there might even be a water table due to an increase of temperature in the interior of Mars. This, again, would point to these areas as the most promising location for the landing place and the establishment of the Martian station.

Finally, if there is a *biosphere* on Mars,^{32, 33, 34, 35, 36} the dark areas with their seasonal color variations are the regions to be

explored. After all, the search for life outside the Earth is a supreme goal of any manned planetary expedition. (See the chapters of A. A. Imshenetski and H. P. Klein.) For medicine, it poses the problem of prevention of contamination of the areonauts with possibly pathogenic Martian microbes.

EXPLORATORY TASKS

There is no question that a manned Mars expedition is the best way to explore the red, or green and red, planet as a possible abode of life. A precondition in this respect is that contamination with terrestrial microorganisms has not occurred by insufficiently sterilized unmanned probes prior to the manned expedition. An overall synopsis of the pro and contra arguments speaks for the possibility or even probability of *life on Mars*, particularly within its microenvironments found in craters, fissures, and the pores of the soil. Only areonauts during extrastational excursions can take a critical, deep look upon rock formations in craters and fissures, which might give us a hint about the paleontological evolution of the Martian biosphere. They are in the best position to solve some problems concerning the areographic features such as the dark linear markings ("canali") and oases. The latter are, in all probability, impacts of giant meteorites of asteroidal origin, and the linear markings might be "tension cracks" resulting from planetary expansion due to a decrease of the gravitational "constant" (see the chapter of P. Jordan) and triggered by these impacts.

If there is a subsurface ice layer, then humidity might be higher in and around the oases and along the fissures, thus making these locations ecologically more favorable for the growth of plant life. Actually, it might be the soil's humidity and the resulting vegetation that have made these areographic features visible to earth-based optical astronomy in the first place. Furthermore, if there should be a water table below the subsurface ice layer, then there could be, in addition to the surface biosphere, based possibly on some kind of photosynthesis, a subsurface marine habitat for microbial life based perhaps on chemosynthesis.³⁷

All this is hypothetical, but we cannot ignore any one of these possibilities. Everything is in flux. Recently, radar studies suggested that the dark areas are the highlands and the bright areas the lowlands, but more recently radar studies and other considerations³⁸ indicated just the opposite again.

A manned expedition to Mars will be the most dependable method of extending the spectrum of our knowledge about its paleological evolution and biotic realities beyond that range that has been gained so far and will be explored in the future by earth-based astronomy and instrumented planetary probes.

To perform all these scientific tasks, the Martian explorer must be kept in the state of best health, well-being, and on the highest physical and mental level. To secure this is the responsibility of Mars medicine. And, last but not least, it is medicine's responsibility to control the safe return of the Mars-adapted terrestrials on their way back to their bluish-green home planet, and to prevent backcontamination of the latter with possible Martian microbes. (A summary of environmental biomedical data of Mars is offered in Table III.)

Table III. Martian Medical Data Table

Atmospheric Pressure	10 mb
Chemical Composition	CO ₂ , N ₂ , A
Oxygen Condition:	
Human Physiological	Anoxia at ground level
Ebullism	At ground level
Mean Total Solar Irradiance:	
Martian Solar Constant	0.64 cal cm ⁻² min ⁻¹
Mean Solar Illuminance:	
Extra atmospheric	60,000 lux
Albedo	0.15
Surface Temperature:	
Noon—Maximal	+25° C
Midnight—Minimal	-70° C
Day-Night Cycle	24 hr 37 min
Extension of Umbra	1.18 million km
Gravity	0.38 g
Gravisphere (radius)	½ million km
Orbital Velocity at 200 km	3.46 km/sec
Velocity of Escape	5 km/sec
Orbital Velocity of Mars	24.1 km/sec
Sidereal Revolution Period:	
Mars Year	669 Martian Days = 687 Terrestrial Days

In conclusion, a manned landing mission on Mars, from a medical point of view, is in the realm of possibility if the interplanetary flight is based on a fast transfer trajectory. Of course, the experiences which will be gained in a Lunar Laboratory³⁹ will be of great benefit for the manned Mars project. These two ventures can be considered the highlights during the last quarter of this century. As to what we might expect in the next century, see the Chapter by A. C. Clarke.

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XXIV

Next - The Planets!

Arthur C. Clarke*

It has been said that history never repeats itself, but that historical situations recur. To anyone who, like myself, has been involved in astronautical activities for over 30 years, there must be a feeling of familiarity, of "I have been here before," in some of the present arguments about the exploration of space.

Like all revolutionary new ideas, the subject has had to pass through three stages, which may be summed up by these reactions: (1) "It's crazy—don't waste my time." (2) "It's possible, but it's not worth doing." (3) "I always said it was good idea!"

As far as orbital flights, and even journeys to the Moon, are concerned, we have made good progress through all these stages, though it will be a few years yet before everyone is in category (3). But, where flights to the planets are involved, we are still almost where we were 30 years ago. True, there is much less complete scepticism—to that extent, history has *not* repeated itself—but there remains despite all the events of the past decade a widespread misunderstanding of the possible scale, importance, and ultimate implications of travel to the planets. There is a big job of education to be done—not only the general public but also the scientific community urgently requires enlightenment.

Let us start with some fundamentals which are not as well known as they should be. Please forget all about today's astronautical technologies; imagine you've never even heard of rockets. Just consider the problem of lifting a man away from the Earth,

*Colombo, Ceylon.

purely in terms of the work done to move his mass through the gravitational field.

For the average man,* the energy requirement is about 1000 kilowatt-hours, which customers with a favorable tariff can purchase for \$10 from their electric utility company. What might be called the basic cost of a one-way ticket to space is thus the modest sum of \$10.

For the terrestrial planets and all satellites—Mercury, Venus, Mars, Pluto, Moon, Titan, Ganymede, etc.—the exit fee is even less: you need only 50 cents worth of energy to escape from the Moon. Giant planets like Jupiter, Saturn, Uranus, and Neptune are naturally much more expensive propositions. If you are ever stranded on Jupiter, you'll have to buy almost \$300 of energy to get home. Make sure you have enough Traveller's Checks!

Of course, the planetary fields are only part of the story; work also has to be done travelling from orbit to orbit, and thus moving up or down the enormous gravitational field of the Sun. But, by great good luck, the Solar System appears to have been designed for the convenience of space-travellers: the planets lie far out on the gentle slope of the solar field where it merges into the endless plain of interstellar space. In this respect, the conventional map of the Solar System, showing the planets clustering round the Sun, is wholly misleading.

If we employ the value of gravity at the Earth's surface as our unit of measurement, then the work necessary to lift an object from the Sun all the way to Pluto—or for that matter to Alpha Centauri—is the same as that involved in a 12,000,000-mile climb. From the gravitational point of view, the Sun is therefore at the bottom of a pit or crater 12,000,000 miles deep. Almost vertical at first, the walls of this imaginary crater soon start to flatten outwards; it is shaped, in fact, very much like a whirlpool, and this provides quite a good dynamic analogy of the Solar System, which I have developed at some length elsewhere.¹

The point I wish to emphasize is that whereas the full depth of the solar whirlpool is 12,000,000 miles, all the planets are spread

*Taken as 180 lb, which is probably high for the global average.

out across the upper 1% of its slope; even Mercury is only 10,000 miles below the rim. We can say, therefore, that the planets are 99% free of the Sun's gravitational field, so that the energy required for orbital transfers is quite small; usually it is considerably less than that needed to escape from the planets themselves. Reverting to dollars and cents, the energy-cost of transferring a man from the surface of the Earth to that of Mars is less than \$20. Even for the worst possible case (surface of Jupiter to surface of Saturn), the pure energy figure cost is less than \$1,000!

Since we are still disporting ourselves in the realm of pure theory, we can go even further. A gravitational field is conservative, in the best sense of that misused word. If you do work against it on the way out, it puts it all back on the way home; the net energy expended on the round trip—and hence the basic cost—can therefore be precisely zero! Of course, if you are foolish enough to squander all your hard-earned kinetic energy by air-resistance braking, it's gone for good and you have to start all over again. How nice it would be if we had some kind of *energy accumulator*, so that our spaceships could operate on the same principle as an electric railway or automobile in mountainous country, where the motors act as generators on the way downhill and pump energy back into the system. . . . Don't bother me about the practical details; I've no intention of putting any rocket engineers out of work by inventing gravitational propulsion. But one day, I suspect, something like this is going to arrive.

You may well consider that the above energy arguments, purporting to prove that space travel should be about 10^9 times cheaper than it is, have no relevance to the practical case. Another fact that necessarily makes these bargain-basement prices unrealistic is that serious, *manned*, space travel cannot utilize long-duration, minimum-energy Hohmann orbits, which even for the nearer planets involve round-trip times that are measured in years. As Maxwell Hunter has pointed out in his stimulating book *Thrust Into Space*²—and Krafft Ehricke also emphasises at this conference—really practical space flight will demand high-speed, hyperbolic trajectories to give reasonable transit times. These imply velocities ten or more times as great as those attainable today, so that energy costs may be increased a hundredfold. This does not worry me in the least; by the time we can consider

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such exploits, our energy sources will also be correspondingly cheaper.

It may also be objected that, even today, the cost of the fuel is trivial compared with the cost of the hardware. Most of the mountainous Saturn V you see standing on the pad can be bought for, quite literally, a few cents a pound. The expensive items are the precision-shaped pieces of high-grade metals, and all the little black boxes that are sold by the carat.

Although this is true, it is also to a large extent a consequence of our present immature, no-margin-for-error technology. Just ask yourself how expensive driving would be if a momentary engine failure was to write off your car—and yourself—and the fuel supply was so nicely calculated that you couldn't complete a mission if the parking meter you'd aimed at happened to be already occupied. This is roughly the situation for planetary travel today; it will not always be so.

Meanwhile, let us come back to the harsh realities of the Twentieth Century and get some of these ideas in perspective. The best—perhaps the only—way of doing this is to look at the record of the past and to see what lessons we can draw from the early history of aeronautics.

Soon after the failure of Langley's "Aerodrome" in 1903, the great astronomer Simon Newcomb wrote a famous essay worth rereading which prove that heavier-than-air flight was impossible by means of known technology. The ink was hardly dry on the paper when a pair of bicycle mechanics irreverently threw grave doubt on the Professor's conclusions. When informed of the embarrassing fact that the Wright brothers had flown, Newcomb gamely replied: "Well, maybe a flying machine *can* be built. But it *certainly* couldn't carry a passenger as well as a pilot."

Now, I am not trying to poke fun at one of the greatest figures in celestial mechanics. When you look at the Wright biplane, hanging up there in the Smithsonian, Newcomb's attitude seems very reasonable indeed, and I wonder how many of us would have been prepared to dispute it in 1903.

Yet, and this is the really extraordinary point, there is a smooth line of development, *without any major technological*

breakthroughs, from the Wright "Flyer" to the last of the great piston-engined aircraft such as the DC 6. All the many orders of magnitude improvement in performance came as a result of engineering advances which in retrospect seem completely straightforward, and sometimes even trivial. Let me list the more important ones: Variable-pitch airscrews; slots and flaps; retractable undercarriage; concrete runways; streamlining.

Not very spectacular, are they? Yet these things, together with steady improvements in materials and design, lifted much of the commerce of mankind into the air. For they had a synergistic effect on performance; their cumulative effect was much greater than could have been predicted by considering them individually. They did not merely add; they multiplied.

All this took just about 40 years; and there was the second technological breakthrough—the advent of the jet engine—and a new cycle of development started.

Unless the record of the past is wholly misleading, we are going to see much the same sequence of events in space. As far as can be judged at the moment, the equivalent items on the table of aerospace progress may be: refuelling in orbit; airbreathing boosters; reusable boosters; refuelling on (or from) the Moon; lightweight materials (e.g., composites), see Table I.

Probably the exploitation of these relatively conventional ideas will take somewhat less than the 40 years needed in the case of aircraft; their full impact should be felt by the turn of the century. Well before then, moreover, the next breakthrough or quantum-jump in space technology should also have occurred, with the development of new propulsion systems—presumably fission powered but, hopefully, using fusion as well.

And with these, the Solar System will become an extension of the Earth—if we wish it to be so.

It is at this point, however, that all analogy with the past breaks down; we can no longer draw meaningful parallels between aeronautics and astronautics. As soon as aircraft were shown to be practical, there were obvious and immensely important uses for them: military, commercial, scientific. They could be used

Table 1

Date	Aeronautics	First Breakthrough	Astronautics	Date
1903	Streamlining	↓	Reusable boosters	1957
	Retractable u/c		Airbreathers	
	V/p propellers		Orbital techniques	
	Slots and flaps		Refuelling on/from Moon	
	Concrete runways		Lightweight materials	
		Second Breakthrough		
1945	Jet propulsion	↓	Nuclear propulsion	1975
			Electric propulsion	
			Gaseous fission?	
			Fusion?	
		Third Breakthrough		
	None required	↓	Beamed momentum transfer?	
			Cosmic energy sources?	
			"Space drive"?	

to provide swifter connections between already highly developed communities: a state of affairs which almost certainly does not exist in the Solar System, and may not do so for centuries to come.

It seems, therefore, that we may be involved in a peculiarly vicious circle. Planetary exploration will not be really practical until we have developed a mature spaceship technology—but we won't have good spaceships until we have worthwhile places to send them. (Places, above all, with those adequate refuelling and servicing facilities now sadly lacking elsewhere in the Solar System.)

How can we escape from this dilemma? Fortunately, there is one encouraging factor. Almost the whole of the technology needed for long-range space travel will, inevitably and automatically, be developed during the exploitation of *near* space. Even if we set our sights no higher than a thousand miles above the Earth, we would find that by the time we had perfected the high-thrust, high-performance surface-to-surface transports, the low-acceleration interorbital shuttles, the reliable, closed-cycle spacestation ecologies, we would have proved out at least 90% of the technology needed for the exploration of the Solar System. And the most expensive 90%, at that. . . .

Perhaps I had better spend a few moments here to deal with those strange characters who think that space is the exclusive province of automatic, robot probes, and that we should stay at home and watch TV, as God intended us to. This whole man-machine controversy will seem in another couple of decades to be a quite baffling mental aberration of the Early Space Age.

I won't waste any time arguing with this viewpoint, as I hold these truths to be self-evident: (1) unmanned spacecraft should be used whenever they can do a job more efficiently, cheaply, and safely than manned vehicles; or (2) until we have automata superior to human beings (by which time all bets will be off), all really sophisticated space operations will demand human participation. I refer to such activities as assembling and servicing the giant applications satellites of the next decade; running orbital observatories, laboratories, hospitals, factories—projects for which there will be such obvious and overwhelming commercial and scientific benefits that no one will dispute them.

It is true that a great deal can be done by *telepuppets* or radio-controlled slaves, but these cannot be used over astronomical distances because of the time delay. Even for an object as near as the Moon, the 2½ second lag is almost intolerable. For planetary exploration, we will only be able to use such devices under the control of *manned* ships in close orbit; and they will doubtless be invaluable during our first assaults on Venus and Jupiter.

Even closer at hand, I would like to ask any doctors, engineers, research scientists, astronomers (practical, not theoretical, ones!) just how efficiently they could do their jobs *via* TV camera and

remote manipulator. (Routine procedures may be, but experimental and development work on the frontiers of science and technology, certainly not.) One might as well attempt to run Cape Kennedy by remote control from Washington, without any human beings on the spot. Oh, it *could* be done; but everything would take ten times as long and cost fifty times as much. This may seem a ludicrously far-fetched analogy, but it isn't. The Cape Kennedys for the Solar System will be above the atmosphere, and they will *have* to be manned.

And here is a thought-provoking paradox I would like to present. For the efficient exploration of the planets, even by automatic robot probes, *manned* orbital facilities will be essential. Today's robot spacecraft already start their flights from parking orbits; but that is where they should be assembled and tested in the first place! Instead of spending hundreds of millions of dollars to duplicate conditions in space—which can never be done perfectly in any event—we should do the whole job in orbit.

The advantages (and, admittedly, the problems) are obvious; but some of the greatest advantages are perhaps not so immediately apparent. The reliability of a planetary probe which has been fully checked out in space by an orbital lab will be far higher than one which has been folded into a high-acceleration launcher and shot through the atmosphere. Perhaps most important of all, large zero-gravity structures—especially the huge and flimsy antennae essential for transmitting information at high bit-rates back from the far reaches of the Solar System—can be built *in situ*. This may well be a decisive factor.

Now, all this is not a digression from the subject of my talk; what we first learn about the planets by other means will determine the priorities, and often the procedures, of manned exploration. Here again, the facilities that are going to be set up in near space will be vital—none more so than the orbital observatories which within the next generation are going to revolutionize almost every field of astronomy.

In particular, the impact on Solar System studies of medium-sized telescopes outside the atmosphere—a mere couple of hundred miles above the Earth!—will be overwhelming. Until the advent of radar and space probes, everything we knew about the planets

had been painfully gathered over a period of about a century and a half by astronomers with inadequate instruments hastily sketching details on a tiny, trembling disc glimpsed during moments of good seeing. Such moments, when the atmosphere is stable and the image undistorted, may add up to only a few hours in an entire lifetime of observing.

In these circumstances, it would be amazing if we had acquired any *reliable* knowledge about planetary conditions; it is safest to assume that we have not. We are still in the same position as the medieval cartographers with their large areas of "Terra Incognita" and their "Here Be Dragons," except that we may have gone too far in the other direction—"Here Be *No* Dragons." Our ignorance is so great that we have no right to make either assumption.

As proof of this, let me remind you of some horrid shocks the astronomers have received recently when things of which they were quite sure turned out to be simply not true. The most embarrassing example is the rotation of Mercury; until a couple of years ago, everyone was perfectly certain that it always kept the same face towards the Sun. In Volume III of the monumental series *Planets and Satellites* (edited by Dr. Kuiper), A. Dollfus sums up his extended observations of Mercury with these words: "The period of rotation of Mercury is thus found to be equal to the period of revolution, *with a precision of better than one in ten thousand.*" [My italics]³

Oh dear! For now, of course, the radar measurements indicate a period of only 59 days, not 88; and with the best will in the world, I don't call *that* a precision of one in ten thousand.

An astronomer friend, Carl Sagan, has tried to explain to me how, by a curious set of coincidences, the visual observations could support *both* values. I was too stupid to understand the argument, but could eye and radar both be right? Could Mercury have an 88-day surface period and a 59-day ionospheric one? I don't for a moment believe it, but it does look as if Nature has somehow played a dirty trick on several generations of patient astronomers.

Einstein once said: "The good Lord is subtle, but He is not malicious." The case of Mercury casts some doubt on this dictum.

And what about Venus? You can find, in the various reference books, rotation periods for Venus ranging all the way from 24 hours up to the full value of the year, 225 days. But, as far as I know, not one astronomer ever suggested that Venus would present the extraordinary case of a planet with a day longer than its year! And, of course, it *would be* the one example we had no way of checking, until the advent of radar. Is this subtlety—or malice?

And look at the Moon. Five years ago, everyone was certain that its surface was either soft dust or hard lava. If the two schools of thought had been on speaking terms, they would at least have agreed that there were no alternatives. But then Luna 9 and Surveyor 1 landed, and what did we find? Good honest dirt. . . !

These are by no means the only examples of recent shocks and surprises. There's the unexpectedly high temperature beneath the clouds of Venus; the craters of Mars; the radio emissions from Jupiter; the complex organic (not necessarily biotic) content of certain meteors; the clear signs of extensive activity on the surface of the Moon. And now Mars seems to be turning inside out. The ancient, dried-up seabeds may be as much a myth as Dejah Thoris, Princess of Helium, for it looks as if the dark *Maria* are actually highlands, not lowlands as we had always thought.

The negative point I am making is that we really know nothing about the planets. The positive one is that a tremendous amount of reconnaissance—the essential prelude to *manned* exploration—can be carried out from Earth orbit. It is probably no exaggeration to say that a good orbiting telescope could give us a view of Mars at least as clear as did Mariner IV. And it would be a view infinitely more valuable—a continuous coverage of the whole visible face, not a single snapshot of a few percent. I suspect that when we can build large optical systems no longer limited by those two bugbears, atmospheric distortion and gravity, such improvements in resolution will be possible that much of the work we have planned for Orbiters, and even Landers, can be performed visually without leaving home. Which means, of course, that we can save our unmanned spacecraft for the tasks that only they can carry out.

Among these tasks is one which, though of great scientific value, is of even more profound psychological importance. I refer to the production of low-altitude oblique photographs.

It is no disparagement of the wonderful Ranger, Luna, and Surveyor coverage to remind you that what suddenly made the Moon a real place, and not an astronomical body up there in the sky, was the famous photograph of Copernicus from Luna Orbiter 2. When the newspapers called it the picture of the century, they were expressing a universally-felt truth. This was the photograph which first proved to our emotions what our minds already knew, but had never really believed—that Earth is not the only world. The first high-definition, oblique photos of Mars, Mercury, and the satellites of the giant planets, will have a similar impact, bringing our mental images of these places into sharp focus for the first time.

The old astronomical writers had a phrase that has gone out of fashion, but which may well be revived: The plurality of worlds. Yet, of course, every world is itself a plurality. To realize this, one has only to ask oneself: How long will it be before we have learned everything that can be known about the planet Earth? It will be quite a few centuries yet before terrestrial geology, oceanography, and geophysics are closed, "surprise-free" subjects.

Consider the multitude of environments that exists here on Earth—from the summit of Everest to the depths of the Marianas Trench—from high noon in Death Valley to midnight at the South Pole. We may have equal variety on the other planets, with all that this implies for the existence of life. It is amazing how often this elementary fact is overlooked, and how often a single observation or even a single extrapolation from a preliminary observation based on a provisional *theory* has been promptly applied to a whole world.

It is possible, of course, that the Earth has a greater variety of more complex environments than any other planet. Like a jet-age tourist "doing Europe" in a week, we may be able to wrap up Mars or Venus with a relatively small number of "Landers." But I doubt it, if only for the reason that the whole history of astronomy teaches us to be cautious of any theory purporting to show that there is something special about the Earth. In their various ways, the other planets may have orders of complexity as great as ours. Even the Moon—which looked like a promising candidate for geophysical simplicity less than a decade ago—has already begun to unleash an avalanche of surprises.

The late Professor J. B. S. Haldane once remarked—and this should be called Haldane's Law: "The universe is not only stranger than we imagine, it is stranger than we *can* imagine." We will encounter the operation of this law more and more frequently as we move away from home. And as we prepare for this move, it is high time that we face up to one of the more shattering realities of the astronomical situation. For all practical purposes, we are still as geocentrically-minded as if Copernicus had never been born; to all of us, the Earth is the center, if not of the Universe, at least of the Solar System.

Well, I have news for you. There is really only one planet that matters; and that planet is not Earth, but Jupiter. My esteemed colleague Isaac Asimov summed it up very well when he remarked: "The Solar System consists of Jupiter plus debris." Even spectacular Saturn doesn't count; he has less than a third of Jupiter's enormous mass—and Earth is a hundred times smaller than Saturn! Our planet is an unconsidered trifle, left over after the main building operations were completed.

This is quite a blow to our pride, but there may be much worse to come, and it is well to get ready for it. Jupiter may also be the *biological*, as well as the *physical*, center of gravity of the Solar System.

This, of course, represents a complete reversal of views in a couple of decades. Not long ago, it was customary to laugh at the *naive* ideas of the early astronomers—Sir John Herschel, for example—who took it for granted that all the planets were teeming with life. This attitude is certainly over-optimistic; but it no longer seems as simple minded as the opinion, to be found in the popular writings of the 1930's, that ours might be the only Solar System and, hence, the only abode of life in the entire Galaxy.

The pendulum has indeed swung, perhaps for the last time, for in another few decades we should know the truth. The discovery that Jupiter is quite warm, and has precisely the type of atmosphere in which life is believed to have arisen on Earth, may be the prelude to the most significant biological findings of this century. Carl Sagan and Jack Leonard put it well in their book, *Planets*:⁴ "Recent work on the origin of life and the environment of Jupiter suggests that it may be more favorable to life than any other planet, *not excepting the earth.*" [My italics]

One of my friends at NASA (Dr. James Edson) once remarked to me: "Jupiter is a problem for my grandchildren." I suspect he may have been wildly optimistic. The zoology of a world outweighing 300 Earths could be the full-time occupation of mankind for the next thousand years.

On the other hand, it is also possible that we shall discover no trace of extraterrestrial life, past or present. This will be a great disappointment, but even such a negative finding would give us a much sounder understanding of the conditions in which living creatures are likely to evolve, and this in turn would clarify our views on the distribution of life in the Universe as a whole. However, it seems much more probable that long before we can certify the Solar System as sterile, the communications engineers will have settled this ancient question—in the affirmative.

For *this* is what the exploration of space is really all about, and this is why many people are afraid of it, though they may give other reasons, even to themselves. It may be just as well that there are no contemporary higher civilizations in our immediate vicinity; the cultural shock of direct contact might be too great for us to survive. But, by the time we have "cut our teeth" on the Solar System, we should be ready for such encounters. The challenge, in the Toynbian sense of the word, should then bring forth the appropriate response.

Do not for a moment doubt that we will one day head out for the stars—if, of course, the stars do not reach us first. I think I have read most of the arguments proving that interstellar flight is impossible, and you are probably familiar with many of them. They are latter-day echoes of Professor Newcomb's paper on heavier-than-air flight; the logic and the mathematics are impeccable; the premises wholly invalid. The more sophisticated are roughly equivalent to proving that dirigibles cannot break the sound barrier.

In the opening years of this century, the pioneers of astronautics were demonstrating that flight to the Moon and nearer planets was possible, though with great difficulty and expense, by means of chemical propellants. But even then, they were aware of the promise of nuclear energy and hoped that it would be the ultimate solution. They were right.

Today, it can likewise be shown that various conceivable, though currently impracticable, applications of nuclear and medical techniques could bring at least the closer stars within the range of exploration. And I would warn any skeptics who may point out the marginal nature of these techniques that, at this very moment, there are appearing simultaneously on the twin horizons of the infinitely large and the infinitely small, unmistakable signs of a breakthrough into a new order of creation.

Although I am sure that Dr. Teller and Dr. Zwicky will be talking about this, I would like to quote some remarks made recently in my adopted country by a Nobel Laureate in Physics, Professor C. F. Powell: "It seems to me that the evidence from astronomy and particle physics which I have described make it possible that we are on the threshold of great and far-reaching discoveries. I have spoken of processes which, mass for mass, would be at least a thousand times more productive of energy than nuclear energy . . . it seems that there are prodigious sources of energy in the interior regions of some galaxies, and possibly in the 'quasars', far greater than those produced by the carbon cycle occurring in the stars . . . and we may one day learn how to employ them."⁵

And, if Professor Powell's surmise is correct, others may already have learned, on older worlds than ours. So it would be foolish indeed to assert that the stars must be forever beyond our reach.

I am sure that you all know Tsiolkovski's famous and moving metaphor: "The Earth is the cradle of the mind—but you cannot live in the cradle forever." Now, as we enter the second decade of the Age of Space, we can see still further into the future.

The Earth is indeed our cradle, which we are about to leave.

And the Solar System will be—our kindergarten.

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XXV

Importance of the Use of Extraterrestrial Resources to the Economy of Space Flight Beyond Near-Earth Orbit

Dr. Ernst A. Steinhoff*

INTRODUCTION

While during the 1961 to 1966 period, mainly the Working Group on Extraterrestrial Resources devoted its efforts to analyzing the economy of space flight utilizing extraterrestrial resources; during the last 2 years, the American Astronautical Society as well as the Institute of Aeronautics and Astronautics has begun to devote special sessions to problems either associated with the potential use of extraterrestrial resources and/or dealing directly with the subject. In October 1968, the XIX International Congress of Astronautics will hold special sessions in New York City, also dealing with this timely subject.

During the XVIII International Congress of Astronautics, Prof. Fritz Zwicky of Cal Tech presented a very impressive lecture on this subject, and, more recently, Prof. Donald Menzel, Director Emeritus of the Harvard Astronomical Observatory, called the attention of the scientific community to apparently obvious indications of water action having taken place in the remote past on several locations on the Moon. These described phenomena can be clearly seen on recent Lunar Orbiter pictures. In a recent private communication, Prof. Harold C. Urey of the University of California at San Diego also supports this view. These interpretations can have considerable bearing on the work done by the

*Chief Scientist, Air Force Missile Development Center, Holloman Air Force Base, New Mexico.

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Working Group, and could be of far-reaching influence on the future course of space flight. Those who have followed the work of this group will remember the frequently stated fact that support of extraterrestrial space flight and the logistics of manned stations on the Moon or in interstellar space will require that ~90% in weight of all vital logistic supplies will consist of water or its derivations, if oxygen and hydrogen are used as fuels.

Another subject recently discussed more frequently in space flight-related meetings is the quest for utilization of the extraterrestrial environment for commercial and industrial uses in addition to research objectives. Many processes performed on Earth are subject to limitations as a consequence of our particular Earth environment. To achieve particular objectives, man has artificially changed his environment, for instance, to make these commercial objectives more efficient or more economic at a cost. However, our state of technology and the Celestial Body we happen to live on sometimes do not permit us to duplicate environments on Earth with the same economy; we could achieve them more easily in space or on the surface of celestial bodies within reach of our Earth by space flight.

A third observation I would like to make is that space flight at the present cost level will not become attractive to many of the proposed uses, particularly those which entail commercial uses, much beyond the ones recognized as economically feasible. Substantial reduction in space flight cost would attract into the "orbit" of commercial utilization of space flight many other uses, which in themselves would tend to reduce space flight cost due to increased volume of space flight and the factors involving reaction to cost as a function of volume and time.

FUTURE COMMERCIAL USES OF SATELLITES AND SPACE STATIONS

One of the areas Nobel Laureate Prof. Willard F. Libby predicts is "space chemistry" which will be performed in orbiting space stations. He calls "space chemistry" the chemistry of the strange conditions of outer and inner space (inside the stars or the sun)—the chemistry of highly ionizing radiations, of temperatures too high to be produced on Earth commercially, of extremely high pressures to be found inside the cores of planets, and of the chemistry of the ultrahigh vacuum. He suggests, for example, since

oxygen is an extremely inhibiting material, it would be highly desirable that chemical factories for producing superpure metals should work in the higher regions of near-Earth orbits (~22,000 statute miles above the Earth) to produce certain exotic but important chemicals and minerals. The brittleness of many metals is a consequence of oxide films on the grain boundaries of the metal crystals. Avoiding these would permit materials of much higher strength properties and possibly greater resistance to corrosion. As one example, he cites that if beryllium was distilled in orbit, it could be expected to become much more ductile than if it were produced on Earth—somewhat like tin, but with its superior tensile and strength-to-weight properties. This material could then serve as construction material for spacecraft and atomic reactor parts. Prof. Libby currently has two students trying to grow large diamonds directly from carbon vapor, which also requires superpure materials to be successful with the distillation under high-vacuum conditions. The value of such products is so high that space transportation and manufacturing costs still make this approach very attractive.

In a paper which I presented to large audiences in Europe almost 2 years ago, I predicted that manufacturing in space of microelectronic components, so-called "integrated circuits" or "chips" could be performed with much smaller rejection rates and therefore cheaper under ultra-high vacuum conditions available to us in space. Since then, much study of the details of the required techniques has been performed, and these chances look even better than I predicted at that time. Dr. Alfred Mayo, a well-known space physicist, and colleagues have studied the separation of pure ionized elements from metal vapor streams, thus accomplishing just the objective Prof. Libby talked about.

Dr. Mayo has suggested that the experimental production of microelectronic modules in space become one of the tasks of the Apollo SIVB workshop. Such experimental manufacturing in vacuum can be done by remote control, and, according to Mayo, it could be done in 1970. Current processes already use short-link remote control, to which only the Earth-to-orbit link would have to be added. Since the value of the components produced on a per kilogram basis is very high and the amount of materials needed is very small, almost one-to-one yields can be expected. With the expected reduction of the impurity-related imperfections of chips,

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transportation of materials to orbit and of the products from orbit would still provide strong economical incentives. He further suggests that complete electronic components and electronic subsystems of communication and other satellites be manufactured in space on an experimental basis including in-orbit manufacture of circuit boards, multi-integrated circuits, and molecular electronic subsystems, using ion-beam deposition techniques, etc. He believes that these techniques will have reached this state about 1974 or 1975. Besides providing components and subsystems for direct use in space, increasing volume of manufacture for Earth use is predicted. With the greater purity of the materials used, considerable increase in reliability, or, what is equally important, mean time to failure will be extended—an important feature needed in spacecraft operation. Similar to the deflection of electrons in TV picture tubes, ions can be deflected in a controlled manner and can be deposited on substrata in which density and geometry of the deposited materials can be very closely controlled, ion-by-ion if necessary. This makes possible computer-control of very complex manufacturing processes and generation of any pattern for which a program can be designed. This way, any combination of metals which can be separated from an ionized vapor stream can be under control of a computer deposited in any way possible to produce atom-to-atom or molecule-to-molecule combinations of value for complex electronic functions. It is quite obvious that the variety of manufacturing processes of great promise will be difficult to duplicate with equal economy and flexibility on Earth. The stakes are so high that I would not be surprised if we have the first industrial research laboratories in space before the next decade is over.

Another area of considerable industrial interest is an area my colleague Hans Wuenschel of NASA-Marshall has recently proposed. Although our technology, more than two decades ago, produced foamed plastics of a wide variety of properties, technology has not yet equally succeeded in producing foams of equal-perfection high-strength metals such as steel, aluminum, titanium, tungsten, etc. However, space applications and high-speed aircraft design would gain greatly if we could, for example, produce curved-foam sheets of these materials and then deposit on their surfaces thin covers of compact material of the same metal to produce three-dimensional honeycomb. According to Wuenschel, director of manufacturing methods development at Marshall, lack of gravi-

tational force in space and ultrahigh vacuum will permit liquid metals to foam in space and to be formed in any desired way and in any density per liter with a wide range of properties, very similar to plastic foam. Heat reflection to cosmic background will permit quick cooling, as well as quick exposure to near freezing noble gases like Argon or Helium, to avoid contamination. Ion beams or liquid metal spray, after shaping the foamed three-dimensional sheet, then could deposit the face material.

Wuenschel also showed that steel and steel alloys could be atomized to droplet sizes of less diameter than that of a droplet of fog. The surface tension of these steel droplets would produce an internal pressure of 500 to 1000 atmospheres, affecting and determining the crystal structure of the obtained material. The droplet could be sprayed against the cooled foam sheets and would be solidified at impact. Again, computers could control face sheet thickness within very close limits. The cost of 30 × 30-cm panels of such curved sandwich panels of highly heat-resistant sheet alloys, of columbium and tungsten ore, would be in the order of \$1,000 to \$1,500, if manufactured on Earth. It is believed that in-orbit manufacturing methods, after successful development in orbiting labs, would reduce this cost substantially and pay for the two-way transportation of material and product.

I could go on to cite additional samples because many different attractive operations are in the thinking or planning stages, but I believe I have given you some exciting and promising samples which will progress to the stage of operational feasibility almost certainly within less than a decade, as will many others that are not described here. These are sure to usher in a decade of space exploitation even more exciting than the one devoted mainly to exploration, which is just about to pass.

WHAT ARE EXTRATERRESTRIAL RESOURCES?

Extraterrestrial resources can be considered resources which can maintain space flight and human life in space and on extraterrestrial bodies without Earth-derived logistics. In other words, self-contained exploration, operation and settlements (e.g., on the Moon) and maintenance of traffic and logistics between different extraterrestrial bodies—without continuing logistics from Earth—would require extraterrestrial resources. But we can define this

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term even broader. Physical phenomena can be considered extraterrestrial resources too, if these permit us to conduct processes or operations which would be more difficult or less economical to achieve in the natural Earth and Earth atmosphere environment, such as lowered or disappearing gravity, wide spectrum of radiation level, varying degree of vacuum, extreme temperature environment, or potential or kinetic energy levels difficult to achieve from Earth.

These resources (Fig. 1) could be—minerals used to produce fuel, breathing oxygen, building materials for encampments, or life-support-providing replenishments. Of the consumables, water and oxygen require the highest support level in weight to maintain human life in extraterrestrial space. Since oxygen is the major weight component of water (~89%), availability of water alone could reduce logistics requirements to support life by almost 90%. Oxygen and hydrogen, a highly effective fuel and oxidizer combination for chemical rocket motors, could be supplied from water and could increase this logistics percentage far above the 90% fraction.

More recently, many proposals have been made to use extraterrestrial environment for manufacture of products which would

WHAT ARE EXTRATERRESTRIAL RESOURCES?

- * INDIGENOUS RAW MATERIALS TO PRODUCE FUEL AND LIFE SUPPORT
- * INDIGENOUS RAW MATERIALS TO SUPPORT CONSTRUCTION AND OPERATION ON THE MOON
- * RAW MATERIALS OF VALUE AND QUALITIES TO BE FURNISHED FROM EXTRATERRESTRIAL RESOURCES TO THE EARTH
- * ENVIRONMENTAL CONDITIONS DIFFICULT TO ACHIEVE ON EARTH AS E. G. LACK OF GRAVITY, DIFFERENT RADIATIONS OR LACK OF RADIATIONS, AND DEGREE OF ACHIEVABLE VACUUM
- * NATURAL RADIATION SPECTRA AND PROPAGATION PHENOMENA NOT DIRECTLY AVAILABLE ON EARTH.

Figure 1

be difficult to produce on Earth. These difficulties could be due to high gravity effects, insufficient vacuum, the need to add or to remove heat economically at high rates or to provide conditions of peculiar radiation or its absence. If the product is of sufficiently high value with respect to its weight or volume, cost of transportation included, it may be economical to have it produced outside the terrestrial environment. In turn, I might say, if transportation cost to extraterrestrial space is low enough, the candidates that are potentially capable of taking advantage of this environment may increase to such a magnitude that use of space for commercial purposes may become increasingly attractive and eventually self-supporting. Prof. Zwicky, in his paper given during the XVIII International Astronautical Congress, made an eloquent case for the Moon as a resource of fuel and life support using minerals of expectably high abundance to produce fuel- and life-supporting oxygen.

THE CASE FOR THE PRESENCE OF WATER IN THE MOON AND OTHER INNER PLANETS

Prior to unmanned lunar landings and lunar orbital flights, the prevailing theories of the composition of the lunar crust and the lunar interior were mainly based on the assumption that the Moon, being a part of the system of the inner planets of the solar system, would have to have a similar distribution of elements as that found on the Earth. If this should be the case, then one could expect that water, not now observable on the surface of the Moon, could possibly have played a role in the Moon's past or one could expect it in the form of water of crystallization or hydration within the rocky material of the surface and interior of the Moon. It might even be found in underground lunar deposits in the form of liquid water or as permafrost, particularly in areas of permanent surface temperatures below freezing level. The presence of liquid water could be particularly expected if volcanism had been active in the Moon's past, or if it is present even at this time, or, if interior temperatures, due to compression and possibly radioactivity, reach levels required to start dehydration of the rock material (300° to 1400° C).

Analysis of the α -scattering experiment, used on Surveyor 5 after its lunar landing, as recently reported by Dr. Newell of NASA and his team, particularly Dr. Anthony Turkewich of the University of Chicago, shows preliminary results of composition of

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surface rocks (Fig. 2) similar to that observed on rock samples of the Earth, confirming the expectation of approximately the same relative abundance of elements as on Earth. *This scientific achievement can be considered as one of the greatest in human history!* Even if this fundamental experiment to obtain the chemical composition of the lunar surface material only reflects the composition of a very thin surface layer and does not give insight into the composition of rocks of the crust below, it could reveal much information based on the meteoritic dust (not originally from the Moon at all) spread over the Moon's surface; this achievement loses none of its significance. Another characteristic of this experiment is that it cannot disclose or detect the presence of hydrogen, which is necessary to prove the presence or certainty of water within the Moon. To arrive at the relative abundance of water, it has to be derived by indirect means of rather high uncertainty.

Before I come to another observation, which may point to the presence of water at some point of time in the history of the Moon, I would like to present two figures (Fig. 3 and Fig. 4), originally published by NASA, which compare abundance of the

CHEMICAL COMPOSITION OF THE LUNAR SURFACE
AT SURVEYOR V AND VI SITES (PRELIMINARY RESULTS)

ELEMENT	PERCENT OF ATOMS	
	SURVEYOR V	SURVEYOR VI
CARBON	< 3	< 2
OXYGEN	58 ± 5	57 ± 5
SODIUM	< 2	< 2
MAGNESIUM	3 ± 3	3 ± 2
ALUMINUM	6.5 ± 2	6.5 ± 2
SILICON	18.5 ± 3	22 ± 4
"CALCIUM"	13 ± 3	6 ± 2
"IRON"		5 ± 2

Figure 2

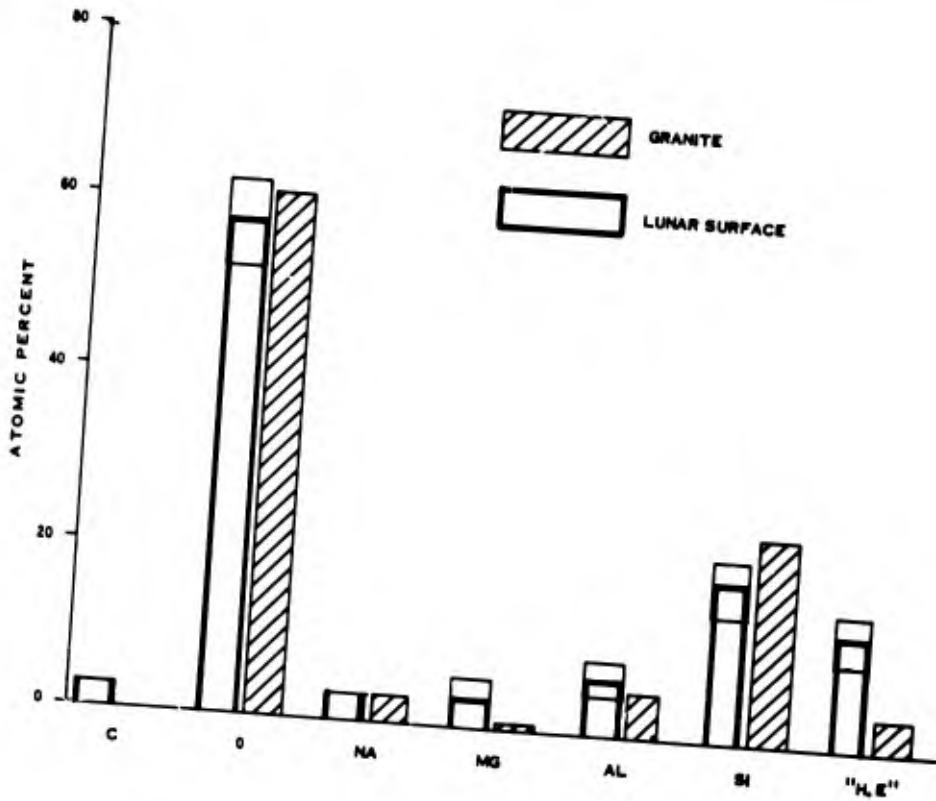


Figure 3

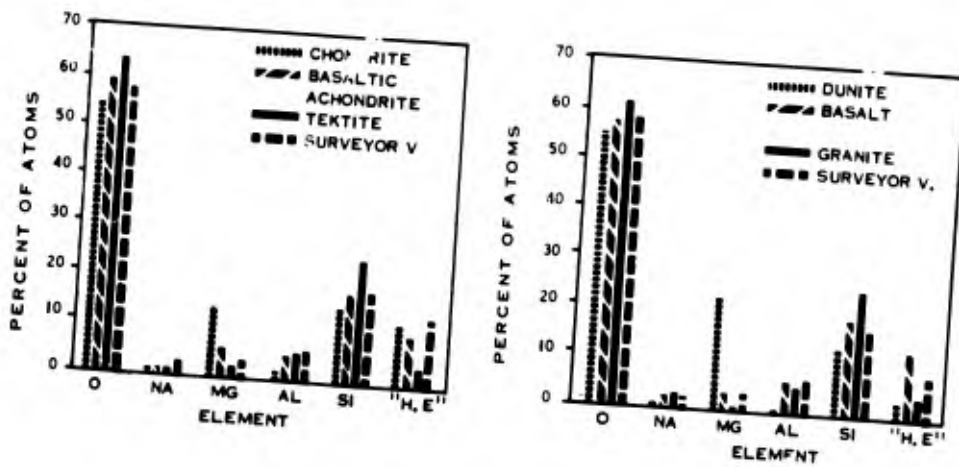


Figure 4

elements represented in terrestrial rocks to that obtained on the surface of the Moon by the α -scattering experiment of the Surveyor 5. Dr. Gault's interpretation, as published in the preliminary

results of the Surveyor mission, postulates that the lunar surface material as presented by the α -scattering experiment is best interpreted to consist of a general basaltic composition, confirming the prediction of Dr. Jack Green, in particular, who has been a distinguished speaker to the Working Group. Proof of presence of basaltic material, confirmed in parallel to the α -scattering experiment by a magnetic-properties test and a proton-scattering test, points to the fact that, within the interior of the Moon, rock material of an ultrabasic type has reached temperatures necessary to drive out water of crystallization or of hydration, but in some cases or locations has not reached temperatures sufficient to melt the original rock material in at least some areas of the lunar sphere. I would not postulate at this time whether such melting took place as a result of mechanical heat generation due to impact of large meteors (which possibly resulted in the existing maria) or whether it is a direct consequence of internal heat generation (independent of heat of impact) or as a consequence of a source of the material being not originally of the Moon.

Prof. Donald Menzel—in his paper presented to the last technical conference of the AIAA at Anaheim, California, in October 1967—showed a number of specific surface features of the Moon which, according to his interpretation, could only have been caused by liquid erosion by a medium like water or by one having similar properties. These erosion features are distinguished by meandering tracks which begin, mostly, near a crater's fractured wall and continue towards lower territory and then gradually fade out. Figure 5 shows such a case, taken from Lunar Orbiter V. Pictures obtained from Gemini missions show similar erosion features on the surface of the Earth caused by water erosion in desert areas (Fig. 6). Both Dr. Urey and Dr. Menzel agree that these features point toward active water erosion sometime in the Moon's history and to the possibility that, in spite of the apparent barrenness of the surface, the existence of underground liquid water storage is a distinct possibility. Dr. Menzel goes even further in his conclusions; he postulates that, under the assumption of cosmic relative abundances of elements on the Moon, the Moon must have had an atmosphere in its distant past and evidence of this should turn up in future observations on the Moon itself. These thoughts and conclusions are not much different from those presented in past years by Dr. H. Strughold and this author.

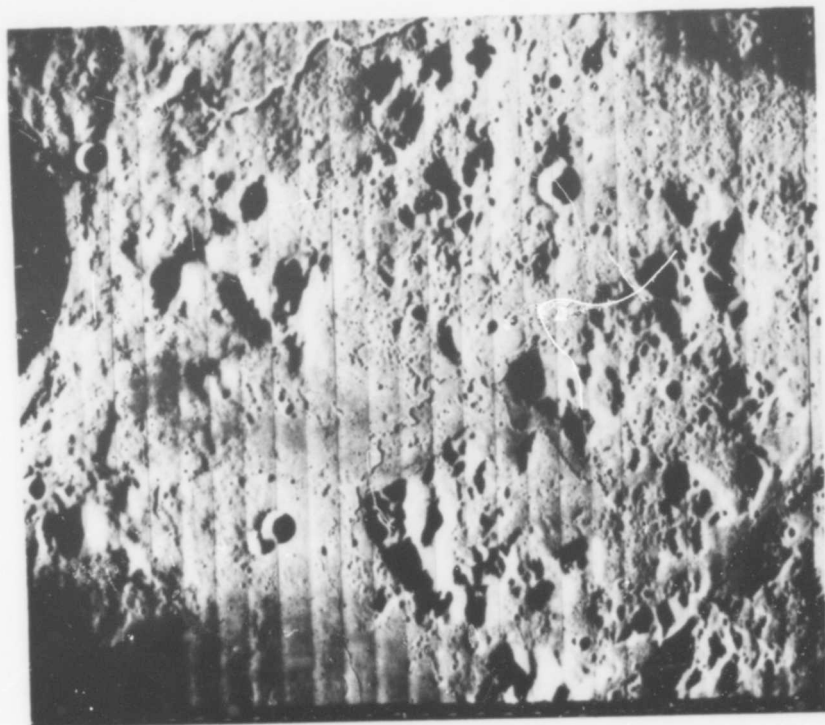


Figure 5

EFFECT OF INDIGENOUS FUEL SOURCES ON SPACE TRANSPORTATION

The problems of producing fuel and an oxidizer on the lunar surface or planetary surface based on indigenous raw materials have been studied, and a number of processes have been developed or proposed as conceptual approaches which are derivatives of industrially known processes that take into account the particular operational and environmental peculiarities of extraterrestrial application.

Since transportation cost to a lunar or planetary location is very high as compared to the specific cost of establishment, operation, and maintenance of industrial chemical plants and its manpower for conventional Earth use, design has to reflect extremely

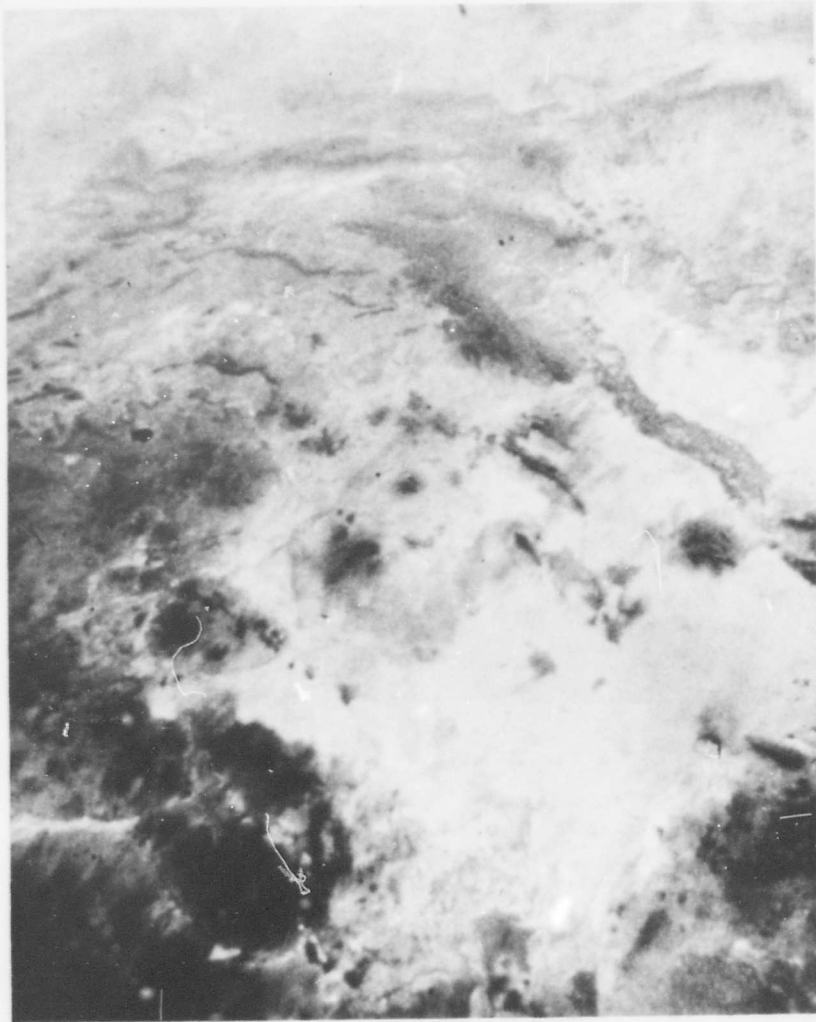


Figure 6

low weight construction, long life design, minimum-type preventive maintenance, resistance to wear, and a very high degree of automation to save operating manpower. Also, installation and assembly are areas which require a very high degree of sophisticated engineering; therefore, final assembly needs to be accomplished at the

extraterrestrial destination with a minimum of manpower and equipment. Use of construction materials of materials properties on the fringes of our technology may be cheaper in total cost (including transport, emplacement, and long-term operation) than current chemical plant construction technology and practices may be able to provide—requiring a considerable amount of advanced engineering and fabrication research. Also, the subject of waste disposal from the manufacturing site may cause problems, which are easily surmountable but frequently bothersome in the case of fabrication on the Earth but under extraterrestrial environment and extreme shortage of manpower are important factors to deal with. The magnitude of this problem is directly proportional to the *yield of waste* as compared to the *useful yield* and, in the case of fuel, to the inverse specific impulse produced per pound of fuel.

If pure water is the raw material, the case of *no waste* would be optimum; while, for a raw material of 1% extractable water content, the waste would have 100 times the weight of the product and possibly between 30 and 100 times the volume of the useful yield. This ratio can become a problem as to waste disposal which would be difficult to handle with a minimum of physical labor and would require considerable analysis of engineering solutions and many other aspects: e.g., the cost per construction man-hour or assembly man-hour involved to complete the plant to turn-key conditions. Studying one such example, an hourly value of \$15,000 per man-hour was arrived at. Depending on details of the assembly and duration of the job, this number may fluctuate in a wide range around \$15,000 per hour. Studies by members of my staff indicate that, given a lunar source for fuel, the amount of fuel needed to maintain a certain level of space flight activity between Earth orbit and lunar surface—broken down in one traffic section (Earth orbit to lunar orbit) and a second section (lunar orbit to lunar surface)—shows advantages for lunar-based systems (Fig. 7). One can immediately see that a substantial advantage for the lunar-based system extends, in the case of the round-trip payload mode, to between 1,000 and 2,000 nm above the Earth, and, in the case of the one-way payload/empty return mode, down to 300 nm. In this mode, apparently, Earth launched payload fractions never show an advantage. For example, assume 1-million-pound vehicles are launched from the surface of the Earth and from the lunar surface. The Earth-based system will deliver approximately 3.9% of its launch weight as payload, or 39,000 pounds. Using the same

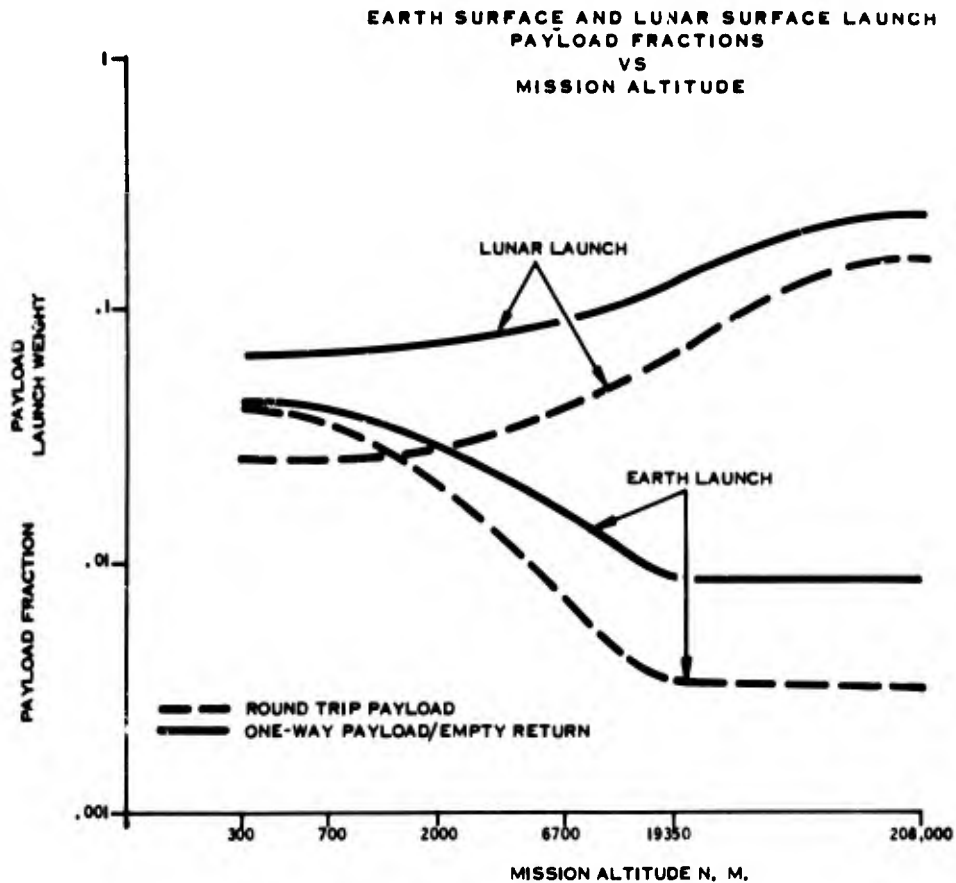


Figure 7

level of technology, the lunar-based system on the other hand will deliver 6.5%, or 65,000 pounds, to the 300-nm Earth orbit.

While fuel per pound produced on the Moon will be more expensive than that produced on the Earth, the implication of the lunar supply permits the classification of operations into individual traffic sections and to achieve an optimum traffic pattern such that the space flight system can be designed as a fully reusable system permitting hundreds or thousands of round trips with little cost of maintenance and spare parts, as soon as the used powerplants are designed for a high reuse level. In such a use pattern, currently employed stages (e.g., the Saturn SIVB and SII) show spectacular payload weight fractions, even if unmodified from their standard configuration. Since thrust-to-weight fractions for

the Earth orbit to Moon orbit shuttle can be considerably smaller than one and meantime to failure due to reduced power setting can already provide considerable extension of lifetime without major engine redesign, an approach to use already existing hardware, modified in orbit, may be the easiest way to convert space flight operations, using fully expendable components, gradually to such a use pattern of increasing reuse of components. Such a space flight pattern, when introduced, could be supplied with fuel from lunar resources and provide an extraterrestrial transportation system of potential economic superiority as a function of productive plant sophistication. Having analyzed such a system, the yield of the extraterrestrial raw material and plant operating cost associated with this yield then become trade-off factors. To obtain a complete Earth surface to lunar surface round-trip system, the transportation system's final link from Earth surface to Earth orbit and return to Earth surface has to be considered and its operating cost determined. If the Earth-Moon section cost level is low, as compared to the per pound cost of transportation from Earth surface to Earth orbit, design and development of a reusable link between Earth surface and Earth orbit terminal system of improved economy may eventually lead to a trend of increasing space flight economy, and may finally result in increasing use of space traffic to Earth orbit and to the Moon—for research, industrial, and commercial reasons. While achievement of space operations for commercial purposes beyond the current practical cases (Comsat, Intelsat, weather satellites, possible navigation-satellite use for commercial air- and ship-traffic use, conventional TV satellites, and near future educational satellites for transcontinental TV transmission) may take decades, introduction of and increased use of more economical reusable sections in our space-traffic pattern may accelerate lead-time to commercial uses to less than a decade if systematically made the objective of our military and civilian space plans.

If, for instance, one would salvage SII and SIVB stages in orbit and perform overhaul and preventive maintenance on them from an orbital space station, they could be refueled in Earth orbit and lunar orbit, and could fly to and from either terminal. As the lunar-orbit terminal, a second orbital space station, as those proposed for the Apollo Application Program, could be established and serve as a support base for vehicles returning from the Moon. These could be parked on the lunar-orbit terminal, receive preventive maintenance, and be reused, obviating the need to bring new

ones from Earth for every landing on the Moon. In this case, only the lunar landing module must be brought from Earth.

After establishing a small fuel-generation plant supplied with electric energy from nuclear electric plants (e.g., SNAP-50), fuel could be produced first for the sole purpose of returning LEMs back to lunar orbit, obviating the need to bring new LEMs from the Earth to the Moon. Since the LEM has a greater payload capability than the lunar return vehicle, now a new capability of return payloads begins to take shape. Increasing the fuel-plant capacity further could lead to providing an increasing percentage of the return fuel for SII and SIVB stages from lunar orbit to Earth orbit. Excess fuel, arriving from the Moon in Earth orbit, could be stored at the Earth-orbit terminal and could now be used to refuel outbound trips whenever possible, reducing further the need to bring fuel to Earth orbit from the Earth itself and increasing the payload capability of the Earth surface to Earth orbit transportation system even further.

Before achieving this stage of operation, there could be an interim case in which, instead of fuel and oxidizer only, water could be brought from Earth to the Earth-orbit terminal and there dissociated and liquified for use as fuel, using spent SII stages attached to the Earth-orbit terminal as fuel-storage tanks, requiring only a minimum of conversion equipment including a space nuclear electric plant. The lunar-orbit terminal could be similarly equipped, permitting assumption of the operation first with water brought from Earth and later with water extracted or mined from the Moon. The next step would then be to dissociate water directly on the Moon and so supply the fuel for the return to orbit of LEMs and lunar return vehicles. Payload of the LEMS could be lunar water to be converted to fuel in lunar orbit. Those familiar with the components of the Apollo system will agree that such a bootstrap-type expansion of our space flight capability would considerably widen our space flight horizon. Work done by and for NASA-MSFC under the Mimosa Study and work done by Howard Segal deal with the use of Apollo components, beyond use of the original Apollo concept, and represent work extremely promising toward increasing economy of space flight.

Some of the thinking of Howard Segal should be reviewed here. If one looks at the lunar-orbit rendezvous mode, this combination can deliver from lunar orbit 5750 pounds of return fuel and

2410 pounds of cargo to the lunar surface. If fuel would be available from sources on the Moon, the 5750 pounds of fuel could be replaced by payload (8160 lb). One could return not only the ascent portion of the LEM back to lunar orbit but also the complete original landing vehicle which carried the LEM, and in addition to payload it would carry also fuel for the next landing on the Moon on its return flight; Howard Segal has investigated cases to return it and the command module to Earth orbit. With these two vehicles, one could maintain two levels of shuttle operation between lunar surface and orbit. Figures 8 and 9, describing the Segal case, show a two- or three-man crew rotation case and a five- or six-man crew rotation case, with the associated objectives to return to lunar orbit or to Earth orbit. (I did not prepare new figures, as I believe Howard Segal's original figures make my point.)

One interim approach which could be expected to reduce Earth logistics by a factor of ~2.3 would be an approach which would use lunar rocks recently proven to exist on the Moon by Surveyor V. In 1964, Dr. Rosenberg investigated the use of silicate rocks rich in oxygen (e.g., $MgSiO_3$) which are expected to be abundant on

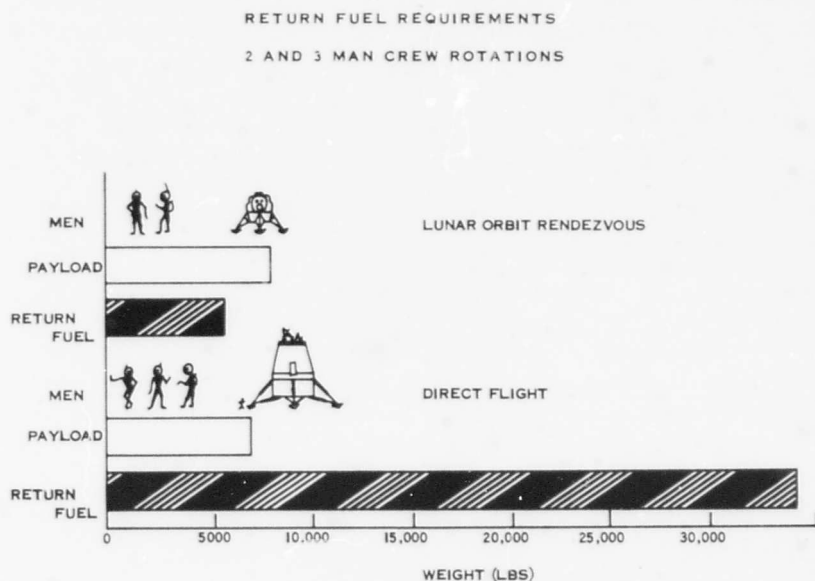


Figure 8

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RETURN FUEL REQUIREMENTS 5 AND 6 MAN CREW ROTATIONS

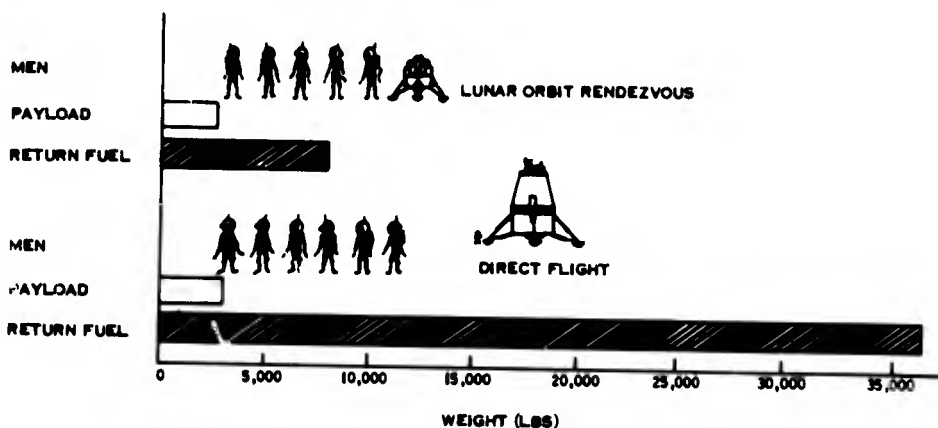
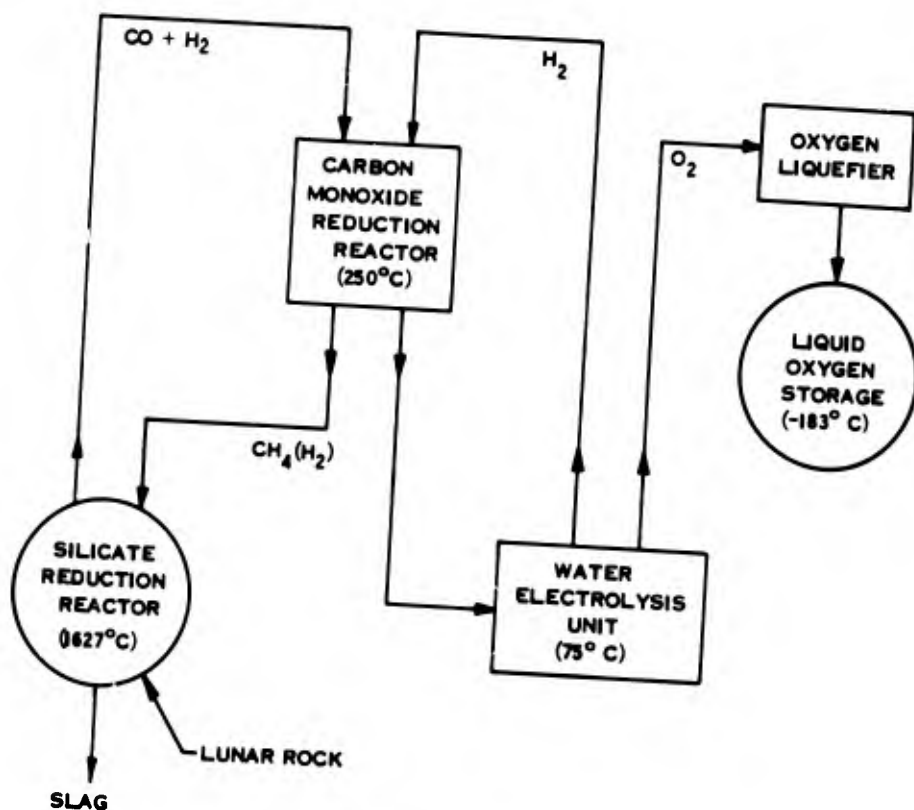


Figure 9

the Moon and to provide oxygen for life support and for an oxidizer for use in rocket and extraterrestrial surface vehicle propulsion. Figures 10, 11, and 12 describe the process Rosenberg came up with which is within the state-of-the-art of chemical manufacturing. In order to get the process started, an initial supply of methane is needed, which is recycled in the process. The product is water, but it needs to be dissociated to recycle the hydrogen into the process again. If methane, hydrogen, acetylene, ammonia or other fuels could be found on the Moon and easily collected, dissociated to hydrogen and liquified, no further resupply from Earth would be needed.

To obtain an insight into the yield of the process, it takes 29 pounds of lunar rock to produce 8.33 pounds of oxygen, a yield of ~28.8%. However, at the site of the first lunar base, where according to recent surface material analysis (Fig. 2) rocks rich in oxygen, silicon, and magnesium should be found, one cannot expect that with these other raw materials providing above or similar fuels to go with oxygen would be immediately available. A long time may pass before raw materials for these companion fuels may be found. I think the prospect to find water in minable form may look better.

However, this process could be the second step in a bootstrap buildup of space flight capabilities. The first step would be not to



SIMPLIFIED FLOW SHEET FOR AEROJET CARBOTHERMAL PROCESS

Figure 10

bring oxygen and hydrogen separately as fuels, but to bring water to Earth orbit and lunar orbit and eventually to the lunar surface—and to dissociate and liquefy it there: using packaged nuclear electric powerplants to dissociate it and radiators to reject excess heat to cosmic background to liquefy its components. After getting Rosenberg's process in operation, one could bring only half the amount of weight in methane instead of water to the lunar location. Methane packs more than twice as much hydrogen per pound than water does, and one would use methane to dissociate hydrogen from it. This means that for return flights from the Moon, having an oxygen supply there, only half the weight of that of water would have to be ferried from Earth, leaving carbon gas as an extra bonus on the Moon for further use as fuel. One can see that this approach has the potential to cut fuel logistics to the lunar base in better than half. This possibility turns up the need for further analysis

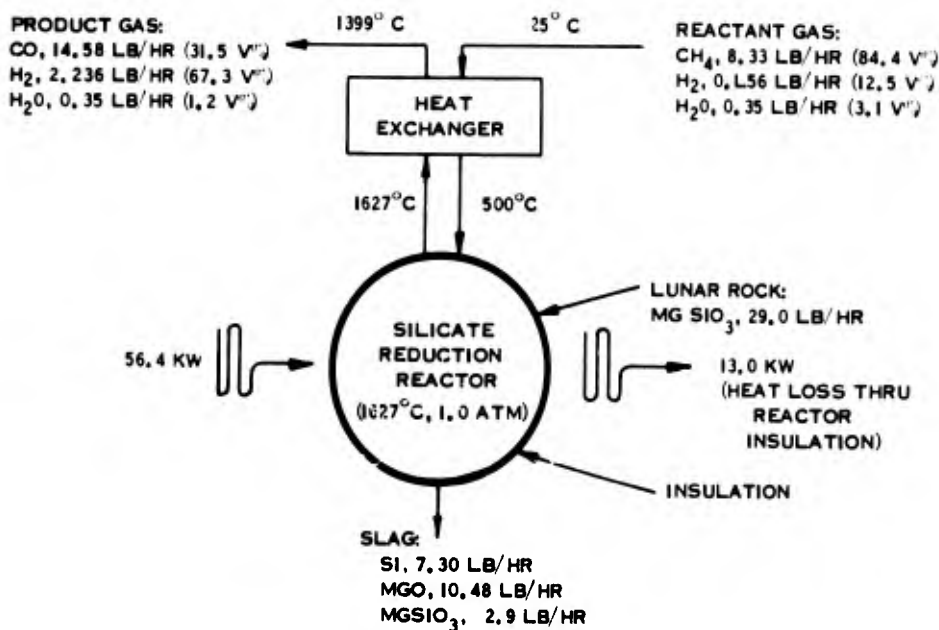


Figure 11

as to other possibilities of processes and compounds which have still higher hydrogen yields, but have a high enough specific density to reduce the transport volume further.

While the weight fraction, 1/9 of water, of hydrogen is attractive, the low density of even liquefied hydrogen gas requires storage volumes and structural tank weight fractions which might be impractical as an avenue toward the final goal of independence from Earth logistics, using current space systems components as reusable carriers. Then, if water as a compound is found in minable and processable qualities, the Rosenberg process could be replaced by more efficient processes involving extraction and dissociation to obtain LO₂ and LH₂. Every one of the described steps would reduce the logistics requirement and lead to a higher degree of economy and independence from Earth. For a while, these processes could be used parallel to each other until the less efficient ones could be replaced by a proven and more efficient, newer process.

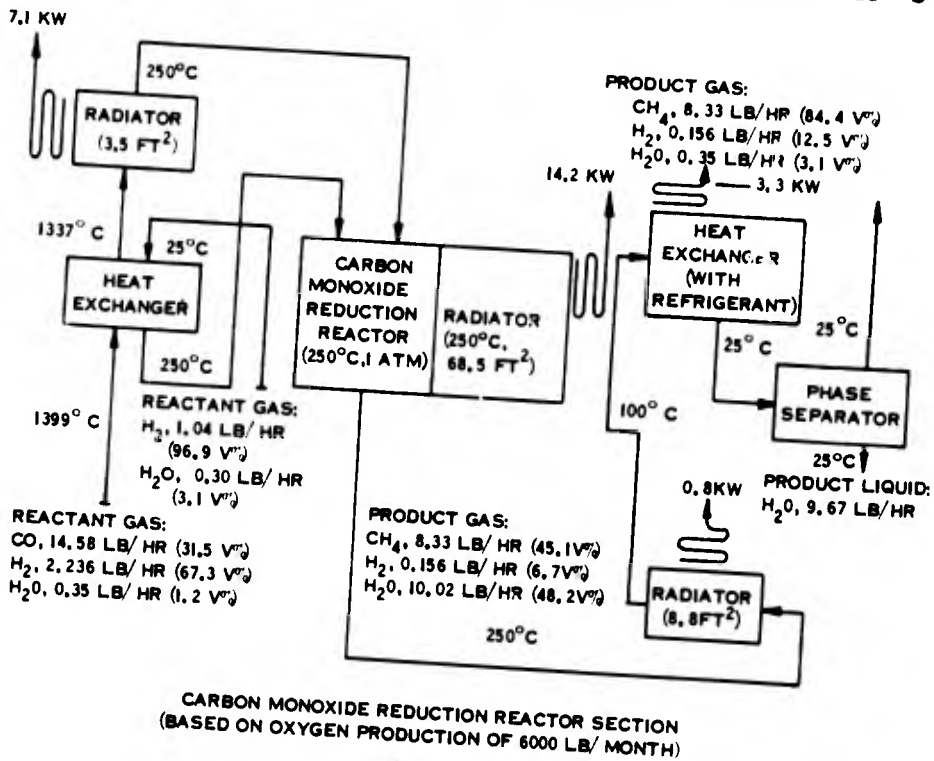


Figure 12

A next step could be the establishment of a third space terminal at one of the lunar libration points, serving as a point of departure for interplanetary missions and being supplied with fuel, first from Earth and later from the Moon.

RECOMMENDATIONS TO AND MODEL OF SUCH A SPACE TRANSPORTATION SYSTEM

From the preceding, we can conclude that a partly reusable transportation system to include landing at and establishment of a lunar orbital, as well as a surface, terminal can be considered well within the realm of possibilities of current technology and planned vehicles. To make use of this proposed approach, however, it must be included in our national space plans and implemented as we go along in using the Saturn V system to expand our space capabilities. The real step forward toward a highly economic Earth-surface to Earth-orbit system, however, would come when this part of the space transportation link would also be made at least partly recoverable and would use components which are part of existing or near future aerospace systems, as far as either components or technology

of these are concerned. The current limited number of annual space launches of NASA and the Department of Defense does not justify the early replacement of the current nonreusable space launch systems, and a desire for their replacement would not find strong support in either camp. However, thoughts have been advanced throughout the scientific community to gradually improve subsystems which eventually would prepare the road toward more economic space flight, including at least partial reusability. One item that could pave the way is a fully recoverable reentry vehicle with a capability to bring to and return from orbit considerable payload weight (40,000 to 60,000 lb per flight). The other possibility would be to develop a mobile, reusable space launch platform using horizontal take-off and landing on existing military runways such as are needed for B-52 and C5A. Several approaches for such a launch platform, covering the range from subsonic launch speed to hypersonic launch speed, have been advanced by the scientific community and by industry. While one can obtain higher payloads per pound of take-off weight by going to high separation speeds, there is much indication that degree of reusability, level of preventive maintenance, cost of initial development, test and procurement, as well as technological risks and uncertainty involved would make such an approach a long lead-time approach and could be detrimental to the level of cost effectiveness needed even with high launch numbers to affect space launch cost favorably. Use of the lower speed spectrum from high subsonic to supersonic transport speed range, besides reduction in technological risk, provides interesting possibilities and could turn out to be economically superior to other advanced solutions. It should find further scrutiny; however, it would place a higher Δv burden on the upper stage or stages; or it would require the reentry vehicle to have a limited Δv capability of its own. The interim stage or stages would use conventional space launch systems technology.

This approach, if jointly undertaken by DoD and NASA, could first lead to a space rescue system which would be desirable as a point of departure and as a means to rapid access to low Earth-orbit targets, independent of inclination and ephemeris, as well as to space stations which could serve as a crew rotation vehicle. The initial use of a subsonic space launch platform would not involve major advances in space technology and would only require the typical lead time of a development within current state-of-the-art of design and construction or modification of aircraft and rocket

boosters. It could, therefore, be available within less than a decade, if such an approach would become part of a national program.

Even though the military side of our national space effort would only gain a rescue, crew rotation, or in-space maintenance capability out of this approach, possibly with the take-off site independent of the ephemeris data of the target orbit, and could have it land-based on one of our military bases, this possibility would simultaneously result in a big step forward to enhance industrial and research utilization of space. Increased industrial utilization of space then would tend to increase progressively the annual number of space launches and so in turn make reusable space systems increasingly more attractive as compared to currently uneconomic cases.

History may have witnessed a similar situation in early air transportation, in which improvements in military aircraft spawned greater commercial use which in turn spawned military aircraft improvements. If this element of mutual interaction would have been found lacking, the progress of aviation would have been less dramatic. This story may be repeated again in space flight, if as a nation we look at those elements of progress which are affected by a high degree of mutual support between commercial-use and military-use aspects.

Based on the preceding, one could recommend that a vigorous national program be established which would study the adaptability of subsystems of all our current space launch and spacecraft systems from the aspects of usefulness as reusable components of a new system consisting of:

- a. Earth-orbit and Moon-orbit terminals, made up mainly of spent SIVB and SII stages and equipped so that they could be used to house personnel, shop facilities, and fuel storage appendices.
- b. A plan to reuse lunar landing and rendezvous modules as reusable shuttles between lunar surface and lunar orbit.
- c. The use of SIIs and SIVBs, modified so that they become optimum for shuttles between Earth orbit and Moon orbit on a reusable basis.

d. An augmentation of the current space launch vehicles by an Earth-surface to low Earth-orbit system which is partially reusable in which the first stage be a horizontal take-off, horizontal landing aircraft of subsonic ($Ma = \leq 0.9$), or a low supersonic second stage launch speed ($Ma = 2.7$ to 3.0). The second stage should be a hydrogen-oxygen-fueled expendable rocket stage and should be augmented by the already proposed moderate Δv ($\sim 5,000$ fps) fully recoverable upper stage (3rd) of a 40,000- to 60,000-pound payload capability. In the event a Mach 2.7 to 3.0 first stage is used, it could be possible to lay out the third stage capability so that all of the second stage would reach orbit and all expensive major components could be recovered again with the third, fully land-recoverable stage, after disassembly of the second stage at the orbital terminal. The tanks of the second stage could be salvaged for orbital fuel storage and for other purposes. This possibility is based on LH_2-LO_2 as the standard fuel for these missions. Such missions would be more difficult to achieve if use of LH_2-LF_2 would be planned.

With liquefaction and dissociation capabilities for water, it can be visualized that by equipping these terminals with nuclear electric powerplants, water rather than fuel could be brought to orbit and there converted to fuel, thus saving transport volume and insulation during ascent through the dense Earth atmosphere. Utilizing this capability, the return fuel should be dissociated in lunar orbit and the lunar, reusable, shuttle system inaugurated to establish service between the lunar-orbit terminal and the lunar surface.

The next step could be the establishment of a lunar oxygen-extraction plant, as proposed by Dr. Rosenberg, which would provide interim oxygen supply. If the water is now replaced by methane brought from Earth, SII and SIVB stages could then return to Earth orbit by using hydrogen fuel derived from methane and using oxygen supplied from the Moon. It is quite obvious that this approach increases cargo capabilities both ways and could already lead to industrial exploration and possible exploitation of commercial uses in Earth and Moon orbits as well as on the lunar surface.

With progressing lunar surface exploration and growth of our selenographical knowledge, sources for lunar water may now be

established and the mining technology may be projected which is needed to convert lunar water from either water of hydration, permafrost, or subseleian water, to liquid oxygen and hydrogen.

I have only presented a gross layout of these possibilities. By a closer analysis, one will find that there exist a number of interim steps in which newly achieved capabilities will, as they reach their eventual maturity and capacity, gradually replace the earlier modes of operation.

Contributions of the members of the Working Group toward the approaches sketched in this treatise may go a long way toward increase of U. S. space flight capabilities and its increasing contributions to this nation's welfare and to its future stature. Some recent spectacular findings of U. S. lunar landers and orbiters confirmed earlier postulations of our group and have brought many technical thoughts advanced by the group members closer to reality than the majority of the scientific community would have believed probable. The fact that the major professional societies are now paying increasing attention to this area by including it in their session programs is testimony to the importance our work may achieve in our nation's space operation and exploration objectives. Timely inclusion of these presented possibilities within advanced technology plans would aid the U. S. to remain in the forefront of progressive space technology by providing the means to advances that would otherwise be difficult to achieve.

Before closing, I would like to acknowledge and sincerely thank those whose material and conceptual thinking I was privileged to refer to or include in this treatise and those who have helped me to round out its content by their valuable assistance and suggestions.

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XXVI

Problems in Detection of Extraterrestrial Life

A. A. Imshenetsky*

INTRODUCTION

For ages the problem of the existence of extraterrestrial life was mainly the preoccupation of philosophers and novelists, while a few scientists tried to approach it purely by way of abstract reasoning. The situation changed little up to the 1950's. Some indirect experimental evidence, like the data on seasonal variations on Mars' surface and other planets was supplied by astronomers. But only 12 years ago, as a result of certain achievements in space research and modern biology, this problem emerged as one to which experimental approach became possible.

It seems obvious that the search for life on other planets is a task which needs combined efforts of scientists of different specialties. It was readily realized that detection of extraterrestrial life is a rather complicated problem. The sending of specially equipped biological laboratories to planets of our solar system is not the kind of experiment which can be repeated too often as it tends to complicate and further increase the demands on specialists engaged in preparation and planning of such experiments. These specialists should try to select the most specific, reliable, and precise method or combinations of methods.

This paper discusses various methods for detection of extraterrestrial life suggested in the literature as well as those which have been worked on in the laboratory of the author.

*Soviet Academy of Sciences, Moscow, U.S.S.R.

CHEMICAL EVOLUTION

There are several reports in which detection of certain organic compounds on other planets is considered to be a proof of life existing there. However, one should hardly accept such a conclusion in view of the following:

1. Synthesis of various organic compounds undoubtedly took place, and is still taking place, in outer space. Various hydrocarbons, aromatic and fatty acids, porphyrines and other organic compounds were found in certain meteorites (carbonaceous chondrites) which reached the Earth surface.
2. Some compounds (like ATP and iron — porphyrines) were believed to originate only as a result of biosynthetic processes. It was shown, however, that these and other compounds can be synthesized without any participation of living cells. Occurrence of porphyrines in natural oil and meteorites lends further support to such possibility.
3. The idea of optically active substances being indicative of life should be also critically revised. Biogenic origin of optically active substances, should they be found, is probable. But, on the other hand, modern chemistry considers the possibility of abiogenic synthesis of optically active compounds to be established beyond doubts. Conditions under which meteorites are formed might be very favorable for such synthesis.
4. As is known, the Moon has no atmosphere, and all meteorites would be expected to reach its surface. One should not be surprised to find a significant number of carbonaceous chondrites accumulating on the Moon's surface. If organic substances contained therein have not been destroyed, one could reasonably expect that the Moon's surface would be enriched in certain organic compounds. And these might be detected there. Obviously, such detection would prove nothing, insofar as the existence of life on the Moon is concerned.
5. The most important arguments against certain organic compounds being indicative of extraterrestrial life stem from recent progress in the field of organic synthesis. Using as energy sources certain factors (ionizing radiations, ultraviolet rays, electrical discharges, pressure, temperature) not uncommon to space, and using carbon dioxide, ammoniac, hydrogen cyanide, and other simple inorganic compounds as starting materials, a number of scientists succeeded in synthesizing various organic compounds: amino acids, carbohydrates, hydrocarbons, adenosin, etc.

Thus, abiogenic synthesis of organic compounds in space seems likely. But the detection of organic compounds in the ground of planets does not necessarily prove existence of life there. This conclusion, of course, does not diminish the specific value of detailed chemical examination of the soil on a planet.

The fundamental question of whether life exists on a planet or not should therefore be approached by the following direct methods.

ON THE NATURE OF EXTRATERRESTRIAL LIFE

Current astrophysical and astrochemical data show that the same chemical elements and radicals which exist in space exist on Earth. The above mentioned chemical evolution in space seems to result in synthesis of organic compounds which are apparently the same, or very similar to those found on our planet. The question of the origin of life on planets cannot be considered separately from that of the problem of the origin of life on Earth. Chemoautotrophic microorganisms are no longer considered to be life pioneers, contrary to suggestions made earlier by some eminent scientists. The possibility of abiogenic synthesis of organic compounds lends support to the idea that heterotrophic microorganisms are the original forms of life. All above considerations speak in favor of search for extraterrestrial life which has chemical, energetical, and biosynthetic characteristics similar to those of life on Earth. Hence, one should look for organisms which have among their constituents carbon, nitrogen, and phosphorus: water being the principal solvent.

This assumption, of course, does not refute the possibility of organisms, quite distinct in their resistance and metabolic pattern, being a product of evolution on other planets. There is a tendency to underestimate the creative power of selection under peculiar conditions. Evolution on other planets might have produced organisms which are quite odd in their chemistry, metabolism, and behavior from the point of view of Earth inhabitants. Nevertheless, it would seem logical to start the search for extraterrestrial life by utilizing our knowledge of Earth organisms which has been provided by modern ecology, physiology, biochemistry, microbiology, and biophysics.

There is a definite academical interest in the theories which consider the possibility that life is based on germanium or silicon: sulfur playing the main role in energy transformation processes instead of phosphorus. Ammoniac and some other low-temperature melting compounds are thought to be able to replace water as the main solvent on planets where low temperatures predominate in soil. But it would seem reasonable to start the search for life forms which lack carbon only after failure of consistent and

repeated attempts to find life forms which are based on carbon. One would hardly need to argue with Lovelock's opinion that it is highly impractical to send spaceships ". . . to detect speculative life forms."

Judging from conditions prevailing on Mars, one may risk to speculate on possible physiological groups of microorganisms which might be met on the planet (Table 1).

Table I. Possible Occurrence of Various Physiological Groups of Microorganisms on Mars

MICROORGANISMS	OCCURRENCE
Photosynthesizing bacteria	Quite possible
Chemosynthesizing bacteria	Possible but oxidation not on account of the absence of free oxygen
Heterotrophic bacteria in the atmosphere	Low possibility
Heterotrophic bacteria in the ground	Quite possible
Xerophytic bacteria	Possible near equator
Psychrophilic bacteria	Possible in various regions of the planet
Anaerobic bacteria	Quite possible

POSSIBILITY OF DETECTION OF EXTRATERRESTRIAL LIFE ON EARTH

The idea of extraterrestrial life being imported to Earth is not a new one: many distinguished scientists and philosophers have contributed to this idea's development. But, so far, there is no experimental evidence in support of this hypothesis.

Much attention was paid to the search for living organisms in meteorites. Some reports on microorganisms in meteorites were made. But on subsequent examination it was shown that meteorites which fell on the Earth's surface rapidly became contaminated with soil microflora. Only those which have fallen on snow in the Arctic (or Antarctic) or on the surface of desert soils during arid periods are considered to be useful for microbiological analysis.

In this context, microbiological examination of cosmic dust particles falling on snow or ice in the Arctic or Antarctic in remote areas is of interest.

Theoretically, the survival of microbial spores within a meteorite body seems possible despite the high doses of irradiation with ultraviolet light and ionizing radiation to which meteorites are exposed in space. Less apparent is the possibility of a living cell surviving anabiosis for millions of years. In his Loevenhoek lecture, Prof. Keilin gave several examples of protracted anabiosis, but the most striking examples were those of the order of hundreds or thousands of years. Would it be possible for a protein molecule to exist for millions of years without being denatured? In this case, any extrapolation seems to be difficult, but the negative answer to the above question looks more likely. Living microorganisms were once reported to be recovered from 200- to 250-million-year-old salt deposits. Subsequent reexamination failed to confirm this report. Some inclusions in carbonaceous chondrites appear to look reminiscent of living organisms (the term "protobionts," as well as some others, was even applied to these inclusions)—but—interpretation of these structures is very complicated.

Morphology of these structures is not expressive enough to permit any definite conclusion. Even less reliable are the results of microchemical reactions, especially if one takes into account the presence of various organic compounds in carbonaceous chondrites. Some considerations apply to both examination of meteorites and to polished sections of ancient ores.

In summary of what has been said above, one comes to the conclusion that representatives of extraterrestrial life on Earth were never revealed with certainty.

METHODS FOR DETECTION OF EXTRATERRESTRIAL LIFE

Requirements to the Method

All methods so far suggested for this purpose can be subdivided in two groups: direct and indirect. Among the indirect methods, one counts the various chemical methods for analysis of soil and atmosphere on the planet in question, the astronomical methods, and the microscopical examination of soil. Among the direct methods, one counts the transmission of pictures obtained

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by "panoramic survey" equipment and the recording of growth and multiplication of unicellular organisms. The last method deserves special consideration as only results obtained by this method are absolutely irrefutable. Here are some of the requirements to the method:

1. **Optimal sensitivity:** This means that life should not be detected where it does not exist, but should be detected where it does exist.
2. **Results should be reproducible.**
3. **Method should be reliable.**
4. **Necessary equipment should be of acceptable size and weight.**
5. **Absolutely sterilizable reagents and equipment should be employed.**
6. **Method should not rely on analyses which depend in their precision on some unknown chemical characteristics of soil and/or atmosphere of the planet to be examined.**
7. **Method should not be used as a sole one. It seems reasonable to try to employ more than one method to record the same phenomenon or process.**

Now we proceed to discuss current methods for detection of life.

Indirect Methods

Astronomical methods. Some of the astronomical data have direct bearing on the problem in question. Although some of them have outstanding academical interest (to mention seasonal variation on Mars' surface, Sinton's absorption maxima), it seems improbable that data provided by such methods will offer a final solution to the question of whether life exists on Mars or not. Some new and interesting data will probably be obtained through the use of equipment (telescopes, among other things) installed on a spacecraft encircling a certain planet.

Microscopy. This method occupies an intermediate position between direct and indirect methods. In a drop of liquid mixed with soil particles, by use of a microscope one can reveal cells of microscopical plants and animals. What is important is that active motility of such cells can be ascertained. In such capacity, microscopy can be regarded as a direct method. There are, however, certain complications, which make employment of microscopy more difficult if compared to those methods of direct

recording of growth and multiplication of unicellular organisms. Among these complications are the techniques used in preparing specimens, focussing the microscope, and chemical modification of the solvent to prevent brownian movement.

Microscopical examination of fixed and stained preparations seems to be promising for revealing microscopical algae, fungi, and animals. Much more difficult is the detection of bacteria, since experience in paleobotany shows it is impossible to tell exactly whether a given spherical body is a fossilized bacterium or not. The more complex the morphology of an organism under examination is, the more hope there is that the microscopical picture would be rightly interpreted. Significant contribution might be made by luminiscent microscopy. Use of various fluorochromes might help in revealing such cells constituents as nucleic acids, amino acids, and might help in distinguishing with reasonable certainty dead and live cells. The use of fluorochromes conjugated with specific sera might enable identification of microorganisms and as their assignment to certain species known on Earth. Microscopy can also be used in examination of cell morphology in mixed cultures resulting from inoculation of planet soil samples on nutrient media.

Employment of electron microscopy seems difficult because of the significant weight and power demand of the electron microscope. It is probable that these difficulties will be eliminated and some kind of miniaturized form of electron microscope will be used.

Detection of organic substances. Speaking on chemical evolution in space, we reached the conclusion that detection of organic compounds on a planet should not be regarded as absolute proof of life existing there. This conclusion in no way diminishes the scientific value of data obtained in examination of a planet soil and atmosphere by physical and chemical methods. Quantitative determination of porphyrines, flavins, amino acids, carbohydrates, and some other compounds will yield valuable information. The prospective program should certainly include the use of spectrophotometry, fluorometry, gas chromatography, mass-spectrometry, polarimetry, and various analyser devices for these purposes. We emphasize again that all these methods can only detect the presence of the above compounds. They can not furnish data on whether there is any relationship between synthesis or degradation of the above compounds and activity of living organisms.

Direct Methods

Transmission of panoramic survey. Transmission of panoramic pictures taken for a considerable time and covering a significant portion of a planet landscape certainly deserves serious consideration. Especially valuable might be color pictures obtained by a camera moving on the planet's surface.

However, if there are no plants or animals of appreciable size on the planet, the panoramic survey pictures will fail to yield valuable information. More promising seems to be the transmission of pictures of the soil surface taken with low magnifications.

Recording of growth and multiplication. Demonstration of cellular ability to grow and reduplicate the biopolymer molecules is beyond doubt the most convincing method to prove existence of extraterrestrial life. Only this method permits one to follow the cellular multiplication, metabolism, assimilation of nutrients, and energy sources. One of the fundamental advantages of this method is in its giving a dynamical picture, while most of the chemical analysis give a statical picture. This method includes the following main procedures: (a) taking a sample and inoculating it onto suitable media; (b) recording the microbial growth; and (c) transmission of the results of the experiment to the Earth. The last step will not be considered in the present paper.

Taking a sample. Several techniques for taking a sample of a planet soil were suggested. We shall not analyze their respective advantages. Instead, we shall formulate requirements any such method should meet:

- a. Ground sample should be taken on a distance from the landed spacecraft.
- b. The ground sample taken should be large enough to permit reliable inoculation, but not too large an inoculum should be used.
- c. Samples for inoculation should neither be taken from the very surface of the planet, nor, on the other hand, from the deep layers of the ground.
- d. Inoculum should not interfere with subsequent evaluation of growth and multiplication of cells.

- e. Sampling of ground or soil is preferable to sampling of atmosphere.

One of the sampling techniques which looks attractive consists of throwing away small sterile "shells" from the station. These shells are connected to the station with sticky tape or thread; ground particles stick to the tape and serve as inoculum when the tape is pulled back.

Nutritional medium. Some considerations as to what kind of microorganisms might be encountered on Mars were presented in Table I. It seems probable that initial synthesis of organic matter on Mars might depend on photosynthesis or chemosynthesis or even both. Heterotrophic bacteria would be expected to thrive at the expense of the organic matter accumulated in the soil. Hence, one should try to use nutritional media which would reveal maximal numbers of heterotrophic soil bacteria. Comparative evaluation of various media suggested for the purpose can be made by inoculating them with decreasing desert soil samples. Media on which distinct growth appears after inoculation with minimal samples deserve special consideration. Search for heterotrophic microorganisms should be made in the first rate, not only because their detection is easier, but also because their number in samples to be examined is expected to be larger if compared to that of photosynthetic or chemosynthetic bacteria.

Detection of growth and multiplication of cells. Method is based on detection of growth and multiplication in dynamic. All data relevant to changes occurring immediately upon inoculation might serve as controls. Subsequent recording of changes should continue for not less than 48 hours. Periodicity of taking a record registering some changes might vary.

Accumulation of biomass might be followed nephelometrically or photometrically. These methods, or modifications thereof, might be employed if their sensitivity will permit revealing of 10^3 to 10^4 cells per ml of a culture. Use of these methods requires that the turbidity of the nutritional medium to be used should not change during the spaceflight. Too large a soil inoculum should not be used because it might alter the turbidity of the medium. Recording of turbidity immediately upon inoculation should be included as one of the controls. As a rule, development of a mixed culture is associated with a drop in the redox (RO)

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potential of the medium. Hence, automatic recording of RO potential of a developing culture might yield valuable information. Less valuable might be recording of pH changes, since medium composition and physiology of inoculated microorganisms might affect pH changes significantly. Use of media containing glucose with a limited supply of nitrogen sources might be attempted. Such media are usually acidified during development of microorganisms from desert soil samples. In this case, potentiometry might be included among recommended techniques to detect microbe growth—especially since it has been recommended for this purpose by eminent specialists.

The process of cell multiplication in a microbial culture is accompanied with the processes of degradation of organic compounds. Carbon dioxide evolution accompanies both respiration and fermentation. In the last case, evolution of hydrogen might also be expected. The increase in pressure of evolving gases in a closed chamber might be followed manometrically. Increase in pressure might be registered, and then excess of gases might be withdrawn. This procedure can be repeated when necessary, and pressure changes might be registered in dynamic. However, the manometric method seems less perspective than that of the employment of nutritional media with constituents containing labelled carbon. Destruction of such compounds by microorganisms will be accompanied by evolution of carbon dioxide containing radioactive carbon. A miniaturized counter would enable continuous recording of evolved carbon dioxide.

Among the advantages of this method is the possibility to include in the media various compounds containing radioactive carbon as well as compounds labelled in different positions. Use of labelled proteins, uniformly labelled glucose and some other labelled compounds, looks promising. By employing variously labelled compounds, one can get some preliminary insights into the decomposition physiology of developing cultures.

Recording of organic compounds containing labelled sulfur might be interesting. Among the isotope techniques, one counts also a method employing ^{17}O and ^{18}O enriched substrates with subsequent registration of increased heavy oxygen concentration in water. Sulphates, nitrates, and phosphates are used as substrates, while changes in heavy isotope concentration are followed

mass-spectrometrically. This latter method would hardly compete with the labelled carbon dioxide technique for the following reasons:

1. Partial exchange of heavy oxygen might occur without participation of the enzymatic systems of the living cell.
2. There is no information concerning ^{17}O and ^{18}O concentration on planets.
3. Heavy oxygen transferred from an anion to water might be incorporated into silicates if the latter are present.
4. Ion exchange is directed by enzymatic systems which are less common in microorganisms than those participating in decomposition of organic substances serving as carbon and energy sources.

Nevertheless, oxygen isotope technique deserves careful consideration.

Biomass accumulation in a soil inoculated chamber might also be followed by recording an increase in concentration of several organic substances believed to be characteristic for living cells. Among such substances are iron porphyrines containing proteins. As with other methods, it is important to show that accumulation of such substances parallels biomass growth. Qualitative estimation of iron porphyrine proteins is made by chemoluminescent methods. The latter reveals presence of hemine, catalase, peroxidase, hemoglobin, cytochromes, etc. A mixture of luminol and hydrogen peroxide responds to introduction of catalyzators of hydrogen peroxide decomposition with a bright chemoluminescence. This might be registered with a photomultiplier, connected to galvanometer, oscillograph, and recording device. Maximal chemoluminescence is observed in alkaline medium (pH 11.0), hence some sodium hydroxide is added to a reaction mixture. This is important, since, in a highly alkaline medium, permeability of cells is altered in such a way that there is no need for preliminary disintegration of cells (iron porphyrine protein is released into surrounding liquid). The chemoluminescent method outlined above is appreciably sensitive and permits detection of 10^{-9} g/ml of catalase. It should be mentioned that minerals containing iron, as well as mineral salts of iron, if present in nutritional medium, might cause some background luminiscence. This was the case for instance, when some powdered limonite was added to the reaction cuvette. However, such ground luminiscence does not interfere with subsequent determinations.

Biomass accumulation might be followed by checking the increase in the enzyme phosphatase which might be assayed by fluorescent technique. Increase in flavine concentration accompanying growth of a mixed culture upon inoculation of suitable medium with planet soil sample might also be followed in this manner.

Careful consideration is understandably given to a method of qualitative estimation of ATP contained in growing microbes. This method utilizes the phenomenon of bioluminescence: a process in which luciferin is the energy substrate while the enzyme luciferase acts simultaneously both as a catalizator and a light-emitting agent. Presence of Mg^{++} ions and oxygen is required for the reaction. The presence of ATP light emission occurs and might be registered by the same device employed for chemoluminescent assay of iron porphyrines. Sensitivity of the method for ATP assay is appreciably high and permits detection of 10^{-9} to 10^{-11} g/ml of ATP. It is considered to be one of the most likely methods to be employed in search of extraterrestrial life. Unfortunately, this method might be successfully used only with preliminary disintegrated microorganisms. Use of ultrasonic or mechanical disintegrators for the purpose seems difficult because of the increase in weight and power demand. Possible solution might lay in utilizing various enzyme preparations obtained from microbial cultures and able to decompose microbial cell walls. Use of lysozyme might also be recommended.

As a rule, multiplication of microorganisms is accompanied with accumulation of optically active compounds. Dynamic of their accumulation might be followed using polarimeter or spectropolarimeter. Such observations can give interesting information; since, in this case, increase in biosynthetically produced optically active substances is recorded.

Utilization of calorimetric technique might also be contemplated. Growth of microorganisms in a closed thermoisolated chamber is associated with some rise in temperature of the cultural liquid. The rise in temperature is more pronounced as the growth and biomass accumulation becomes more intensive. However, the growth might not be vigorous enough to give measurable temperature shift, especially since optimal conditions for growth of unknown microorganisms must first be ascertained. Poor growth might not result in measurable temperature shift.

Comparative study of methods suggested for detection of extraterrestrial life allows their tentative arrangement into three groups: (1) most perspective, (2) interesting, and (3) those of which employment is less probable. This arrangement is illustrated in Table II and deals only with the most known recommendations.

EXPRESS METHODS FOR DETECTION OF EXTRATERRESTRIAL LIFE

These are the methods in which no inoculation of soil samples and subsequent recording of ensuing changes are employed. Thus, estimation of changes in dynamic of events, which is the most reliable approach, is eliminated. Strictly speaking, there is no possibility to get irrefutable proof of life existence employing isolated short-term analyses; but a series of functional tests might nevertheless be interesting. Naturally, in analyses continuing for only 1 to 2 hours, it is important to have larger samples of material to be examined than those used in experiments with inoculation of nutritional media.

It was shown in our laboratory that in desert soil in isolated short-term analyses it is possible to demonstrate the presence of iron porphyrine proteins, ATP, and the ability of soil microflora to evolve radioactive carbon dioxide from labelled glucose. Other methods could also be used for this purpose. It should be emphasized again, however, that express methods are less reliable than those based on the recording of growth and multiplication of microorganisms.

ON SOME PRINCIPLES OF CONSTRUCTION OF BIOLOGICAL VOYAGE LABORATORIES

Design of equipment for detection of extraterrestrial life is beyond the competence of biologists. Some tentative recommendations, however, could be formulated. First of all, registration of cell growth and development upon inoculation with a soil sample should preferably be performed simultaneously with several methods. The number of methods might vary from three to six. Selected methods should register phenomena or processes which are most directly associated with growth and multiplication. In most cases, several tests might be made with one and the same mixed culture (for instance, estimation of the number of cells

Table II. Analytical Procedures Suggested for Detection of Extraterrestrial Life

Most Reliable	Worth Consideration	Least Reliable
Measuring biomass accumulation	Estimation of optical activity	Use of ^{17}O and ^{18}O
Quantitative estimation of iron porphyrine proteins (in dynamic)	Quantitative estimation of flavines	Use of sulfur isotopes
Quantitative estimation of ATP (in dynamic)	Quantitative estimation of proteins, nucleic acids, and amino acids	Calorimetry (estimation of heat evolved during growth of microorganisms)
Quantitative estimation of released radioactive carbon dioxide	Estimation of phosphatase activity	Estimation of mitogenetic radiation
Measuring pH of the culture	Manometry (estimation of pressure shifts in culture chamber)	
Measuring Eh of the culture		

and the accumulation of various physiologically active compounds accompanying growth of a culture).

A number of cultivation cuvettes should be employed if disruption of cells would be deemed necessary prior to analysis. Disintegration of cells and their analyses follow in succession, so repeated use of culture is impossible. If the same registering devices (photomultiplier, etc.) are used to collect information concerning different processes, these devices can be moved while cultural chambers are kept motionless. It is well known that the temperature on a planet's surface (Mars' surface, for instance) undergoes marked shifts. It seems unreasonable, however, to try to imitate these variations in cultivation chambers. Psychrophillic bacteria on Earth do not lose their ability to multiply vigorously (much more vigorously, in fact, than at low temperatures) at elevated temperatures. Hence, it would be advisable to keep the temperature within the cultivation chamber in the interval of 20° to 30° C. Growth should be registered at least three times a day, but more frequent registration is preferable.

All equipment components of a voyage biological laboratory should undergo preliminary tests to show that vibration, start, and landing will not interfere with their effectiveness. No reagent or nutritional medium should change its properties and sterility during flight.

Results of experiments might be immediately transmitted to Earth, but accumulation of data in memorizing devices with subsequent release of the whole information seems more expedient.

CONCLUSION

It is highly probable that before voyage biological laboratories will be sent to planets of our solar system (Mars, in the first instance) information concerning these planets will improve. This improvement in knowledge will necessitate correction to both our ideas concerning extraterrestrial life and to our construction of our voyage laboratories.

In this paper I mentioned that the most reliable method for detection of extraterrestrial life is based on recording of growth and multiplication of heterotrophic microorganisms which might occur in the surface of a planet. Microbe existence is probable in

two cases: either various organic substances accumulated on a planet as a result of chemical evolution, that is, abiogenic synthesis; or chemosynthetic or photosynthetic bacteria are present which synthesize organic compounds at the expense of atmosphere carbon dioxide. This last assumption looks more probable. Hence, as a next step in search for extraterrestrial life, attempts to detect photosynthetic and chemosynthetic bacteria might be considered. This would require modification of methods suggested for detection of heterotrophic unicellular organisms. Such modifications will not be principal, since the ability to utilize carbon dioxide for building cell constituents might be followed by several methods.

Two interesting possibilities might arise in search for extraterrestrial life: First, active life may be absent, but, upon chemical and morphological examinations, remnants of former life might be found. The research program should include paleobotanical and paleozoological studies. Second, there is a possibility that microorganisms, which are complex organisms in an evolutionary sense, will not be found, but that some very primitive forms of life will be detected. Discovery of such primitive forms of life will no doubt be more interesting than the detection of microorganisms which resemble those inhabiting Earth. However, at present, no method for detection of such primitive forms of life is available. However, that does not mean that they could not be suggested in the future.

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XXVII

Extraterrestrial Biology—Prospects and Problems

Harold P. Klein*

INTRODUCTION

People have probably speculated about the existence of living organisms on other heavenly bodies since the beginnings of human existence on this planet. Certainly, even a cursory examination of the interests of contemporary man, as exemplified in his news media, his entertainment, and even his current literature would reveal the inroads that the concept of extraterrestrial life have made on his thinking. Today, as the United States and the Soviet Union stand at the threshold of intensified activity in "space exploration," it might be useful to examine briefly what the prospects and some of the problems are in the coming search for extraterrestrial life.

MAJOR THEMES

Two general arguments form the basis for the view that extraterrestrial life is not only possible, but widely distributed in the universe. The first of these is that living organisms are essentially complex organizations of organic molecules resulting from a long and continuing process of chemical evolution. This idea holds that the process of evolution began with the origin of the universe and led to the formation of the elements within the stars themselves (e.g., Refs. 1, 2). Then, following the formation of planetary systems, over relatively short periods of time, simple components of primitive planetary atmospheres condensed to yield organic molecules of increasing complexity until at some point a

*Assistant Director, for Life Sciences, NASA-Ames Research Center, Moffett Field, California.

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primitive replicating system resulted. Experimental support is growing for the contention, first propounded by Oparin³, and soon thereafter by Haldrane⁴, that the origin of terrestrial life had its beginnings in a reducing atmosphere of methane, ammonia, water, and hydrogen in the primitive terrestrial atmosphere. Miller⁵ showed in 1953 that certain amino acids and other organic compounds were formed when this "primitive atmosphere" was subjected to a spark discharge continuously in a closed system. Since those initial results, numerous investigators using a wide variety of energy sources and the "primitive atmosphere" as starting material have been able to detect a large array of organic compounds of biological interest. The rapidly moving developments in this field, recently reviewed by Ponnampertuma^{6, 7}, are briefly summarized in Figure 1.

That the initial period of transition from simple precursors to living systems on Earth may have been relatively short is now

Primitive Atmosphere	Energy Sources	Building Blocks	Basic Components	Living Cells
Water	Ultra Violet	Amino Acids	Proteins	
Hydrogen	Electric Discharge	Purines	Nucleic Acids	
Ammonia		Pyrimidines		
Methane	Ionizing Radiation	Carbohydrates	Polysaccharides	
	Heat Meteoroids	Fatty Acids	Lipids	

Figure 1. Summary of experiments on chemical evolution (after Ponnampertuma⁶). The "primitive" gases, methane, ammonia, water, and hydrogen, have been condensed, using the energy sources shown, with the result that amino acids, sugars (including hexoses and pentoses), and organic bases have been formed. In addition, under these conditions, porphyrins and simple peptides and polynucleotides are also made. High molecular weight polymers of amino acids (proteinoids) have been produced from amino acids with heat.⁴¹

becoming apparent. Fossilized microorganisms resembling both bacilli and algae have recently been discovered in terrestrial samples that are 3.0 to 3.4 billion years old.^{8, 9, 10} Therefore, if biological evolution had progressed to the point where both bacterial and algal forms were already present 1 to 1.5 billion years after the formation of the planet, the critical era during which life *first* appeared on Earth must have occurred soon after the Earth was formed, certainly well within the first billion years.

The second major theme concerns the probable number of sites in the universe where chemical evolution, of the type envisaged on this planet, may have taken place. The astronomers point out that the Sun, about which the planets of our solar system orbit, is but one of more than 100 billion stars in our galaxy, the Milky Way. For comparison, Figure 2 presents a photograph of the neighboring



Figure 2. Great galaxy in Andromeda. Satellite galaxies are also shown. (Courtesy of Mount Wilson and Palomar Observatories).

galaxy, in the constellation Andromeda, with its billions of stars. In turn, as the astronomers probe the distant recesses of the universe, it is evident that hundreds of millions or billions of additional galaxies are visible (e.g., see Figure 3). The number of stars in the universe thus seems to be staggering.

That many stars may have planetary systems of their own has been considered by a number of astronomers. For example, Hoyle¹¹ estimated that in our galaxy there are probably about 100 thousand million planetary systems. Brown¹² came to the conclusion that just about every star should have a planetary system associated with it. Indeed, he went so far as to suggest that, on the average, each star should have two planets in its planetary system at distances that would receive sufficient radiation to support life. Other authors (Huang¹³, Shklovskii and Sagan¹⁴) also considered the probable occurrence of planets capable of supporting life, that is, planets having appropriate temperatures, masses, and life times. And in this connection, the latter authors concluded that at least

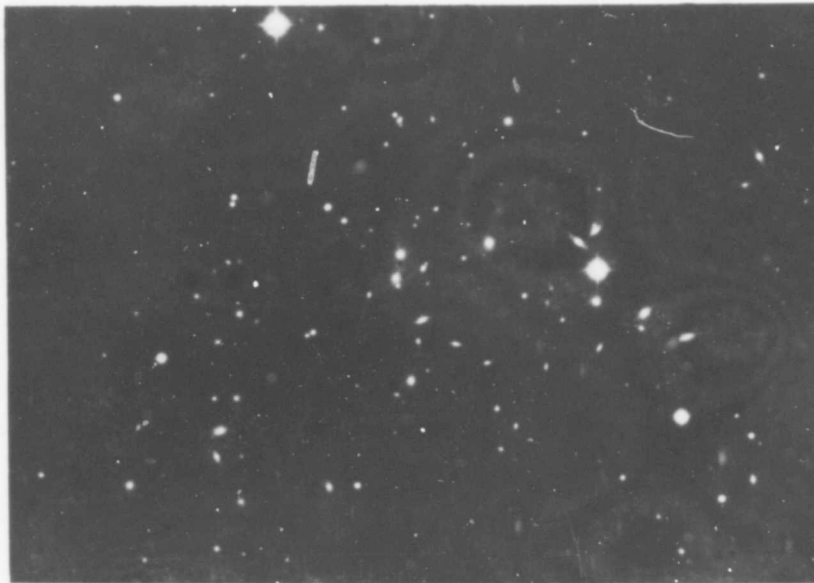


Figure 3. Cluster of galaxies in Corona Borealis. Distance about 120 million light years. (Courtesy of Mount Wilson and Palomar Observatories).

a billion stars with potentially habitable planets exist within our own galaxy.

The interplay of these two themes—first, that life evolves from simple precursors when conditions on a planet favor the condensation of these materials to more complex substances; second, that among the enormous number of stars in the universe, planetary systems and, indeed, planets with suitable environmental characteristics will appear—suggests that the search for extraterrestrial life can hardly meet with failure.

DIFFICULTIES OF DISTANCE

While the “statistics” discussed above tend to lead us to the conclusion that extraterrestrial life is widespread and invite us to imagine ourselves in some not too distant time making detailed expeditions to distant stellar systems, the vastness of space itself may well preclude any explorations beyond the solar system. In an interesting paper in which he considered some of the limitations to interstellar space travel, Von Hoerner¹⁵ emphasized the enormous distances involved as follows:

“In order to help visualize (these) astronomical distances, I will describe them with a model of scale of 1:180 billion. The Earth, then, is a tiny grain of desert sand, just visible to the naked eye orbiting around its Sun, which now is a cherrystone a little less than 3 feet away. Within approximately the same distance, some few feet, lies the goal of our present space travel: the other planets of our solar system, such as Mars and Venus. But the nearest star, Proxima Centauri, is another cherrystone 140 miles away . . . just for fun, one may add the distance to the Andromeda Nebula, the next stellar system comparable to our own galaxy: in our model, it is as far away as, in reality, the Sun is from the Earth.”

Will man be able to span the tremendous distances involved? While the stars closest to the Sun are about 4 light years away, it has been pointed out^{13, 14} that within the immediate vicinity of our solar system, stars about 10 light years away might be of more potential interest from the point of view of extraterrestrial life. To reach such a star would, of course, require a rocket system that could escape from our solar system. Such a rocket is well beyond our present capability, since a speed of 18 mps would be required. A system of this type travelling to one of the stars of

interest, 10 light years away, would take about 100,000 years to reach the star and another 100,000 years to make the trip back to Earth.

Von Hoerner¹⁵, in considering the possibilities of interstellar space flight, pointed out that if a rocket engine could be developed capable of using the energy of fusion of hydrogen into helium for propulsion, a spacecraft could be accelerated to about 36,000 mps. Even such a system, however, would only reduce the roundtrip to such a star to about 200 years.

It has also been claimed¹⁴ that if spacecraft could be propelled to reach velocities approaching the speed of light, the time dilation phenomenon would come into play. For passengers on the spacecraft, the elapsed time for a trip could be less than for those on Earth. The advantages of such relativistic travel would become increasingly great as the distance to be traversed increased. At such velocities, a round trip to the Andromeda galaxy, for example, would require about 30 years for the crew while the elapsed time back home would be a few million years!

Clearly, if relativistic travel could be achieved, and it should be mentioned that some authors (cf. Ref. 16) have challenged the time dilation concept, it would necessitate the development of completely new forms of propulsion, such as one based on the complete annihilation of matter. Whether such engines can ever be developed, of course, is open to conjecture. But even if this were possible, other considerations enter in. Oliver¹⁷ estimated that for a crew of several men making a round trip to the nearest stellar system, alpha-Centauri, in a spacecraft weighing a thousand tons, 33,000 tons of matter would have to be annihilated *en route*! His conclusion, shared by others who have analyzed the prospects for interstellar space travel^{15, 18}, is that almost certainly the technological requirements are so overriding that for all practical purposes we will be restricted in our space travels to the solar system.

SOME TARGETS IN THE SEARCH

It now appears reasonably certain that the Earth's neighbor, the Moon, will be the first extraterrestrial body to be explored. Both the Soviet Union and the United States are rapidly moving

toward the development of this capability. The prospects of finding life on the Moon are extremely slim, however. The present lunar physical characteristics—lack of an atmosphere, both very high (daytime) and very low (nighttime) temperatures, high ultraviolet flux—would seem to rule out the Moon as a likely abode of life.

Of the other planets in the solar system, the inner planets, Mercury and Venus, do not appear to be reasonable targets in the search for extraterrestrial life, at least on the basis of current knowledge of these planets. Although relatively little is known about the planet Mercury, it is known to sustain extremely high temperatures on the side facing the Sun, and low temperatures in the reverse hemisphere. Together with an extremely thin atmosphere, these conditions would seem to preclude life on this planet.¹⁴ Similarly, Venus, with its high surface temperatures (Refs. 19, 20, and data from the Venera 4 spacecraft, which reported temperatures of 280° C on the *dark* side of the planet) appears to be very inhospitable to life. On the other hand, Libby²¹ recently claimed a possibility that water icecaps exist at the poles of Venus and suggested that, therefore, there might be regions on the planet mild enough to support life.

Beyond Mars, the planets Jupiter, Saturn, Uranus, and Neptune are thought to be similar in their general physical characteristics.¹⁹ The current information about Jupiter indicates that this planet has abundant quantities of ammonia, methane, hydrogen, and probably water vapor in its very deep and turbulent atmosphere.²² Sagan²³ has pointed out that the current atmosphere of Jupiter is analogous to the "primitive atmosphere" from which terrestrial life is presumed to have been formed and that the turbulent conditions in the Jovian atmosphere could, even today, be the site of production of large quantities of abiogenically produced organic matter. Despite the presumed low temperatures on that planet, it has been suggested²² that, at some levels of the upper atmosphere, temperatures from 0° to 80° C probably exist, leaving open the possibility that some forms of life may be present in the "hostile" Jovian atmosphere. Indeed, Siegel and Giumarro²⁴ recently described the isolation of a unique organism from terrestrial sources that was grown in the presence of high concentrations (50% to 95%) of ammonia together with methane and hydrogen.

Beyond Jupiter, Saturn is thought to have an atmosphere similar to that of Jupiter. If this is the case then many of the considerations, however tentative, about Jupiter would also apply to Saturn. We know so little at this time about the more distant planets of our solar system that very little can be said, even speculatively, about the chances of finding living organisms on them, although it would appear that these planets are too cold and too dark to support living systems.

MARS

Of all the planets of the solar system, Mars seems to have a range of environments most like that of the Earth; therefore it represents the best available target in the search for extraterrestrial life. Mainly as a result of astronomical observation, but also from data obtained from the Mariner IV flyby of 1965, many of the gross physical characteristics of that planet are reasonably well known.²⁵ The planet, which orbits the Sun at a mean distance of approximately 140 million miles, has a diameter approximately one-half that of the Earth and a mass one-tenth that of the Earth. Mars is inclined at an angle of approximately 25° perpendicular to its orbit (compared to an angle of 23.5° for the Earth); thus that planet experiences seasonal changes as it rotates about the Sun. Since the Martian period of rotation is also very similar to that of the Earth, being 24 hours and 37 minutes, day-night cycles are analogous to that on Earth.

The major surface features of the planet (Figure 4) include the white "polar" regions, now thought to be composed of frozen carbon dioxide and ice²⁶, and the so-called "bright" and "dark" areas. The polar caps are known to wax and wane with the seasons, diminishing in extent during the "summer" season in a particular hemisphere and then growing larger in the "winter" months. As the ice cap recedes with the approach of summer, there is also a *wave of darkening* in the hemisphere, during which the dark regions appear to become darker. In the past, this darkening has been ascribed by many authors to be the result of stimulation of plant growth, related to the presumed increase in available water. While the "darkening" phenomenon is generally accepted by astronomers, the biological explanation remains without experimental verification.



Figure 4. The planet Mars.

The results of determining the surface temperature by various techniques agree that the average surface temperature, across the planet, is about 50°C colder than that of the Earth. Maximum temperatures near the equator have been estimated to rise to as

high as about 30° C for a few hours per day during a Martian summer, but to fall to -70° to -80° C that same night in the same place. Daily temperature fluctuations in the range of 100° C are the general rule across the planet.

The atmosphere of Mars has been probed spectroscopically from balloons and from Earth-based telescopes and also by radio-occultation methods.²⁷ The total pressure of the atmosphere is probably close to 10 millibars, or about 1/100th of the total atmospheric pressure on Earth. Within the Martian atmosphere, two gasses have been identified, carbon dioxide and water, although neither of these has been quantitatively determined with any great accuracy. Carbon dioxide is thought to represent the major gaseous component of the atmosphere while water at best constitutes only a very minor constituent. The water vapor in the Martian atmosphere has been estimated to be of the order of 1/1000th the amount in the Earth's atmosphere. Repeated efforts to detect oxygen in the Martian atmosphere have failed, and, if it is present, oxygen must represent a minute fraction of that atmosphere. Whether or not nitrogen is present is not known, although it is presumed to be a constituent of that atmosphere.²⁵

The Mariner IV flyby not only yielded results of interest in connection with the structure and composition of the Martian atmosphere but also it collected data on the density of cosmic dust *en route* between Earth and Mars. It also made measurements of the magnetic fields around that planet. In the latter connection, the data indicate that little or no magnetic fields exist around Mars. Not only does this conclusion indicate the possibility of a different internal structure than that of the Earth but also the absence of a magnetic field may mean that the surface of the planet is subjected to considerably greater bombardment by charged particles from the Sun. The rarity of the Martian atmosphere, together with the absence of oxygen (and, therefore, ozone) in that atmosphere would also suggest that the planetary surface is subject to far more intense ultraviolet radiation than is the Earth, although the planet is often covered by a thin "blue haze," which may effectively absorb considerable ultraviolet radiation.²⁵

MARINER IV PHOTOGRAPHS

The Mariner IV, of course, had as its primary mission the photographic reconnaissance of the surface of the planet as it flew

past, roughly from pole to pole. Approximately one-half of 1% of the surface was photographed as the Mariner relayed twenty-one pictures to Earth, the closest approach to Mars being 6,118 miles.

Figure 5 is one of the most interesting of the pictures, the eleventh picture. This was taken from about 7,800 miles above the planet and covers an area of approximately 25,000 sq miles. As in other pictures of the series, numerous craters are visible over the surface of the planet; the largest one seen here is over 100 km in diameter. Of interest is the fact that the large crater seen in the center has been extensively eroded so that only about half of the

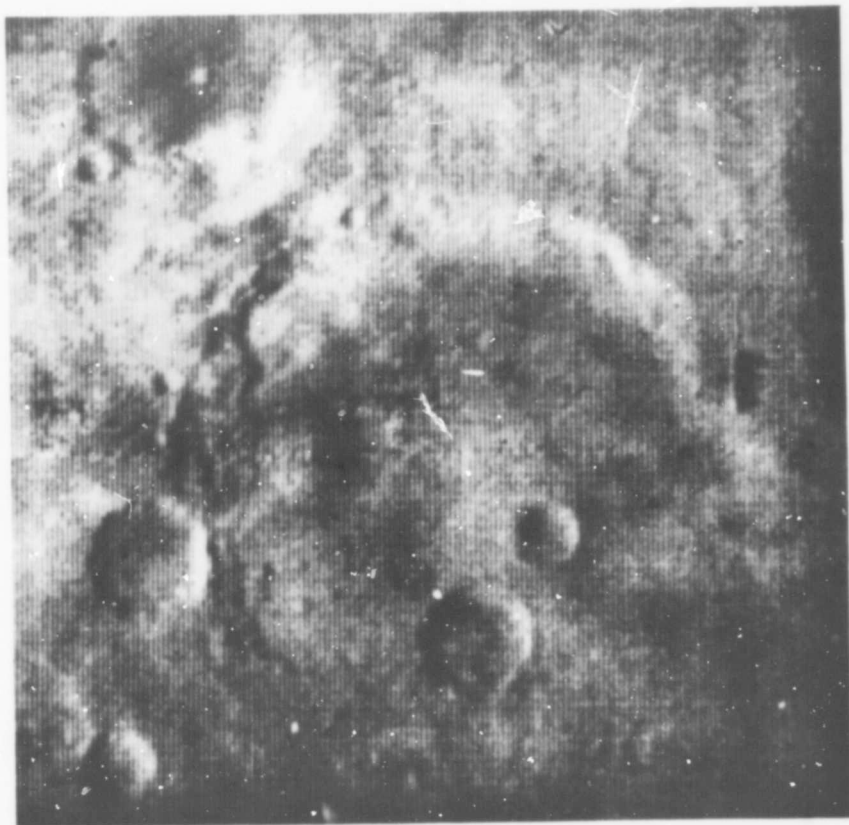


Figure 5. Mars surface features; Mariner IV picture No. 11.

crater wall is now visible. From this and from the other photographs of the series, it can be deduced that variations in surface elevation of the order of several thousand feet exist. We must anticipate, then, that over the surface of the planet large variations in local environments are possible as one goes from pole to equator and from low to high regions of the planet. On this basis²⁴, there should be a wide spectrum of ecological "niches," affording many permutations and combinations of environments for a Martian biota.

That the Mariner IV photographs did not detect life on the planet came as no surprise—even to the most enthusiastic exobiologists. As pointed out¹⁴, it has been virtually impossible to detect life on Earth from the many thousands of photographs taken of this planet by U.S. weather satellites. Mariner IV did not, and could not, settle the question of the presence of life on Mars. It did, however, corroborate or extend many of our estimates of the physical characteristics of that planet.

To recapitulate these properties, the present physical environment on Mars is very bleak. There is little or no oxygen; there are large temperature extremes; the average temperature is low; the atmosphere is very thin and contains extremely small quantities of water. There is probably no free water on the surface and probably a high flux of ultraviolet radiation at least some of the time. This is not, by terrestrial standards, a favorable environment for life!

ADAPTATIONS OF ORGANISMS

But, if the biologist is impressed by any overriding property of terrestrial life, it is by the adaptability of organisms. If life on Earth started in a primitive "soup," the first surviving organisms have evolved into an almost infinite number of environmental niches. Organisms, particularly microorganisms, are found to grow under such widely divergent conditions as in boiling springs of Yellowstone Park, where the temperatures are constant at about 96° C²⁵, and in perpetually frozen lakes of Siberia. Some are so fastidious that they cannot long survive outside the warm, moist, nutritive recesses of the animal body, while others, the autotrophic bacteria, live in the soil or in bodies of water using hydrogen or ammonia, or even iron or elemental sulphur, as

their energy sources. Some microorganisms, isolated from the deep sea floor (at 7,000 to 10,000 meters), die at ambient pressures at sea level and grow only at pressures matching their native habitat, 700 to 1000 atmospheres.³⁰ Others isolated from the sea—the halophilic bacteria—are also killed, unless they are cultivated in an environment containing 30% (by weight) of salts.

Modern astronomers^{14, 31} argue that there is evidence to support the contention that Mars may have been warmer at one time and that it contained a heavier atmosphere than it does at present. Under such conditions, the development of living forms, once started, could have proceeded under more favorable conditions than exist on Mars at present. Based on analogy with terrestrial life, then, it is not unreasonable to imagine that evolutionary adaptive processes on that planet could have selected organisms with increasing resistance to dehydration, to lower temperatures, to higher ultraviolet fluxes, etc., as Mars slowly and over long periods of time began to lose its atmosphere.

SIMULATION STUDIES

In attempts to assess the probabilities of life on Mars, several laboratory groups (e.g., Refs. 32-34) have placed terrestrial microorganisms, or terrestrial soil samples, into simulated Martian conditions. In a variety of "Mars boxes," such parameters as temperature, humidity, pressure, and atmospheric composition have been used singly and in combination. Needless to say, this approach is only as good as our information is about the planet itself. Nevertheless, the general findings have been that many microorganisms have survived for long periods under such conditions. For example, Packer *et al.*³⁴ found that organisms survived temperature cycles of -6.7°C to $+20^{\circ}\text{C}$ for several months, even when subjected to "simulated" Martian ultraviolet irradiation.

In one such investigation, Young and co-workers³³ subjected cultures of several bacteria to a Martian daily temperature regimen of 20 hours at -70°C and 4 hours at 25°C . Some of these cultures died while others, after a few cycles, began to increase in numbers (Figure 6). Other strains derived from such "adapted" cultures managed to grow very well under even more rigorous conditions in which they were kept at -70°C for all but 15 minutes of each day (Figure 7).

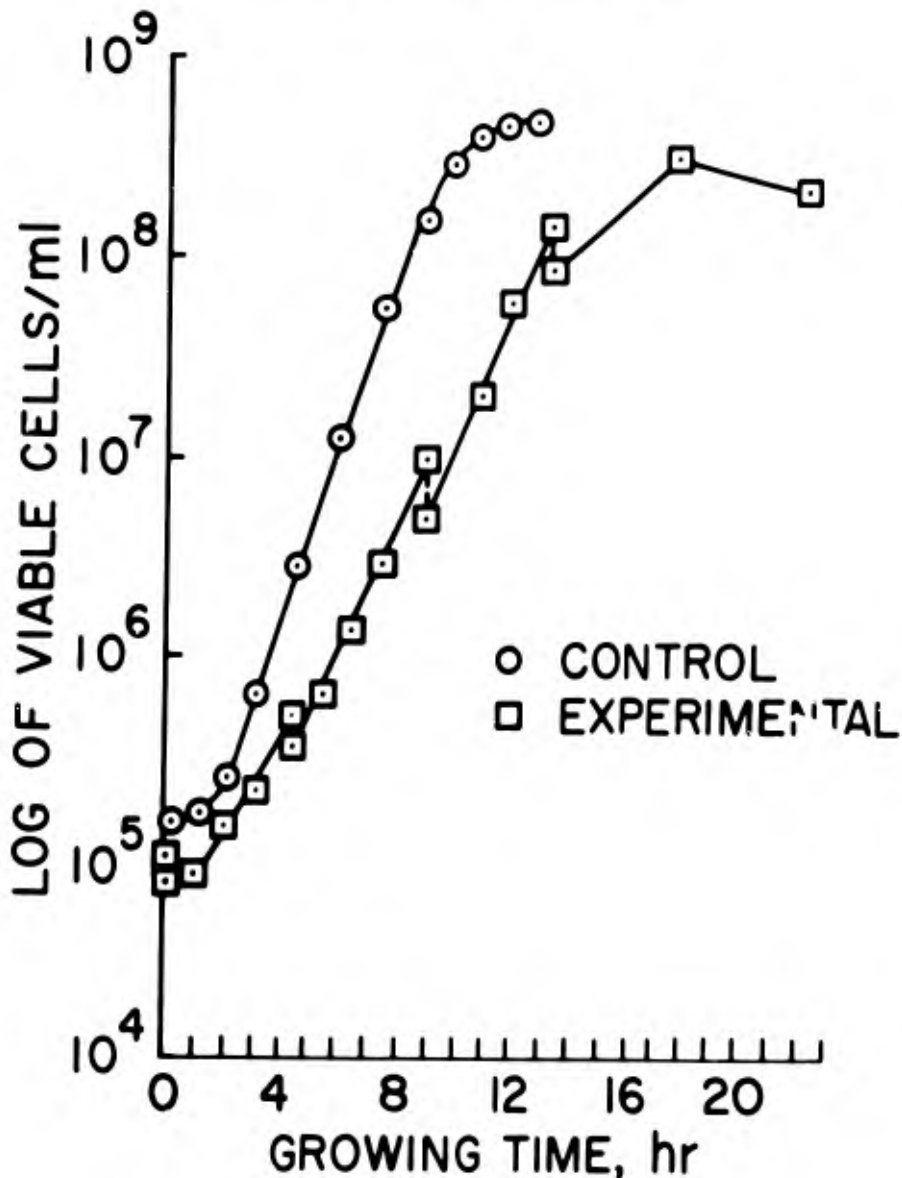


Figure 6. Growth of bacteria under simulated Martian temperature regime. In experimental culture, periods at -70° are not shown. During periods above freezing, both control and experimental cultures increased about a thousand-fold. (Courtesy of Dr. Richard S. Young.)

From what is known about the planet, taking all of the physical characteristics of Mars into account, it seems quite clear that the limiting factor for life on Mars is likely to be the unavailability of water. Temperature fluctuations, low atmospheric pressures, lack of oxygen, ultraviolet and other kinds of radiation are all

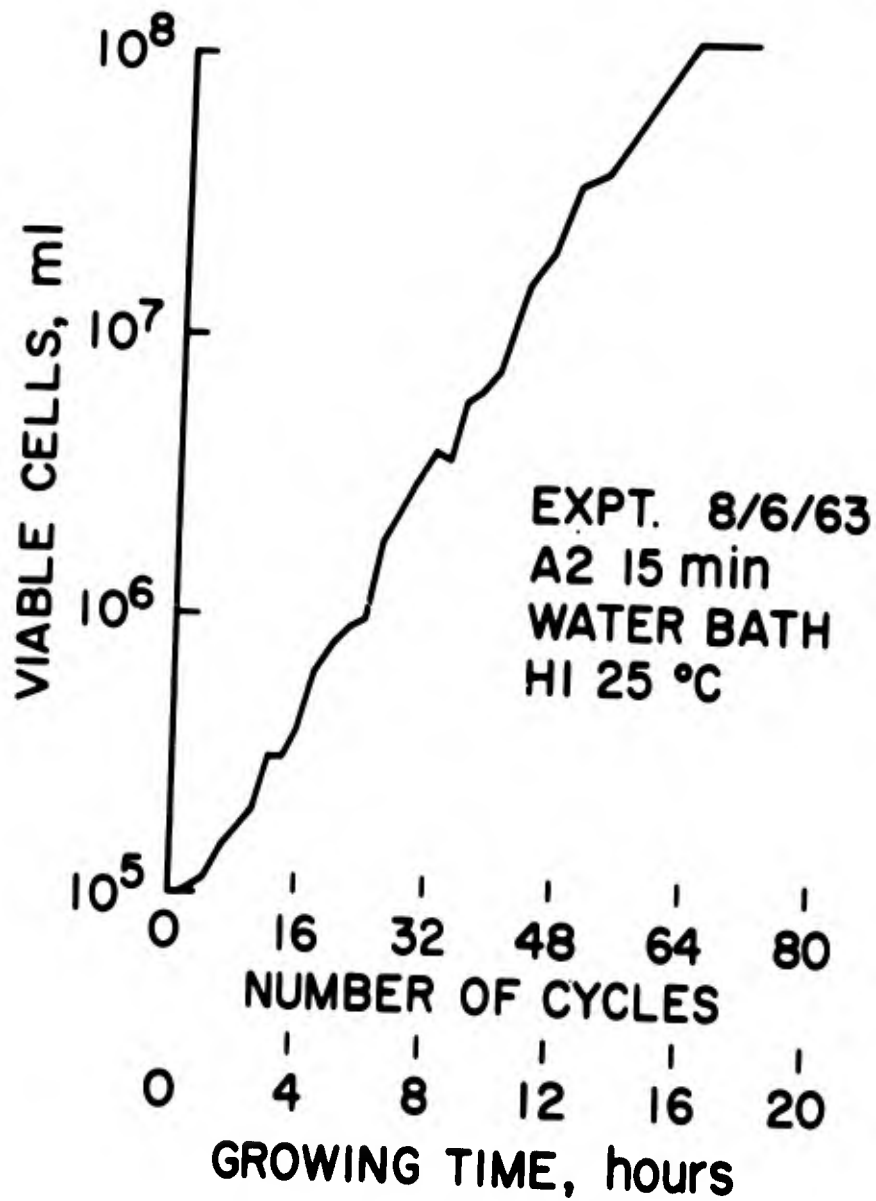


Figure 7. Growth of bacteria exposed to more severe Martian temperature regime. Here, as in Figure 6, only the periods above freezing are shown. Once again the numbers of viable cells have increased about a thousand-fold. (Courtesy Dr. Richard S. Young.)

secondary to this problem. It has been argued³⁵, however, that water in the form of ice may exist as a permafrost layer beneath the surface of the planet. Under that condition, local areas of

thermal activity might well make available liquid water at or close to the surface.²⁸

SOME PROBLEMS IN PLANNING "LIFE DETECTION" EXPERIMENTS

The considerations that lead us to conclude that Mars is currently the best target in the search for extraterrestrial life—the plausibility of the concept of an early genesis of life from methane, ammonia, and water, and the idea that, once formed, living organisms might have successfully adapted to changing conditions on that planet—do not, however, mean that Martian organisms would necessarily be chemically or morphologically analogous to terrestrial forms. Instead of l-amino acids, for example, Martian organisms may have proteins comprised of d-amino acids. Rather than the twenty amino acids common to terrestrial organisms, Martian proteins may be composed of fewer or more amino acids. Furthermore, these acids may not include any of the particular amino acids commonly found in terrestrial organisms. Perhaps, in order to filter out ultraviolet radiation and to conserve water, fats or waxes unfamiliar to us have become major constituents of Martian organisms. The point of these examples is that we really have no idea just how far apart the process of chemical evolution, let alone biological evolution, may have diverged on Mars and on the Earth.

This problem leads to difficulty in planning so-called "life-detection experiments." Chemical tests for compounds commonly found in terrestrial organisms (say, l-aspartic acid or D-glucose) are considered to be "high risk" determinations because a negative result would not be conclusive. As another example, all terrestrial organisms appear to rely on certain adenine nucleotides as their main energy carriers. And exquisitely specific and sensitive assay systems have been devised²⁶ to detect adenosine triphosphate (ATP), the major compound of this type. Suppose, however that Martian organisms use guanosine triphosphate (GTP), instead of ATP, in the same physiological role as we use ATP. Then, the very specificity of an ATP test would preclude our discovery of GTP (and possibly of life) on Mars!

On the other hand, less specific chemical tests (e.g., a test for the presence of organic carbon), while reducing some of the "risk" involved in such a test, have another kind of limitation. In this

case, a positive determination could only be *suggestive* of the presence of living organisms. As we have already seen (Figure 1), large numbers of organic compounds—some of great biological interest—can be formed without the intervention of biological catalysts; therefore the finding of organic matter would by no means constitute proof of a living system.

In considering what kinds of evidence might be most definitive in the search for extraterrestrial life, those that measured some end result of a complex concatenation of subprocesses would be most diagnostic. For example, if we were to land a microphone on the surface of Mars and were to hear, sometime later, a voice yelling, "Watch where you land these things next time!", we could be certain that no simple process, or series of processes, could have produced such a response. Only a remarkably intricate, well-structured series of processes (i.e., only a highly integrated system like a living being) could be the ultimate source of such a message.

Along these lines, several suggestions have been made to measure the growth of extraterrestrial organisms in some suitable medium.³⁶ Clearly, multiplication of an organism requires that all of its nutritive requirements be met; a large array of biochemical processes must be synchronized so that the final result is an increase in the number of organisms. Any single biosynthetic route, if not properly satisfied, could become the limiting factor and prevent an increase in numbers. Measurements to detect growth, then, would be quite convincing if they were positive. They have the further advantage³⁷ of amplification. That is, under appropriate circumstances, a small number of organisms that might otherwise escape detection (e.g., by organic analysis) after several rounds of multiplication could now readily be detected.

But the great dilemma in trying to devise a system to detect the growth of organisms in some largely unknown environment like Mars is that, in our ignorance of the detailed conditions of that environment, we might well attempt to "grow" these organisms under conditions that to them are very hostile. In the case of microorganisms on Mars, should we inoculate them into a medium containing D-glucose or should they be given some other energy source? Should they be incubated at 30° C? at pH 7? Indeed, should we even use an aqueous medium? Perhaps, like the halophilic bacteria that lyse when put into "physiological"

media (where water is much more readily available), Martian organisms would be killed.

Most of the uncertainties associated with trying to design a growth experiment in the search for extraterrestrial life apply also to assays for individual enzymes. It has been suggested³⁷ that, like certain enzymes present in terrestrial soils, Martian surface samples might contain enzymes that could be readily assayed. In principle, there would be certain advantages in testing for individual enzymes. Under optimal conditions, they have very high catalytic activity, generally many orders of magnitude higher than that of inorganic catalysts. Unlike tests for growth, which could be limited by a single factor such as the omission of some essential trace nutrient, enzymatic activity depends on only the availability of the substrate for the enzyme and occasionally of one or two appropriate cofactors. Another advantage is that certain enzymes, like phosphatases and urease³⁸ in terrestrial soils, may be released into the soil upon the death of soil organisms. These enzymes are then often found to be present in samples in which little or no *life* can be detected.

Although tests for enzymes on another planet require fewer assumptions than tests for growth, a number of uncertainties in this procedure still make it a "high risk" type of assay. As in the case of trying to estimate the optimal environment in which to grow extraterrestrial organisms, such factors as pH, temperature, metal-ion availability, water activity, and substrate concentration would essentially have to be assumed in conducting the assays.

There are even possible ambiguities in making inferences from pictures. We can, of course, imagine a picture sent back from Mars that contains one or more objects of such complexity and form that it would provide compelling evidence for the existence of life. But Martian organisms may well be relatively small, scraggly things—perhaps microorganisms too small to be seen except by microscopic methods. Ingenious techniques are being developed^{36, 39} for automated scanning of soil samples for the presence of microorganisms, and it might appear that, at the level of microphotographs, it should be easy to discriminate between the living and the nonliving. But it is a relatively common observation to mineralogists to find inorganic filaments, globules, and



Figure 8. Microspheres produced by heating a mixture of amino acids. Seen under oil immersion (970 \times). (Courtesy Dr. Sidney Fox.)

other *life-like* particles in their specimens of rocks, sediments, and meteorites (cf. Ref. 40).

That pictures may be misleading is also apparent in Figure 8. This is a microphotograph of some of the microspheres synthesized by Fox.⁴¹ This preparation was made by heating a mixture of amino acids and subsequently dissolving the polymerized material in water. As the saturated solution of "proteinoid" cools, millions of microspheres settle out of the solution. As is seen in this figure, the microspheres have obvious similarities to biological materials. Indeed, with no additional information but the picture, a team of biologists might well conclude that the sample photograph showed a large variety of different organisms.

APPROACHES TO THE PROBLEM

Only some of the more obvious difficulties have been presented in the section above. From them it is evident that any *single*

assay or experiment to detect life on Mars or some other planet has a high probability of leading to ambiguous conclusions, except by the greatest stroke of luck. Clearly, the question of determining the presence of life on another planet will probably require many different determinations, preferably on the same material, before reasonable conclusions can be drawn. *Since there is no single, simple definition of life; if in order to "define" life one has literally to describe it in terms of its properties (i.e., its chemistry, physiology, and morphology); if one has to define fully and carefully the gray area between the living and nonliving in order to arrive at a definition of life, it should not come as a surprise that, in engineering terms, no single, simple test will suffice.* Proof for the presence of life on another planet has to be deduced from many observations and tests. These each will yield only partial answers, but, by a series of approximations, we will get closer and closer to a definite conclusion—a process more or less in the nature of approaching the asymptote of a hyperbola.

Basically three schemes can be visualized for obtaining the necessary information. One is to automate a large multifunctional laboratory, which could perform chemical and other analyses and also carry out all the necessary sophisticated tests *in situ* on another planet. Such a concept⁴² visualizes a more or less complete computer-based laboratory capable of sampling an extra-terrestrial environment, making preliminary determinations and then, depending upon the results of these determinations, going on to a variety of tests and procedures, the results of all of which could then additively allow a reasonable inference as to the presence of living organisms. In the face of so much ignorance about the detailed environment of Mars and because of the technical breakthroughs that would have to be solved in order to carry out such a massive effort, it seems unlikely that this approach will be given serious consideration at this time.

The second scheme is less likely to appeal to the enthusiastic exobiologists who are eager to obtain the crucial answers in the shortest possible time and to those who would minimize the number of chances of contaminating the planet. In this view, experiments and analyses would begin with further probing of the Martian environment, its topography, atmosphere, surface composition, etc. Then, armed with more details about the physical properties of the planet, and after further detailed reconnaissance

and study of the planet, we could make a series of determinations, the results of each one being evaluated before designing the next flight until the number of unknowns about the planet is so reduced that what we now consider "high risk" experiments could be carried out with reasonable chances of success.

Finally, the third route would be to obtain samples of Mars and bring them back to Earth where they could be studied in detail with the full armamentarium of science brought to bear on the critical question of whether the samples contained living organisms. This scheme requires considerable engineering development and does not appear feasible in the near future.

SCIENTIFIC MOTIVATIONS

Despite the severe technical problems and the scientific ambiguities that have to be faced, it should be emphasized that biologists are profoundly interested in the search for extraterrestrial life. It now seems to be clear that, on Earth, living organisms, despite their vast diversity, are fundamentally similar. The chemistry, biochemistry, and the cellular structure, are essentially the same in a bacterium as they are in a baboon. The uniqueness of terrestrial life is seen, for example, when animal viruses can be propagated inside a common soil bacterium or when proteins of a bacterial virus can be synthesized by chloroplasts extracted from a green plant!⁴³ The conclusion seems inescapable that all terrestrial life is derived from some single ancestral type.

What is completely obscure, however, is whether—in the biota of some other planet—chemical, biochemical, physiological, morphological, or evolutionary processes similar to those for terrestrial organisms also occur. Are terrestrial organisms the way they are because of some chance accident of early evolution, or are there as yet undiscovered reasons for the *kinds* of chemistry and organization that we find in terrestrial living forms?

Clearly, if living organisms are found on another planet and if they are found to have properties uniquely different from organisms in the "terrestrial class," our concept of life would be significantly broadened. Indeed, even if life is not found elsewhere, particularly on planets where the environmental conditions are not thought to be inimical to living organisms, we would have much

to think about in trying to explain the absence of life there. New hypotheses about the origin of terrestrial life would almost certainly emerge in this case.

So, while we cannot make a very strong case for life on nearby Mars, and while there are obvious difficulties to be overcome in the search for life on that and other planets, there is so much to be learned about biology that the effort must be undertaken. Thus, many biologists feel that the search for extraterrestrial life is the most important scientific objective of the space program. For example, in a study by the Space Science Board of the National Academy of Sciences¹¹, this group concluded, "The biological exploration of Mars is a scientific undertaking of the greatest validity and significance. Its realization will be a milestone in the history of human achievement. Its importance and the consequences for biology justify the highest priority among all objectives in space science—indeed in the space program as a whole."

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XXVIII

Panel Discussion

"Where Do We Go From Here?"

PARTICIPANTS:

- Mr. Martin Goland, Southwest Research Institute
- Dr. Fritz Zwicky, California Institute of Technology
- Dr. Harold P. Klein, NASA-Ames Research Center
- Dr. Willard F. Libby, University of California
- Dr. Hubertus Strughold, Aerospace Medical Division
- Mr. Arthur C. Clarke, author
- Dr. Krafft A. Ehricke, Autonetics

MR. MARTIN GOLAND: The purpose of this session is to attempt to draw the ideas we have heard the past 4 days into some perspective. The planning of this meeting began some 2 years ago. At that time, we did not know how opportune and timely this particular session would be. Dr. Welsh pointed out to me that never before have the space activities of this nation, and of the world, been in so much need of optimistic men, of people who see the vision and the mission, and who state it forcefully. As we have heard many times in these past 4 days, many of our decision-makers seem to be overwhelmed by more immediate problems, and, in being overwhelmed, a pall has settled over many of our space activities. What is needed at this time, more than any other time, is a forceful statement of where we are and where we should go, and it is my hope that among those of you attending the meeting, equally important among the members of the press here, that the word will be spread throughout the country which can help

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to once again rejuvenate the affirmation of why we are in space, what we are attempting to do, and how important it is that we get on with the job.

Now, I am merely the traffic cop here. I am going to call on each of the panel members for a short 3-minute statement, and that 3-minute statement is intended to permit me to change from being a traffic cop to being a chef; from that point on, I will see that the pot keeps boiling, and I will attempt to see that it doesn't boil over. My first request will be for Dr. Zwicky to give us some of his thoughts.

DR. FRITZ ZWICKY: After I came back half-dead from Hiroshima in 1945, the Air Force insisted that I do not go on the first spaceflight. They said they preferred to see me killed on a more useful project. Nevertheless, as the vice-president of the International Academy of Astronautics, I am obligated in 1975 to establish LIL, the Lunar International Laboratory. Before I do that, I must, however, demand several things. Number one, that finally we do what we tried to start in 1948 with the first shots of artificial meteors (from a V-2), to plug a fast-reducing slug into the Moon and see from the reaction how deep crystal water exists in the rocks. If there is crystal water within easy reach, it will be immensely easier to live there. I then shall haul up a special solar furnace, with a magneto-hydrodynamic generator attached to it, which guarantees the production of all necessities of life from rocks on the moon.

Secondly, I must demand that, after 25 years of planning of certain sophisticated jet engines, like the terrapulse and the terraresonator, which I invented as director of research at Aerojet Engineering Corporation, we finally get ready to build and use them on the Earth and especially on the Moon. Otherwise, I am afraid the Russians might appear one of these days with one of my engines of this earth-boring type under the Pentagon.
[Laughter]

Furthermore, there are several other things which should be done and which we have proposed for a long time, among them laminar (whisker) metals of soap-bubble structure, with which you can make strong solid bodies lighter than air and then, before all, launchers for space missiles and vehicles which will work with

thermopropulsive efficiencies of up to 80 and 90%, instead of the 3% as the multistage rockets work now. I have a patent for such a launcher which will propel a single stage rocket into space. Then there is the idea of the interplanetary aeroduct circling the Earth, picking up free propellants (radicals and ions) and picking up enough speed to get away from Earth. In the near future, we shall also succeed in accelerating small slugs to speeds of 1000 km/sec with which we can achieve nuclear fusion in ordinary rocks. When we succeed in that, of course, we can use the same type of ultrafast slugs to shoot into the backside of the Sun, use say 1% of its mass in nuclear fusion reactions, propel the Sun up to 1000-km/sec velocity and get to Alpha Centauri within some twenty generations. [Laughter]

MR. GOLAND: I believe we can adjourn now; everything has been said.

DR. ZWICKY: Well, that's what you wanted, no?

MR. GOLAND: Yes, we certainly did.

DR. ZWICKY: And I intend, you see, to blackmail, to give a black eye to all the fellows who have lousy imaginations, and are lousy constructors. You see, you have to have people with good imagination and who are constructors, and that's what I am.

MR. GOLAND: Good. [Applause] I'll call next on Dr. Klein.

DR. HAROLD KLEIN: Well, I have no patents, and I guess I'm more of a plodder. I'll take a somewhat shorter view than Professor Zwicky. I certainly *can't* take a longer view! I am really worried that our national planetary program is coming, or has come, to a screeching halt. I'm worried about this; we have one 1969 flight approved to go to Mars and another one in the planning stage for 1971, and that's it. I'm worried that in the immediate future we will have to stoke up the furnace and build up some momentum before the whole game is lost; and I'm not talking about the race between the Soviet Union and the United States. I'm talking about the momentum that's been built up in this aerospace industry, not just the engineering momentum, but the scientific, which I consider to be more important. If we don't sustain or accelerate this momentum, scientists will turn

to other things. This is particularly true in biology. Biology is a field that today generally is not looking out into space for new horizons. Biologists are looking at the molecular or submolecular level. If we don't sustain the current interest of those biologists who are interested in the exploration of the planets, I'm afraid we'll lose the support of the biological community. So my plea would be for increased emphasis in a planetary exploration program, a real planetary exploration program. The Soviet Union probably will be sending two or three spacecraft to Mars and Venus at every opportunity. They've done that in the past, and we can expect that they will continue to do so in the future. It would be a shame, politically and scientifically, if the efforts of the United States slowed down to a trickle. [Applause]

MR. GOLAND: Thank you very much, Dr. Klein. I'll call now on Dr. Libby.

DR. WILLARD LIBBY: I'd like to echo Dr. Klein's sentiments in different words. It seems to me that our space program is our present frontier. Our country has always had a frontier; it is characteristic of this country that we live off of discovery, adventure, and new development. In order to continue this well-tested and profitable tradition, we have at this time to ask ourselves, how did we get into the fix that in order to fight in Viet Nam we have to give up the Moon race and the development of the space stations? I see so very clearly that the only way to fight in Viet Nam is to build a base on the Moon and to build a space station; for it is only from the strength that we get out of these efforts that we have any chance—any chance to do what we should do in our worldwide commitment. Now, it should worry all of us that we come to a state in this country that these truths, with which I'm sure most of the people here would agree, are not self-evident. It's something we must correct, to where our congressmen and our leadership understand the value of scientific technology. They mouth enough about it, but, when the chips come down, they are looking elsewhere.

We have our boys being drafted into Viet Nam, our graduate students who are going to be Ph.D.'s and teachers—that was a wise one! But even beyond that, I'd say, is the killing off of the space program, and I advisedly use the words "killing off." I think everyone who contributed to this decision should be examined for

his wisdom, for the reasons that he should be in Washington. Everyone! If you need a list, I'll give it to you.

We, however, shouldn't talk about politics because space isn't really a political question. I mean, you'll find Democrats and Republicans just about equally divided on this. It's a kind of malaise we have, where people just don't understand that this is important. I was for 20 years a main supporter of the atomic energy program and had a lot to do with its development. But I tell you, frankly I hate to say it, the atomic energy program isn't quite as new and shiny as it once was, and I'll tell you where the battle line is—it's with the young kids—how to get them interested in going into science and technology. This is one of the great values of the space program; it is so new, it is so fascinating to them, and it wins them over. This is the real battleground. The atomic program no longer has that, or it doesn't have it to the same degree. It has carried this load for many, many years, and it has kept this country technically strong. For the 5 years that I was an AEC Commissioner, we financed over 90% of the physical science research in this country. For 5 years! Now the AEC no longer has that role. NASA never picked it up; she let it slip into the NSF hands, and we're in a bad way, a very bad way. I think that we, all of us, and particularly those of you in the Air Force, who are charged with the defense of the nation, ought to fight like mad to save this space program. [Applause]

MR. GOLAND: Thank you very much, Dr. Libby. It's not my intention to inject any comments here, but may I say, sir, that those early days on the Atomic Energy Commission, when the program was put together by you architects, not even those of you involved in it could have foreseen the enormously rapid developments of nuclear energy completely outside of the military and defense areas to the point where it is now completely transforming the energy balance of the world. This also is a parallel we should take into account.

Dr. Strughold, may we hear from you?

DR. HUBERTUS STRUGHOLD: Ladies and gentlemen, I am particularly impressed by the theory of the decrease of the gravitational constant suggested by Dirac in 1937, and explained and discussed at our meeting by Professor Jordan of Hamburg. The

point in which I am interested in this respect is: what role does the resulting tendency of our planet to expand play in the occurrence of earthquakes. So far, only volcanic activity is mentioned, but I think behind the scene this tendency to expand plays an important role with regard to the extension of earthquakes.

Second, one of my specialties, or favorite topics, is the day-night cycle, the cycle of sleep and wakefulness, and activity. So far, we talk always about the circadian cycle, which is synchronized with the day and night cycle of Earth, of 24 hours. But it might be that this cycle can be replaced by a shorter cycle in space life, for instance, a cycle of 20 hours. The Russians have made some studies in this respect and have suggested that this might be the best cycle; there are certainly some possibilities for deviations from the norm. That a 20-hour cycle is acceptable for men has previously been suggested by Dr. N. Kleitman, based on his studies in caves in Kentucky, carried out some 20 years ago. I would like to mention another point. It has been suggested that electrosleep could be used in space. But I do not think that electrosleep could ever replace natural sleep.

My third point has to do with the effect of zero gravity. We know now the effects of zero gravity, and one of them is that it leads to decalcification of the bones. Recently, it has been reported that a new hormone has been found in the thyroid gland; it is called thyrocalcitonin which prevents decalcification of the bones. It might be that this will offer a new approach to counteract osteoporosis or decalcification of bone during prolonged zero gravity.

The next point has to do with international cooperation. It is very important that the metric system (or as it is called now, the international system based on the meter, liter, and kilogram) be introduced as fast as possible. Otherwise, there will never be international cooperation in the activities of space. [Applause]

MR. GOLAND: Thank you very much, Dr. Strughold. Now, I'll call on Mr. Clarke.

MR. ARTHUR C. CLARKE: Well, I thought I'd probably said enough already today, but I do see I have a few more points. Professor Strughold mentioned international cooperation. In the

long run, this is the way space travel will be done because in most kinds of space travel there won't be any individual nations any more. I suppose some of you may not have heard the news that the Russians have called for discussion with the United States on some kind of an agreement on antiballistic and missile systems. Perhaps, with any luck, this may be the beginning of a new era of cooperation. On the other hand, we may again have the situation which I have been trying to scare my American friends with for the last few months, that there will be Sputniks again in the very near future, possibly when the 10-megapound booster makes its first flights, whenever that is. Doubtless, there are people in this room who may know; I don't.

We have this ridiculous situation of stop-start space programs, sort of a program running as Bernal once said about wars: "Wars are run in gusts of emotion." This is the way the American space program started. And there is a danger that it may continue, perhaps like in a nuclear-pulsed jet rocket, gusts of intermittent explosions with perhaps inadequate damping between them and smoothing out between the explosions. Someone once said that the real problem always is, "What do we do next?" And the big problem in the American space program now is public relations, and this has been said several times already. Perhaps what we want is some dramatic and striking project which is of obvious, direct benefit to mankind. Now we had, of course, a dramatic and striking project in the Apollo program which I am sure generated a great deal of interest when it hopefully succeeds in a few years' time. But this is not of obvious, direct, practical value to the human race, except in a long-term plan scale. There are many people, though not enough, who know that there will be a tremendous U.N. conference this summer; certainly the biggest international conference on space will be held in about 2 weeks in Vienna. The main theme of this conference is the use of space technology, particularly for the developing nations.

I am very interested, as you know, in the applications of the communications satellites. The Hughes people tabulated that one can guide the educational satellite system and forecast directly from a stationary satellite station into every school. And the cost of the system, for twelve channels of color TV, for a country about the size of Mexico, worked out to be about \$1 per pupil per year. In other words, you could provide a global educational system which could drag the whole of the human race out of the Stone Age in

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a couple of generations, and it would probably cost something much less than a billion dollars a year for the whole Earth. Well, now, if someone had the guts to suggest that the United States should sponsor a program like this (this only occurred to me this morning; I haven't had time to think it out), what a dramatic effect such a thing would have! It would bring the space program back into public respect, and I would like to throw this suggestion out. That is all I have to say at the moment. [Applause]

MR. GOLAND: Thank you, sir. And last on the panel up here, I call on Dr. Ehricke.

DR. KRAFFT EHRICKE: Well, I think I would like to approach the concern we all have regarding the space program, still from a different standpoint. It is quite obvious that we have to have a more continuous and consistently supported space program. The contrast between the apparent consistency and purposefulness of the Soviet space program with the blowing hot and blowing cold type of approach in the American space program is apparent. Part of it is due to the fact that we do not have the proper mechanism to agree on a consistent set of goals, and, in part, it is due to the fact that we are afraid to plan too far ahead. Now, again, spectacular programs are necessary; they are the individual accelerators. But, underlying this has to be a balance which I advocate most urgently at this point. Space is scientifically important; it is in many other respects still more important for the nation as a whole, for the increasing population of the planet, and for the long-range evolution of the human species. Because of the close interrelations between exploration and utilization of space, we must strive toward maintaining a balance between these two processes. This seems to be terribly difficult. I have been involved in our space effort since its beginning. Yesterday, the word was space exploration and today the battle cry is space utilization. And each time one crowds out the other. This "either/or" attitude is not healthy; it is simply not rational. Both must go on simultaneously in a balanced form. Relative emphasis may vary in time to a skillfully-modulated degree, but it is not an "either/or" proposition. The past decade has brought the exploration of geospace, and with it the development of transportation systems and payloads needed to utilize this space region, in existing versions and in still more advanced configurations. I, personally, am very intrigued by the possibilities of resources monitoring and navigation control from space, in addition to communication. A

decade or more ago, very few people foresaw the manifold ways of utilizing geospace, Earth-space. Today, the need to expedite geospace utilization has become (and it's almost asinine) one of the arguments for slowing down lunar and especially planetary exploration. This argument demonstrates, incidentally, how successfully space, at least geospace, has been sold. It has become part of the general sphere of activity of our civilization, something that seemed to be virtually impossible and inconceivable in 1945-47 period. But, at the same time, this argument that we have to now utilize Earth-space and never you mind bothering with the Moon and the planets, strangely rejects the very evidence on which this argument rests. A decade or so from now, we can expect the practical usefulness and importance of lunar operations to our civilization to become recognized and be the "in" thing, and maybe then some will say, "We can't spend money flying anybody to the planets. You have to worry about the Moon only and utilize the Moon." We might as well recognize that exploration and utilization of space are two sides of the same process. Let us, therefore, plan appropriately and continue to develop the technology that will be needed for lunar and planetary operations while, at the same time, we advance the utilization of geospace as well.

Space, the business of experts, has finally, or is finally, on the verge of becoming the affair of humanity. There is no stopping this process. We will see it greatly accelerated in the 70's. Technoscientific world leadership and space operational capability will be inseparable. To a growing extent, both are necessary prerequisites of world-power status, and both are prerequisites for the great powers, eventually perhaps, to come to some form of cooperation. Therefore, we have to have a series of very mundane and very specific immediate goals, some of which I tried to summarize in my paper while, at the same time, we do some of this longer-range planning without being afraid to be called ridiculous because we are looking further than 10 or 15 years ahead.
[Applause]

DR. ZWICKY: I have asked several people whether they thought the space program was lagging. They said, "No, no!" And now, I hear from everybody that they are pessimistic. In fact, I have also been pessimistic because the program has not been thought through systematically. Some friends of mine and I have, therefore, thought of writing a comprehensive monograph

on the observations and experiments in medicine, biology, astronomy, physics, chemistry, psychology, engineering, and so on, which can *only* be done in space, not on the Earth. We think that not even the scientists have anywhere sufficient knowledge about the possibilities of space, not to speak about the general public, Congress, or the President and his advisers.

And secondly, we intend to emphasize those things which are done best on the Earth and not out there. Actually, there has been a lot of unfortunate nonsense: trying to do things in space which can be done on the Earth. So our monograph would ask, "What should be done on the Earth? What can be done best on high-flying balloons like John Strong's observations of Venus, which financially beat the scrutiny of this planet by Mariners by a tremendous margin?" And, finally, we would emphasize what the march into space does for the minds of men and the improvement of their relations.

A second point was mentioned by Dr. Libby, namely, that one really does not know who in Washington is responsible for decisions. For instance, we have had projects for 25 years now, and most of them were turned down by anonymous referees. I say, if a guy in Washington turns down some of these big projects three times, he should be forced to stand up in the open, and if he has been wrong three times, he should depart as a gentleman and resign. [Applause]

DR. KLEIN: I couldn't agree with Dr. Zwicky more that there is a good reason to write a book or a series of books on the scientific and utilitarian value of the space program. I think the big question, though, the reason it makes some of us pessimistic, is this: Who would buy the book? In 1966, the National Academy called on over fifty experts, including several Nobel laureates, to put together a book on the biological exploration of Mars. That book, so far, has sold only about a thousand copies!

DR. ZWICKY: I say that if eight of us sit together, you see, a physician, a biologist, an astronomer, an engineer, a psychologist, etc., and we write a book, this will sell millions of copies.

MR. GOLAND: The discussion has become a public relations discussion, or let's say a public education discussion.

DR. KLEIN: Well, I think education is our problem.

MR. GOLAND: Well, I throw this open for further comment. If the members of the panel would want to face the audience, I will take that course. Dr. Libby, do you have something more?

DR. LIBBY: Let's have some questions.

WILLIAM LEAVITT (Air Force Magazine): I'd like to ask a question about this public relations matter. I've been coming to San Antonio for a long time, and I've been delighted with the meetings, and the people, and the subject. I am personally very interested, as are many of the press corps, from a personal as well as professional point of view. But I honestly get the impression that even you, Dr. Zwicky, have perhaps a remote approach at the moment toward the problems that are now plaguing us on the planet and in our country, and it's a very hard job. I don't know how anybody, on this panel or anybody-else, even Arthur Clarke, can get through the importance of science and technology in a period that is so spectacularly dangerous for the United States right now, internally and externally.

DR. LIBBY: Well, I'd say, not all problems are to be solved by science and technology, and, certainly, the ghetto problem is one. However, we do have our input even in that; we make jobs, and that's one of the things that will help. But, certainly, we would be very presumptuous to assume that science and technology can solve all the terrible sociological problems that the world is faced with, particularly our country. But, because you have terribly difficult sociological problems, there is no reason for killing off technology. We have had abundant demonstration of its value, and I dare say that in the end, technology will contribute to the solution to the ghetto problem, even though it isn't the main part of the solution. So, people who say that we must give over the space program in order to solve the ghetto problem are missing a point. It's necessary to keep the space program going despite having to solve the ghetto problem. When I say the space program, I'm talking about our technological future, for the reason I said in my statement, it happens to be the frontier at this time. In a few years, it may be oceanology, or it may be something else, but, right now, it is the frontier. And giving it over is nothing less than giving over our technological development for several

years, and we cannot afford this, whatever your purposes would be. If it would be that giving up our technological future would help solve the ghetto problem, I might even be for it. I think it won't. It will destroy jobs; it won't help. We'll make jobs, and I don't see these as in very serious conflict. I think there are a number of things we could give over other than the space program.

MR. GOLAND: Dr. Zwicky, do you wish to comment?

DR. ZWICKY: I think the gentleman has a tremendous point, actually. And, of course, the point is against us, the scientists, who have been going their own way and very, very few of them have spent any serious and unselfish efforts for sociological problems. For instance, I am a trustee of a large foundation which established seventy-five villages for destitute children all over the world, and there are only three scientists among our 3000 people. Then take a problem like smog over Los Angeles. Two or three of us at Cal Tech have analysed the situation and made sure-fire constructive suggestions for the past 15 years, only to be ignored by our colleagues. We have also challenged our president, Dr. Du Bridge, the chancellor of U. C. and the president of U. S. C., to come forward and get together twenty independent experts to meet that problem. Well, they must have been running for their lives with flying coattails, because nothing was heard from them. We shall have to get the scientists away from just hunting promotions, medals, and Nobel prizes, and I-don't-know-what. We shall really have to do *science for mankind* as Cal Tech promises to do for the next \$85 million which they are trying to raise from friends. But if we only use this "science for mankind" as a catchword and do not really do it, I predict that coming generations will call ours that of the biggest hypocrisy. And, in fact, everything may then be lost, and, actually, there may not be any future generations to judge us.

DR. KLEIN: I should like to comment on that point, too. I think we have a "red-herring" situation here. Anybody who is frustrated about anything in the public domain compares his pet project to the space program and says why shouldn't we do this or that instead of going into space? I think this is false; it is erroneous. Most of our problems have been with us much longer than the space business. One could also make the argument that the \$15 to \$20 billion we Americans spend per year on cigarettes

should be used for public purposes. That's about five times the NASA budget. Nobody has said, "Why don't we do away with cigarettes and continue the space program?" Or, "Why don't we do away with the cigarette smoking and put all the funds into the ghetto problem?" The point is that America is big enough, strong enough, powerful enough, rich enough to do all these things—if it wants to. But it just isn't smart enough. Maybe that's the problem.

DR. STRUGHOLD: As you know, everything occurs in waves; this is a natural process. And we found this also in the space business. Before the first Sputnik, we had a kind of tidal wave of theoretical activities; when Sputnik appeared which caused everywhere some kind of "Sputnikosis" as I like to call it, this started the second wave. During this wave, fantastic progress was made as manifested in the many flights of the Mercury and Gemini program, as well as in the Russian program. At the present time, there is some kind of lull; but there will be another wave, which will be concentrated on the Moon. After this, say in the early 70's, there might be again a kind of loss, and this will be followed by a new wave, which will concentrate on the planet Mars. Rhythmicity is the rule in the universe and also in the human mind.

Sometimes one hears that the man on the street is against the space program. This is a complete mistake. If you talk with the man on the street about the cosmos, he knows more about it than let's say a scientist 100 years ago, and he's very much interested in this field. I like to express it in this way: The man on the street is no longer a man on the street in the old sense; he is more or less a man on the Milky Way. [Applause]

MR. GOLAND: Dr. Libby.

DR. LIBBY: I'd like to ask Dr. Strughold a technical question: What about solar flares for your Martian spaceship?

DR. STRUGHOLD: This is a very important point because if there is a proton outburst after a solar flare, the radiation dose can increase tremendously. We have to look for effective means of protection of the astronauts and especially for new ways to predict these violent solar flares.

DR. ZWICKY: I think this will be very simple, because, in a while, we'll capture planetoids like Icarus and be safe on their

dark side. We'll not use artificial spaceships, but some of the most easily available tiny cosmic bodies. Once we have that nuclear fission generator I mentioned before and which is activated by the impact of solid particles of 1000 km/sec speed on solid targets, we can kick our planetoid spaceships around at will.

DR. KLEIN: Just a word about that "man on the street" who really is sort of optimistic. During one of the Gemini flights, when the astronauts were doing a docking maneuver, I happened to be in California in a bar watching this on television and wondering what the "man on the street" next to me thought of this. The stranger next to me was quite on the way toward inebriation. As he watched the television screen, he suddenly slapped me on the back and said, "Well, what do you think of that?" I said, "What?" He said, "What those guys are doing." I said, "What do *you* think of it?", whereupon he answered, "I don't mind paying for this as long as they're successful!"

MR. GOLAND: I'm not at all unhappy we got onto a somewhat political-educational overtone because, although space is a scientific and engineering venture in this day and age, it is also a political and economic one. May I say, perhaps in defense of those people in Washington who are not here, that in the last analysis they do not make the decisions--we make them. And I know that Dr. Libby and many others here have dealt with the Congress, dealt with the Senate, and know that perhaps the most compelling drive in both of those groups is to reflect what the people want. If the space program is going to move ahead, we must want it to do so. Perhaps this group, through this meeting and other meetings, can get renewed inspiration and renewed dedication to go out and do the job we must do: to make the people of this country want the space program.

XXIX

Summary and Concluding Remarks

Dr. Roland B. Mitchell*

In the introduction to this volume, General Roadman has outlined the progress which has been made since we conducted the first symposium in this series. We can only speculate on the progress which will be made before we conduct the Fifth Symposium on Bioastronautics and the Exploration of Space. Certainly Colonel Schafer's next history and tribute to aerospace medicine pioneers will emphasize the place called "space." Dr. Welsh and the panel have expressed concern about the funding of future space programs, but I believe we can go along with those sanguine members of the group who state that a virile scientific program once started will continue to expand.

As Dr. Jordan pointed out, our world is shrinking in more ways than one and the universe will constantly expand. When the Fifth International is convened in 1972, it is likely that General Ferguson and Dr. Gilruth, or their counterparts, will deliver their papers from orbiting space stations. It will still be too early to expect that we can hold the symposium there, but the San Antonio Chamber of Commerce is put on notice that they should not expect to be hosts to the convening of the Sixth International Symposium on Bioastronautics and the Exploration of Space.

It is almost certain that we will arrive at the next symposium via at least supersonic transport as predicted by Dr. Bisplinghoff, and there will probably be some brave souls who will use General Ostrander's one-man propulsion devices to get from the Menger Hotel to the Convention Center in San Antonio, Texas.

*Chief, Biological Sciences Division, Directorate of Research and Development, Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas.

There is no doubt it will be a time of change.

By that time, we will know whether Dr. Urey is disappointed in finding the Moon is only a drop out from Earth or if, as he believes and hopes, it is an exciting first new piece of the Cosmos. This finding will give us impetus for pursuing the extraterrestrial life hypotheses of Drs. Imshenetsky, Klein and Ponnampertuma. It will also provide information for Dr. Zwicky to buttress his provocative statements.

It is not likely that we will yet be supervising the harvest on Dr. Ehrlicke's south forty acres on Venus, but we will have a good indication of the planetary mineral prospects which he predicted and Dr. Steinhoff suggested we utilize. We will also have concrete evidence of the possibilities of the new chemistry foretold by Dr. Libby.

Many of the benefits of the space program will then be evident in our every day life. Drs. Whipple, Strong, Evans and de Vaucouleurs have given us early indications of how such information is helping us to revolutionize our thinking about the universe. Dr. Hurtado, one of the space pioneers, has given us evidence of how this medical research on far-out space can be related to such mundane areas as leukemia, heart disease and fertility. Dr. Berry and Colonel Culver have shown us that man's abilities may be extended far beyond the limits which some pessimists placed on them. The work which has been pioneered by Dr. von Gierke, Colonel Swan and Lt. Colonel Clarke will continue to extend the capabilities of the astronauts but (like all their predecessors from Odysseus' crew down) despite the work of Dr. Vanderveen, they will be still complaining about the chow.

It will be a different age, an almost unbelievable age, in which (as Dr. Strighold pointed out) the man on the street will truly be the man of the Cosmos. Even his brilliant imagination and that of Arthur Clarke will have difficulty in predicting future achievements which will match those being made on a regular basis.

And I agree with the belief expressed by almost everyone that the search for truth in the area of space will result in greater insight to the problems which we face up close.

SUMMARY AND CONCLUDING REMARKS 611

Man once saw everything revolving around himself and he felt that he was the center of the universe.

He learned this was not true but he felt he was the only important thing in the universe.

This homocentric universe has been destroyed with a big bang.

Look at the photographs in Dr. Lowman's chapter and then think about yourself and the troubles which we are keenly experiencing on this blue planet.

This planet is beset with immediate problems—problems of a growing population, problems of more people living together, problems of perspective in an ever increasingly introspective world. Perhaps we have been looking at these problems through the wrong end of the telescope and our approaches have become narrower as our field of vision has decreased and so have the chances of reaching adequate solutions been similarly reduced.

The great benefit of the space age is that it gives us a new frame of reference. Let's take the long look at Earthly problems—the look from out there. Surely man will learn humility from a view of his home planet from space—for who can be proud to be a small time king on Earth when he looks on such majesty in the universe?

In a last minute printing change, the introductory material was re-numbered. This has caused the index citations for the Roman Numeral Section to be five numbers less than they are listed. For example, General Armstrong is listed as vi-vii. It should be xi-xii. General Benson is listed on vii and xii. The listing should be xii and xvii. This applies only to the introductory material as the main portion of the book is indexed correctly.

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