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HANDBOOK OF ENVIRONMENTAL ENGINEERING

E. C. Theiss H. Mileaf F. Egan

Technical Writing Service Division
McGRAW-HILL BOOK COMPANY, INC.
1961

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Environmental Division
Engineering Test Directorate
Deputy for Test and Support
Aeronautical Systems Division
Contract No. AF 33(616)-6252

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HANDBOOK OF ENVIRONMENTAL ENGINEERING

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Deputy for Test and Support
Aeronautical Systems Division

Air Force Systems Command, United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

The purpose of this book is to provide a convenient reference source in the field of environmental engineering. It contains up-to-date scientific and technical information and projects the state-of-the-art as far as possible into the future. The book is intended for use by personnel of the United States Air Force and supporting industry in the areas of: preliminary vehicle design; materials application; component, equipment and subsystem design and development; and reliability and environmental testing. A secondary purpose is to provide a general text for use by colleges and universities, with the hope that at least one course in environmental engineering will be given, and that eventually a separate degree will be offered in this field. It is also hoped that this book will inspire the development of texts in each of the various areas covered.

This report was sponsored by the Environmental Division, Engineering Test Directorate, Deputy for Test and Support, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio as Project No. 1305, Task No. 61565, under Contract No. AF33(616)-6252. The report was published November 1961 as ASD Technical Report TR 61-363.

ASDC

During the preparation of the report, E. C. Theiss, of the Environmental Division, Engineering Test Directorate, Deputy for Test and Support, Aeronautical Systems Division, acted as Chief Project Engineer, and Barry Mileaf of the Technical Writing Service Division, McGraw-Hill Book Company was the Project Manager.

For the Technical Writing Service Division, McGraw-Hill Book Company, D. Cohen, F. Egan and W. Maron acted as Associate Editors. Throughout the project, the editors had the active and helpful participation of project engineers G. F. Arthur, Upper Atmosphere Physicist, R. Hankey, Chief, Criteria Unit, and J. R. Millikon, Nuclear Engineering Physicist, each with the Environmental Division. In addition, the following personnel of Aeronautical Systems Division reviewed and commented on various portions of the handbook as it was developed: C. W. Douglas, W. S. Osborne, C. Versic, F. D. Monroe, C. A. Golueke, E. A. Tolle, F. R. Ebersbach, Dr. A. E. Prince, D. C. Kennard, C. W. Gerhardt, Dr. J. P. Allen, M. P. Ornstein, D. L. Earls, and C. E. Thomas.

Because of space limitations, it is impossible to credit by name all of the individuals and organizations that supplied material or information. However, in cases where the editors drew extensively on the work of an individual or organization, specific credit is given.

Of particular value was the material supplied by the following expert consultants: John Cammarata and John Regazzi, Arma Division; G. Chernowitz, American Power Jet Co.; K. A. Ehricke, Convair Astronautics; and Charles Eiwen, American Machine and Foundry Co. Mr. Ehricke supplied the initial data for the Mission Profile portions of Chapter 2, Mr. Eiwen the data for the Environmental Analysis section of Chapter 4, Mr. Chernowitz the data for the Operational Analysis section of Chapter 4 and the Test Procedures section of Chapter 6, and Messrs. Commarata and Regazzi the data for the Test Facilities section of Chapter 6.

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ABSTRACT

As flight vehicle systems and their ground support equipment become increasingly complex, the need for environmental engineering at all levels of system design becomes more acute. New environments are being encountered, and still newer ones will be coming more problematical as more advanced flight vehicles are developed. As a result, an understanding of environments and environmental engineering is mandatory for the design of reliable equipment.

This handbook presents to the designer the many facets of environmental engineering as applied to flight vehicle systems and their support equipment. The entire gamut of environments, both natural and induced, as well as their effects and methods of protecting against them are discussed in detail. The environments are considered both separately, and, where the present state of the art permits, in various combinations. The importance of an environmental and an operational analysis during preliminary system design are also covered.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

This report has been reviewed and is approved:

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PREFACE

For many years there has been an urgent need for an authoritative reference source in the field of Environmental Science. As the field has progressed from an undisciplined testing activity to a well documented science, a wealth of information on its various facets has been developed by both military and civilian activities. Unfortunately, this information has been contained in widely scattered reports, symposia and proceedings. The task of bringing this information together into one source has been under-taken and performed by this handbook. The Institute of Environmental Sciences has reviewed the material presented, and is certain that it will perform a much needed service in the field of Environmental Science.

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agency in the design and development of equipment exposed to cold weather. In the same year, a comprehensive program was initiated to determine world wide recorded maximum, minimum and mean ambient and enclosed compartment temperatures. The results showed a range from -65 F (-54 C) to 160 F (71.1 C).

During the winter months of 1942-43, the Cold Weather Testing Detachment and the Engineering Division combined efforts and ran extensive tests at Ladd Field. The test results showed that no combat or cargo aircraft in any stage of development would operate satisfactorily at temperatures below -25 F (-32 C). The same applied to auxiliary and accessory equipment, both aircraft and ground. All hydraulic systems were unsatisfactory, including shock struts, packings and hoses. It was common to find that hydraulic fluid leaked completely out of the systems. Aircraft and ground heaters were unsatisfactory, not only because of heat output, but also because of general operation. Oils and lubricants solidified and required considerable research, modification, standardization and improvement for cold weather operation. Screw jacks, ball and roller bearings, hinges, bushings and entire control systems locked or became intolerably difficult to operate. Improved hoppers and oil systems that would prevent engines from becoming oil-starved were needed. Oil coolers required extensive work to prevent bursting caused by passage of congealed oil into the cooler core when the engines started. Carburetor air thermometers were not provided in most aircraft, and oil drains were not accessible. It was impossible to keep batteries warm, and difficult to remove them. Ignition systems would not function at the low temperatures, and starter motors broke down.

During 1941 and 1942, an extensive program was conducted to determine the lubricant qualities necessary for cold weather operation, and to produce lubricants with these desired qualities. The new greases that resulted from this program were used in 1942 and 1943 by bearing manufacturers, grease producers and the Air Force for all bearings intended for Air Force use, as well as those already in Air Force stock. Thousands of bearings were washed and relubricated, and bearing problems were greatly reduced.

During 1943, the Cold Weather Testing Detachment was placed under the Proving Ground Command, and was made responsible for service testing of all standard aircraft and equipment. The Engineering Division of the Materiel Command was made responsible for experimental and developmental testing. The program that had begun in 1941 was accelerated at this time to insure that aircraft and equipment would operate satisfactorily in all areas and during all seasons.

In 1944, responsibilities were again reorganized. The Cold Weather Testing Detachment was shifted from the Proving Ground Command to the Materiel Command, which now had the complete responsibility for cold weather testing. However, the Proving Ground Command still controlled operational suitability tests. Test results now indicated that aircraft and equipment were suitable for operation to about -40 F (-40 C). The following areas, nevertheless, were still troublesome: carburetor air heat; oil systems; hydromatic propeller pitch and feathering controls; cabin and cockpit heating; deicing; oils and greases; surface control systems; seals; response time in hydraulically actuated systems; and low temperature starting.

Cold weather experiments were continued through the winter of 1946-47. The building specifications had been written, and plans were made for completion of a Climatic Hangar at Elgin Air Force Base, Valparaiso, Florida, after which Ladd Field would be used solely for field tests. Cold weather testing then became a part of the normal developmental cycle of aircraft systems. The aim was to provide satisfactory operation to -65 F (-54 C), as determined by the program conducted in 1941.

In 1951, the Air Research and Development Command was established, and the responsibility for cold weather testing was included in the responsibilities of the Directorate of Flight and All-Weather Testing group at Wright Air Development Center. About this time, cold weather testing, together with desert and special environmental testing, was established as an integral part of aircraft development. Since then, the All-Weather Testing Group has provided valuable information, and uncovered deficiencies in design and operation of aircraft and equipment intended for global operations.

Desert Tests

Just as the failure of the Germans on the Russian front indicated the need for cold-weather environmental engineering, the trouble that German General Rommel gave us in the Sahara Desert provided the reason for setting up a desert test program.

In the summers of 1942 and 1943, certain of the then currently used aircraft were inspected, modified, lubricated and instrumented and taken into the desert near Blythe, California to determine their operating capabilities under hot weather and sand and dust conditions. As a result of the 1943 desert test, it was determined that solutions were available to practically all of the high temperature problems encountered in the desert, and that much future work could be conducted in high temperature and sand and dust chambers then available to the Air Force. As a result, both the cold weather and desert test design and development programs were put into effect by Headquarters Air Force: the temperature range of -65 to +160 F (-54 to +71 C) was specified. These were established upon recommendations of the Engineering Division of Air Materiel Command.

Tropical Tests

Shortly after the initial desert test programs were completed, it was decided that other environments, primarily those associated with the range of -65 to +160 F (-54 to +71 C), should be investigated. Tropical tests were performed at France Field, Canal Zone during July, August and September of 1944. However, the test period was not long enough to make a thorough evaluation. It was found that some corrosion took place, but what was experienced was not too serious; however, it might have been more serious if the test period had been more extensive. In the case of armament, it was determined which lubricants were the most effective under hot, moist conditions. Adequate maintenance procedures were developed. Proper procedures for the care of bombing equipment were also evolved during these tests. There were some problems in photographic equipment, such as condensation on the cameras caused by the aircraft being cold soaked while at a high altitude and then dropping to a low altitude into moist, hot tropical air. As a result, heating covers were provided for cameras to prevent condensation. Also, the photographic equipment specifications were reviewed to provide for fungus resistance and fungistatic and fungicidal treated materials, for corrosion proofed metals and for packaging. It was found that some of the problems were caused by supply, since operating groups were not furnished with adequate information or properly packed material. In regard to power plant equipment, there were no problem areas that could be attributed to the tropical climate. The requirement for rust preventive hydraulic fluid was also determined to be unnecessary, since hydraulic systems were generally unaffected by tropical climate. In general, it was found that aircraft could operate satisfactorily under tropical conditions with no more than a normal amount of maintenance. However, the corrosion of aircraft structures was found to be a potentially important problem area.

While no serious problems were uncovered in the France Field, Canal Zone tests, it was believed advisable to gather more experience in tropical regions. For this reason, it was decided that a Tropical Science Mission be sent to the many tropical areas where the Air Force operates.

During 1945 and 1946, the Tropical Science Mission, headed by Lt. Colonel Nimmo C. Tyson, and staffed by many scientists and engineers, used a C-54G and studied Air Force operations and problems in:

Hawaiian Islands	Canton Islands
Fiji Islands	New Zealand
Australia	New Guinea
Admiralty Islands	Biak
Philippine Islands	Guam
Saipan	Iwo Jima
Japan	China
Indo-China	Siam
India	Africa
Brazil	West Indies

Generally, it was found that storage conditions were inadequate, and the majority of material stored out-of-doors was unserviceable. Electronic equipment was deteriorated beyond use or repair by either moisture and fungus, or both.

The mission made evident a definite need for research programs on the effects of weather, mycological and microbiological agents on equipment.

Outdoor Exposure Sites

Outdoor exposure sites were developed primarily to evaluate materials under actual conditions of weathering. Later, during World War II, such sites were used for exposing equipment that would have to undergo long periods of storage. These sites were also used in attempts to establish correlation between the actual environments encountered in nature and those simulated in laboratories. The names and locations of Government or Government sponsored exposure sites and other information pertinent to each are shown in Table 1-1.

Table 1-1. Outdoor Exposure Sites

Test Site	Operating agency	Date founded or established	Present status	Climate and atmospheric conditions	Remarks
Air Force or Air Force Contract					
Alaska Exposure Site, College, Alaska	University of Alaska, Geophysical Institute, College, Alaska; under Air Force contract	1947	Active	Arctic, Subarctic, Rural	

Table 1-1. Outdoor Exposure Sites (continued)

Test Site	Operating agency	Date founded or established	Present status	Climate and atmospheric conditions	Remarks
Joint Parachute Facility, Naval Air Station, El Centro, California	United States Air Force and Bureau of Aeronautics	1948	Active	Desert (Arid), Rural	Naval Parachute Facility until 1951. At that time became a joint Bu Aer-USAF operation.
New Mexico Actinic, Las Cruces, New Mexico	New Mexico College of Agricultural and Mechanic Arts, School of Engineering, State College, New Mexico; under Air Force contract	1947	Active	Desert (Arid), Rural	
South Florida Exposure Site, Embry Riddle Air Base, Coral Gables, Florida	United States Air Force	1938	Deactivated 1945	Subtropical, Rural, Seacoast	
Navy or Navy Contract					
Arctic Test Station, Point Barrow	United States Navy, Bureau of Yards and Docks	1948	Deactivated 1952	Arctic, Rural, Seacoast	
Fischers Island, Miami, Florida	United States Navy, Bureau of Aeronautics	1946	Active	Subtropical, Rural, Seacoast	Organic materials exposure site.
Hampton Roads Exposure Site, Naval Air Station, Norfolk, Virginia	United States Navy, Bureau of Aeronautics	1926	Deactivated 1958	Temperate, Urban, Seacoast	Operations moved to Wrightsville Beach, North Carolina.
Lakehurst Naval Air Station, Lakehurst, New Jersey	United States Navy, Bureau of Aeronautics	1957	Active	Temperate, Rural, Seacoast	
Naval Civil Engineering Research and Evaluation Laboratory, Port Hueneme, California	United States Navy, Bureau of Yards and Docks	1948	Active	Temperate, Rural, Seacoast	Originally established at Solomons, Maryland. Moved to Port Hueneme in 1952.
Naval Material Laboratory, Mare Island Naval Shipyard, San Francisco, California	United States Navy, Bureau of Ships	1941	Active	Temperate, Industrial, Seacoast	
Naval Material Laboratory, New York Naval Shipyard, Brooklyn, New York	United States Navy, Bureau of Ships	1945	Active	Temperate, Industrial, Seacoast	

Table 1-1. Outdoor Exposure Sites (continued)

Test Site	Operating agency	Date founded or established	Present status	Climate and atmospheric conditions	Remarks
Tropical Deterioration Test Station, Barro Colorado Island, Panama Canal Zone	University of Pennsylvania; under Office of Scientific Research and Development	June, 1944	Deactivated July, 1946	Tropical, Rural, Seacoast	OSRD contract transferred to Naval Research Laboratory December 1, 1945.
Tropical Exposure Station, Fort Sherman Military Reservation, Panama Canal Zone	Naval Research Laboratory	July, 1946	Deactivated 1953	Tropical, Rural, Seacoast	Fort Sherman Military Reservation closed by Army in 1953.
Tropical Exposure Site, Coco Solo, [illegible] Canal [illegible]	Naval Research Laboratory	1953	Active	Tropical, Rural, Seacoast Dense jungle, open clearing, seashore and huts available as sites.	Facilities available to all military agencies or their contractors. For information contact D.A. Alexander, Naval Research Laboratory, Washington 25, D.C.
Tropical Corrosion Laboratory, Panama Canal Zone	Naval Research Laboratory	1940	Active	Tropical, Urban, Seacoast. Sites at Colon, Miraflores, Fort Amador and Gatun Locks	Started by Panama Canal Company. Operation taken over by Naval Research Laboratory November 16, 1953.
Army or Army Contract					
Aberdeen Proving Ground, Aberdeen, Maryland	United States Army, Ordnance Corps	1919	Active	Temperate, Rural	Most exposure testing done since World War II.
Army Arctic and Mountain Training Center, Fort Greely, Alaska	United States Army, Engineering Corps	1949	Active	Arctic, Subarctic, Rural	
Chemical Corps Engineering Command, Army Chemical Center, Maryland	United States Army, Chemical Corps	Unavailable	Active	Temperature, Rural, Seacoast	
Engineer Research and Development Laboratory, Fort Belvoir, Virginia	United States Army, Engineering Corps	Designated ERDL on March 6, 1947	Active	Temperate, Rural	Prior to 1947 ERDL was Engineer Board Proving Ground.
First Arctic Test Center, Fort Churchill, Canada	United States Army, Engineering Corps	1948	Active	Arctic, Subarctic, Rural, Seacoast	Base used for various Arctic winter exercises (1945-1948) before permanent test center was established.

Test Site	Operating agency
Quartermaster Research and Engineering (QMR&E) Fort Lee, Virginia	United States Quartermaster
Yuma Test Station, Yuma, Arizona	United States
Other Government Agencies	-
Southern Regional Utilization Laboratory, New Orleans, Louisiana	Department culture
United States Forest Products Laboratory, Madison, Wisconsin	Department culture
Roof Exposure Racks, Washington 25, D.C.	National Bur Standards (C Section)

Environmental Testing of Aero
Equipmen

While efforts were applied t
plete aircraft in low and high te
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ture range of -65 to +160 F (-5
was known as the "Yellow Dot
of the requirement to mark
and later all equipment, with
show they were qualified. Th
proval and the test procedure
were described in Report, Ser
T-EESL-5, "Design of Aircra
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matic Conditions" dated 1 Nove
report was prepared by the C
Section of the Engineering Divis
Command). While this progra
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equipment for low and high te
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Procedures Governing the Appr
Equipment," dated August 1
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quired for qualification and ev
government or industry deve

Early in 1946, the Aero Accessories Labora-
tory, in coordination with other laboratories of
The Engineering Division, Air Materiel Com-
mand, prepared a specification for testing aero-
nautical equipment. This was AF Specification
41065, "Environmental Testing of Aeronautical
and Associated Equipment, General Specification
for" which was the first attempt to present environmental test pro-
cedures in one specification for easy adaptation
and application by equipment project engineers.
Because of the possible application of tech-
nical areas, the specification was transferred to
the Climatic Projects Section of the Engineering
Division and applied generally to the develop-
ment of all airborne equipment.

Although this original specification was pri-
marily for climatic test procedures, it was
found in the development tests that many of the
environments were also present, particularly
shock, acceleration and vibration. Test proce-
dure was then evolved for each of these envi-
ronments and included in AF Specification 41065.
It was the original intent in preparing 41065 to
have a specification with more than one test
procedure for several possible applications. It
was hoped that experience would eliminate the
unnecessary test procedures and help evolve
more advanced. This has not yet happened,

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The test requirements, such as temperature, were under review at intervals from 1946 through 1950, but investigation always proved them sound. The temperature requirements of -65 to +160 F (-54 to +71 C) were fairly applicable to all aircraft, because their operational speeds and altitudes were not high enough to induce any temperatures above 160 F (71 C) or below -65 F (-54 C). High temperatures were based primarily on compartment temperatures of the aircraft parked in the desert sun. In late 1949, however, it was found that there was a need to establish extreme temperature atmospheres for use in the design of airbreathing equipment, and in computing aircraft and engine performance within the ranges of temperatures. It was also noted that such atmospheres could serve as baselines for predicting future environmental requirements. This work was initiated by Wright Air Development Center and resulted in the development of hot, cold, polar and tropical atmospheres, which are described in a Wright Air Development Center Memorandum, Report WCSE 141, "Proposed Standard Cold and Hot Atmospheres for Aeronautical Design," dated 20 June 1952. They are also described in MIL-STD 210A, "Climatic Extremes for Military Equipment," and in the "Handbook of Geophysics," which was published by the Air Force Cambridge Research Center. The atmospheres are presently the responsibility of Air Force Cambridge Research Center.

The establishment of the atmospheres pointed out that altitude temperatures considerably below -65 F (-54 C) could be encountered. However, at that time it was realized that the aerodynamic heat rise from the speed of most aircraft, except possibly cargo aircraft, and the heat rise generated in the aircraft from heat producing equipment, would probably raise the internal temperatures high enough to eliminate any necessity to set low temperature requirements below -65 F. Experiments with a number of aircraft provided increments of heat rise for many categories of equipment, and were superimposed on the cold and hot atmospheres. It was established that the -65 F would be adequate at any air temperature. Meteorological surveys have been performed, though, which have shown that it is either too high or too low, depending on the choice of data. Many years' experience testing to this requirement have, on the other hand, pointed out that it is realistic.

The high-temperature requirement, however, became unrealistic. In March of 1954, a study of future temperature requirements extrapolated to 1965 found that the high-temperature requirement for such vehicles as fighters, bombers and missiles could no longer be established on the basis of high-temperature requirements on the ground. The extreme speed of future vehicles was expected to produce an aerodynamic heat rise considerably above 160 F (71 C). That estimate of future temperature requirements is presented roughly in Table 1-2. It should be noted that insulation in the vehicle does have an effect on the temperature, and this particular problem will be treated more completely later in this handbook.

Combined Environmental Testing

In the period prior to 1954, there were some attempts made to perform environmental tests in combination. These, however, were fairly simple combinations, such as temperature-altitude, high temperature-humidity, low temperature-vibration and the like. In early 1954, Wright Air Development Center initiated a requirement to investigate the feasibility of combined environmental testing for qualification and equipment evaluation purposes. It was intended to investigate more complex combinations of environments than simple combinations of two, and to use the mission profile approach. It was expected that many combinations of both natural and induced environments could be evolved, and that one combination might be produced that would have the worst set of interacting environments. The work was performed by American Power Jet Company, Ridgefield, New Jersey, and was completed in September 1956. This gave impetus to combined environmental testing. Combinations were evolved from a mission profile approach, and the prospects of simulating such combinations were analyzed. No effort was made to determine the confidence of such environmental tests.

Table 1-2. Predicted Future Temperatures

Class	Type of equipment	Temperature step, F (C)		
		1955	1960	1965
A	Equipment directly exposed to ram air, or external structure	284 (140)	500 (260)	690 (371)
B	Equipment in isolated areas and uncooled compartments protected to some extent by insulation	252 (122)	350 (177)	500 (260)
C	Equipment protected by cooling system	160 (71)	225 (108)	300 (149)
D	Electronic equipment	230 (110)	300 (149)	375 (191)

In May of 1957, the Development Design Branch of the Aerial Reconnaissance Laboratory of Wright Air Development Center initiated an experimental dynamic analyzer. A feasibility full-scale model was built in the fall of 1957. This facility integrated combined environments with the functional aspects of the equipment being evaluated. For instance, photographic equipment could be exposed to a combined environment of temperature, vibration, roll, pitch, and yaw, while photographing a simulated moving target. This new concept of testing practically eliminated the need for flight evaluation testing of aerial reconnaissance systems. The design of a new space oriented dynamic analyzer has been completed and the analyzer is being built at Aeronautical Systems Division (formerly Wright Air Development Division) under the cognizance of the Design Techniques and Analysis Section of the Environmental Division, Engineering Test Directorate, Deputy for Test and Support. Another state-of-the-art advancement in combined environment testing is the test facility assembled early in 1958 by the Aero-Accessories Laboratory under the authority of the Air Research and Development Command's Ballistic Missile Division. This is the first large test facility where, to the combined environments of sustained and vibratory accelerations, other environmental parameters, such as extreme temperatures, altitude, and noise, may be added either singly or in combination.

Around October 1958, funds were provided to conduct additional combined environmental tests. A contract was let to United States Testing Company, Hoboken, New Jersey for study and test work to determine the confidence level of combined environmental tests in relation to single environmental tests for various categories of equipment. It is anticipated that more concentrated effort will be expended along these lines in the future. The single environmental test will probably still play an important part in the research and development phase of materials, components, equipments, and subsystems, and combined environment testing will play a most important role in qualification and reliability testing.

Hyper Environments

In early 1955, consideration was given in the Environmental Criteria Branch of Wright Air Development Center to the need for reproducing hyper environments. In April 1956, work was initiated on a preliminary investigation of hyper environments and methods of simulation. It was intended that this work should investigate environments occurring in flight vehicles at altitudes above 75,000 feet, define these environments, anticipate effects, develop simulation methods, and evolve a hyper environmental test facility. The work, performed by RCA, Camden, New Jersey, was completed by January 1958; the first report, which described hyper environments and their effects, was available by July 1957.

The launching of Russian and American satellites emphasized the possibility of space exploration and focused attention on a need for more specific knowledge of the space environments.

Nuclear Environments

Nuclear environments became important with the initiation of the nuclear bomber in August 1954. The environments provided by the reactor spectrum, consisting primarily of neutron and gamma radiation, could affect man as well as materials and equipment. Nuclear radiation was recognized as an environment superimposed upon the other environments, with possible interacting, reinforcing and inhibiting effects. At that time, work was already going on to build reactors and hot cells to study the effects of nuclear radiation. Several industries have been engaged in the nuclear propulsion program to build reactors. However, the one being built at Wright Air Development Division is one of the first to recognize the need for simulation of other environments in combination with radiation. A study was made to determine the interacting, reinforcing and inhibiting environments that may be encountered in future nuclear powered vehicles. Many of the results of the study were incorporated into the reactor test cells being built at Wright Air Development Division.

Future Trends

Considerable research is still required before an ideal environmental test procedure will be evolved. The interacting and inhibiting effects of both natural and induced environments and their combinations must be analyzed and reviewed, and from this point we must evolve test procedures to cover both materials and various categories of equipment.

Laboratory testing, as currently practiced, suffers from the problem of inadequate correlation between the effects of test environments and the effects of actual service environments. To keep testing time within practical limits, a laboratory test very often requires increased severity of an environment over that which would be encountered in actual service. This results in accelerated deterioration effects. The confidence of such a test depends upon adequate correlation of the time duration and severity of the test environment with the expected time duration and severity of the actual service environment. To improve correlation, work is currently being conducted in the development of standard environmental test specimens. These are devices that react irreversibly in a known and predictable manner when subjected to a specific environment. It is expected that in the future these standard test specimens will permit the deterioration effects of environmental exposure to be more exactly evaluated in terms of duration and intensity.

In the past, test procedures were evolved by attrition and experience, plus some research and experimentation. In the future, however, both hyper and combined environmental test procedures will be founded primarily on scientific principles. For this reason, environmental engineering has become a separate field of scientific endeavor. It is interesting to note that a program that began with such elementary requirements as cold weather operation, in which practically anybody could either wait for, travel to, or reproduce the environment by the use of a wooden box and some dry ice, has reached a point of complexity that involves a nuclear reactor with environmental chambers, as well as advanced hyper environmental combined facilities. Figure 1-1 gives an indication of the environmental program of the Air Force. Interest is in both the conventional and hyper environments, single and combined, and in establishing requirements, test procedures and new facilities in all technical areas. Considerable work has been done with the single conventional environments, but there has been little work done in conventional combined environments, primarily in the equipment area. In the hyper environment area, only a small amount of work has been completed, but much is still in process. Single hyper environments will have to be understood, but combinations can also be studied. Hence, the transition to combined hyper environments will not proceed as slowly as it did in the conventional environmental area.

Environmental engineering is also important in the development of satellites and space vehicles. Environments near the Earth and on the Moon, Mars, Venus, and other planets, as well as in interplanetary space, must be understood. The atmosphere of the planets and their weather must be determined. These environments must then be expressed as design requirements, and the expression must be simple and easily understood. Then, facilities and test procedures for components, equipment, subsystems and flight vehicles must be evolved.

The ultimate need, of course, is a facility and test procedure of some environmental combination that would provide in one facility and in one test procedure actions of all the integrated environments. This would allow evaluation of systems much more rapidly than we are able to accomplish today.

Figures 1-2 and 1-3 show the progress of environmental engineering, both past and projected. Figure 1-2 indicates the relative advances made in the various areas of environmental engineering, as well as the time at which the different environments became important. Figure 1-3 shows how the types and severity of environments encountered have changed, and how they will change even more in the future, as new and improved flight vehicle systems are developed.

In summary, environmental engineering has evolved from a service engineering problem into

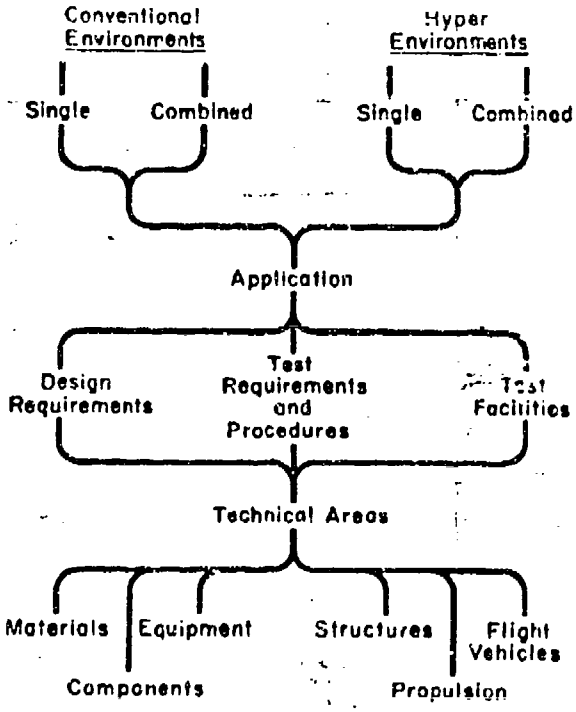


Fig. 1-1. Air Force environmental program.

a complex research program. In reality, the history of environmental engineering is only now beginning.

GENERAL PHILOSOPHY

The Air Force is interested in obtaining high quality, reliable flight vehicles and support equipment at the lowest possible cost. This is a challenge facing the Air Force and the entire industry supplying the Air Force. As flight vehicle missions become more complex, so do the environments, the vehicles, and the job of attaining operational reliability. While the job of attaining operational reliability is not entirely environmental engineering in nature, an increasingly large portion of it is. In the strict sense of the word, even structure and wind tunnel tests are environmental in nature, though environmental engineering has avoided reference to these tests as environmental. The greatest application of environmental engineering is in the development and qualification of materials, components and equipment that can withstand the environments.

In former years, the Air Force evaluated materials, components, and equipment, both for government- and industry-developed items. This was done because performance and requirements were more generally applicable. With the coming of jet aircraft, missiles,

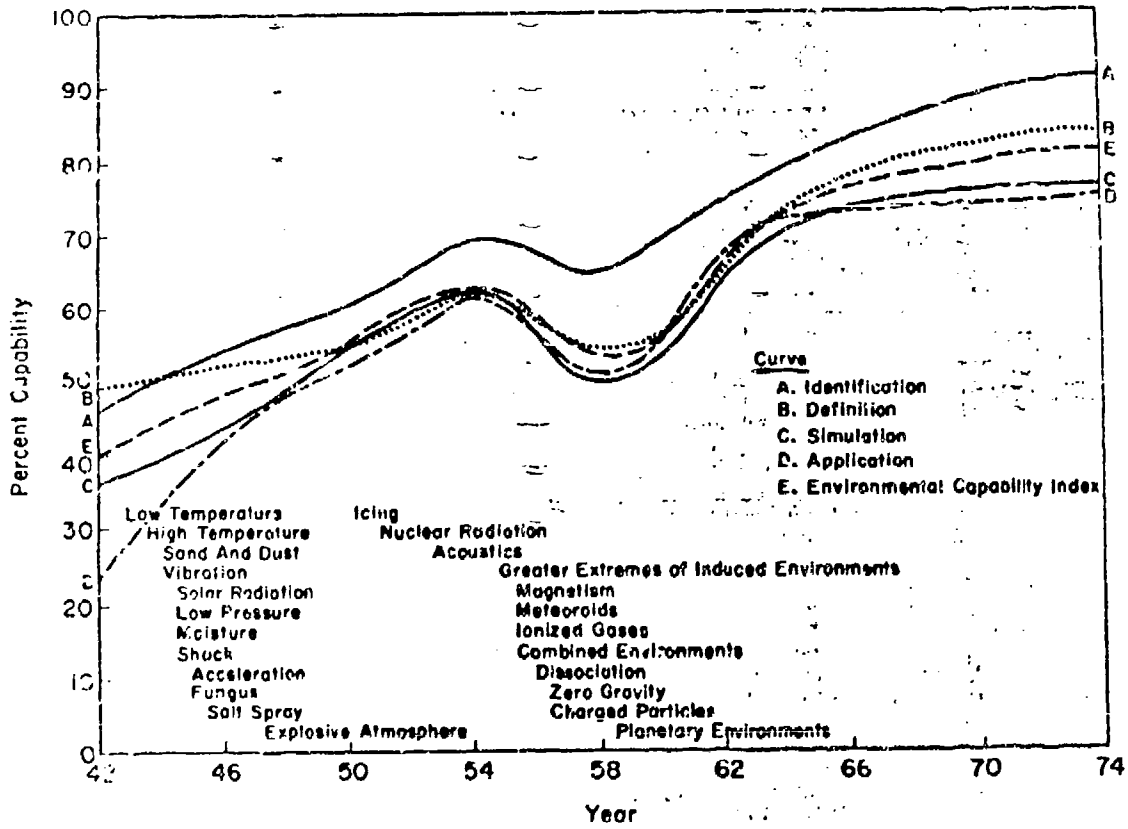


Fig. 1-2. Capability trends in environmental engineering.

and their associated complexities, requirements and performance had to be tailored to specific vehicles. With the advanced vehicles of the future, complexity will still be increasing, as will the variety of environments and the problems of attaining operational reliability. The Air Force, then, will still be evaluating new materials and components, but the bulk of qualifying and developing new equipment will fall on the shoulders of industry. In the equipment area, the Air Force will continue to initiate development of new types and concepts, and may test some of the concepts; however, the Air Force will not engage to any great extent directly in the qualification and testing of equipment to be placed in production.

Environmental engineering is actually a series of requirements that are applied in all phases of system development, from the initial choice of materials, to the ultimate system integration.

Materials Evaluation

New materials are constantly being evaluated for particular properties needed in the future, and under environments expected for future applications. Extreme temperatures, nuclear radiation, short wavelength radiation and vacuum are a few of the environments that must be considered in materials evaluation.

Electronic Components Evaluation

Electronic components are developed for a variety of uses and must be tested for operation under all possible environments. They are given qualification tests and reliability tests, both of which include environmental testing.

Equipment Evaluation and Qualification

In the development of equipment, many engineering tests are run under environmental conditions that are necessary to proper development of the item. This is generally completed with the qualification test, when and if the item is to go into production. This latter test is also predominantly environmental in nature, primarily because of the operational characteristics. The project engineer sets up the test program and, in general, selects tests from a variety of environmental test specifications.

Equipment Reliability

Sometime near the end of the development phase, an item of equipment is required to undergo reliability tests. These tests are run under specified environmental conditions, which do not necessarily represent the extreme operational environment. These tests are run on "lots" of items to assure a statistical population and a probability that the equipment will have an acceptable mean-time-between-failure rate.

Production Sampling Tests (Quality Control)

During production, it is customary to use statistical sampling (one out of ten, one out of fifty, or some other figure established by quality control) to ascertain that an item still meets the rigorous performance and design requirements of the original qualified item. These sampling tests include some environmental tests.

Category III Flight Test

The first end item test of a complete weapon system is the category III flight test, which includes cold weather field tests, desert tests, icing tests, adverse flying, special high performance tests and operational suitability tests.

Operational Use

The real test is operational use of the flight vehicle. Aircraft that are recoverable give much information, and allow corrective action through the use of an unsatisfactory report and service engineering channels. This is not the case with unmanned vehicles. The operational phase, particularly in IRBM's, ICBM's and satellites, is essentially a highly instrumented test flight. The IRBM and ICBM will be operational for only a short period, and no corrective action can be instituted on those launched. Nevertheless, telemetered data will be available for application on successive vehicles. The satellite and space vehicle will, for a long time to come, be essentially a test vehicle. Actually, they are environmental research vehicles.

BIBLIOGRAPHY

1. AMC Cold Weather Tests, Winter of 1945-1946, AAF Technical Report 5503, AMC, Wright-Patterson Air Force Base, Dayton, Ohio, 24 June 1946.

2. AMC Cold Weather Tests, Winter of 1946-1947, AF Technical Report 5650, AMC, Wright-Patterson Air Force Base, Ohio, 25 November 1947.

3. ATSC Cold Weather Tests, Winter of 1944-1945, AAF Technical Report 5230, ATSC, Wright-Patterson Air Force Base, Dayton, Ohio, 31 May 1945.

4. Cold Weather Test Detachment, Winter of 1942-1943, Volume I, USAAC, Wright-Patterson Air Force Base, Dayton, Ohio.

5. Cold Weather Test Detachment, Winter of 1942-1943, Volume II, USAAC, Wright-Patterson Air Force Base, Dayton, Ohio.

6. Desert Tests at Blythe, California, June and July 1943, AAF Memorandum Report, Materiel Center, Wright-Patterson Air Force Base, Dayton, Ohio, 9 September 1943.

7. Feasibility of Combined-Environment Testing, WADC TR 56-546, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Dayton, Ohio, September 1956.

8. McGee, John and Chester Polak, The Development of Standard Environmental Test Specimens, WADC TR 59-697, Inland Testing Laboratories Division, Contract No. AF 33(616)-6116, ASD, Air Research and Development Command, Wright-Patterson Air Force Base, Ohio, October 1959.

9. Preliminary Investigation of Hyper Environments and Methods of Simulation, WADC TR 57-456, "Part I--Survey of the Environmental Field," July 1957, "Part II--Simulation Methods," November 1957, "Part III--Facility," U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, January 1958.

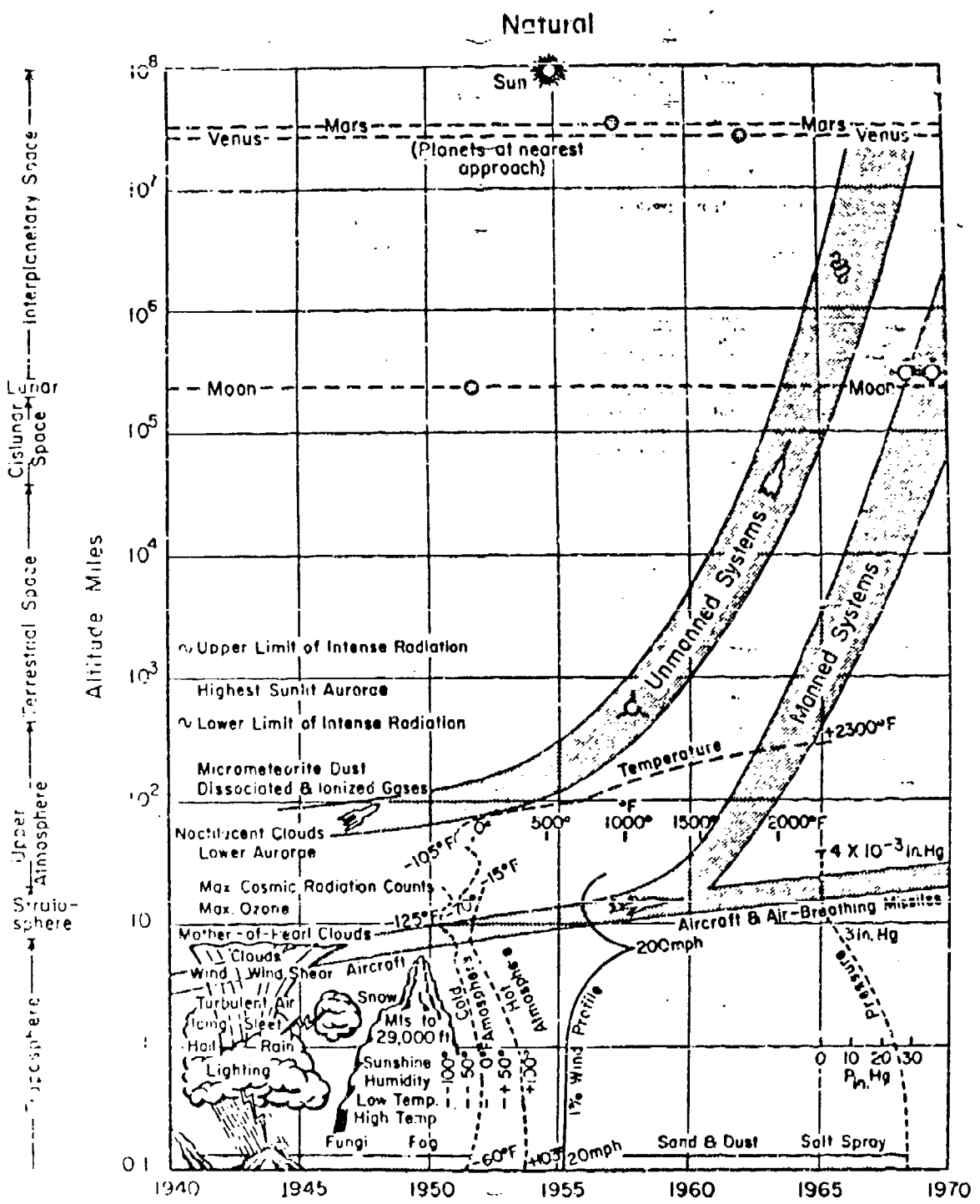
10. Proposed Standard Cold and Hot Atmospheres for Aeronautical Design, WADC TM Report WCSE 141, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Dayton, Ohio, 20 June 1952.

11. Report on Desert Tests of Airplane Structures, June 18 to July 14, AAF Memorandum Report, Materiel Center, Wright-Patterson Air Force Base, Dayton, Ohio, 5 August 1942.

12. Tropical Deterioration of Air Force Material and Equipment, AAF Memorandum Report, ATSC, Wright-Patterson Air Force Base, Dayton, Ohio, 15 May 1946.

13. Tropic Tests at France Field, Canal Zone, July, August and September 1944, AAF Memorandum Report, ATSC, Wright-Patterson Air Force Base, Dayton, Ohio, 1 October 1944.

14. Tropical Test of Armament Equipment, AAF Memorandum Report, ATSC, Wright-Patterson Air Force Base, Dayton, Ohio, 15 March 1945.


Natural
Altitude Miles
Interplanetary Space
Cislunar Space
Terrestrial Space
Upper Atmosphere
Stratosphere
Troposphere
Sun
Mars
Venus
(Planets at nearest approach)
Moon
Upper Limit of Intense Radiation
Highest Sunlit Aurorae
Lower Limit of Intense Radiation
Micrometeorite Dust
Dissociated & Ionized Gases
Noctilucent Clouds
Lower Aurorae
Max Cosmic Radiation Counts
Max. Ozone
Mother-of-Pearl Clouds
Clouds
Wind Shear
Aircraft
Turbulent Air
Icing
Sleet
Hail
Rain
Lightning
Snow
Mts to 29,000 ft
Sunshine
Humidity
Low Temp.
High Temp
Fungi
Fog
Cold Atmosphere
Hot Atmosphere
1% Wind Profile
Unmanned Systems
Manned Systems
Temperature
2300°F
4 X 10⁻³ in.Hg
Aircraft & Air-Breathing Missiles
200mph
3 in. Hg
Pressure
Pm, Hg
Sand & Dust
Salt Spray
20mph
1940
1945
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1960
1965
1970

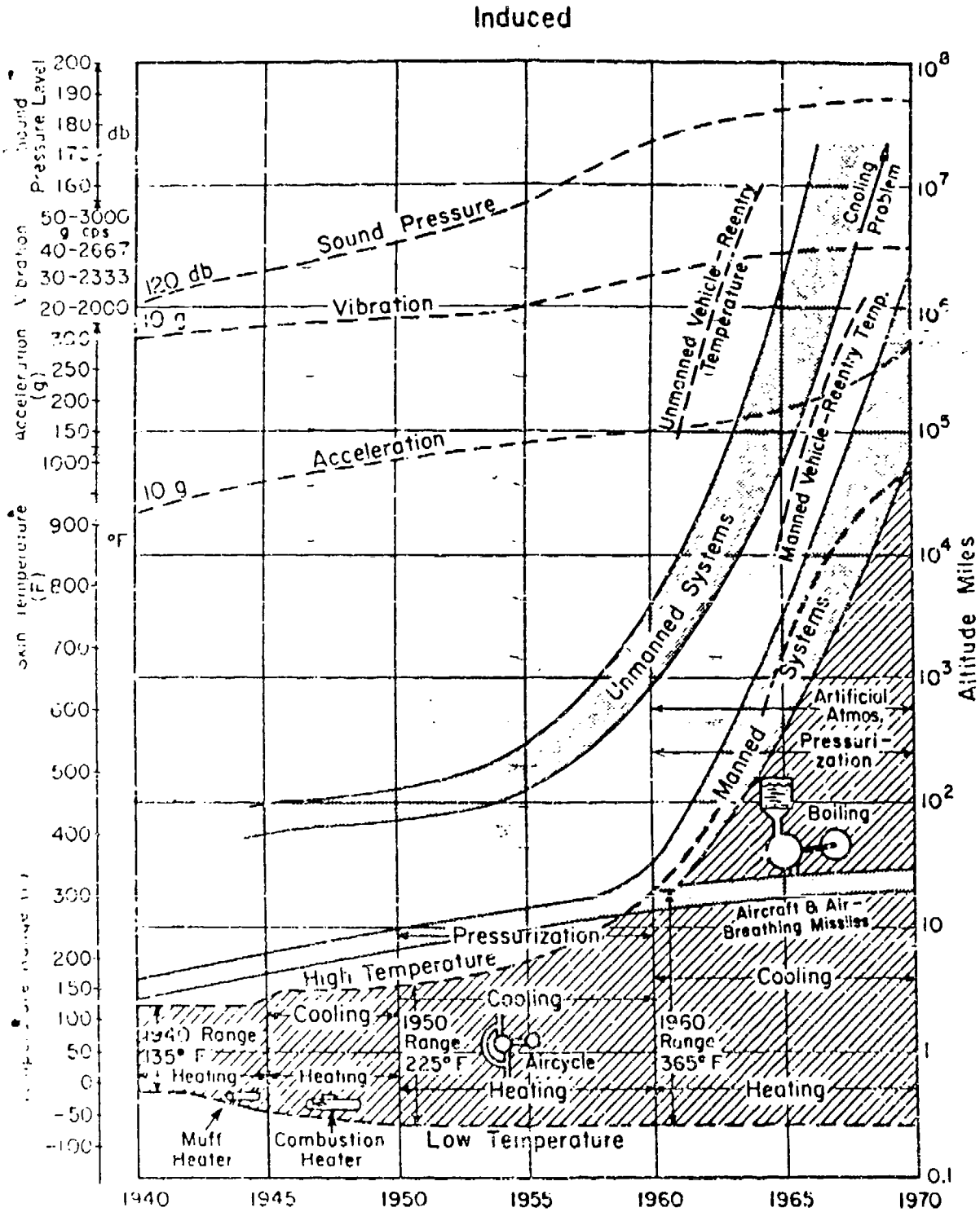


Fig. 1-3. Trends in natural and induced environments.

CHAPTER 2

ASTROPHYSICAL FACTS AND ENVIRONMENTS

The natural environments imposed on a weapon system depend on where and how the system is to be used. Environments differ a great deal from one geographical location to the next, and also from one level of aerospace to the next. The weapon system itself comprises many components that may be located individually in different environments for a single mission. Also, during some missions, different pieces of equipment will probably encounter different extremes of environments. The flight vehicle may be subjected to severe environmental shocks by going from one extreme of an environment to the other in a short period. With ground support equipment, though, opposite extremes of environments may only be encountered over long periods, and so the duration problem is not as great. Nevertheless, it is still very important to consider. For interplanetary systems, a wider scope of environments must be planned for. In space and on some of the planetary bodies, different types of environments become more important than others. This chapter discusses the astrophysical environments existing outside as well as inside the solar system that may be encountered by weapon systems.

GALAXIES / 1, 2, 3 /

The universe stretches far beyond the Solar System. Our galaxy, the Milky Way, consists of over 100 billion stars, interstellar dust and gaseous material. The Milky Way is about 100,000 to 200,000 light years in diameter (a light year is about 6×10^{12} miles) and approximately 25 to 50 thousand light years thick. The sun is an insignificant star in this galaxy, and is located approximately 30 thousand light years from the galactic center.

Beyond our galaxy are countless other galaxies and clusters of galaxies. The galaxies are of three main types: spiral, elliptical and irregular. The Milky Way is one of several galaxies in a small cluster known as the Local Group.

Hydrogen is the most abundant chemical in the sky, as it is in the stars themselves. Astronomers have made use of this fact in determining the radial velocity and distribution of stars in space. Hydrogen emits radiation in a limited number of wavelengths that can be identified by the pattern of lines of the spectrum. If the lines are displaced toward the violet end, or shorter wavelengths, of the spectrum, the star is approaching the Earth. However, if the lines are displaced toward the red end, or longer wavelengths, the star is receding from the Earth. The spectral displacement is known as the red line hydrogen shift. The amount of displacement is proportional to the speed of approach or recession of the star.

There is some indirect evidence for the existence of other planetary systems. However, with our present state of knowledge, communication with such planetary systems is a matter of speculation only.

SOLAR SYSTEM / 1, 2, 4, 5 /

The Solar System consists primarily of the Sun and the nine planets, with their various moons. The nine planets move around the Sun in the same direction in similar planes (see Fig. 2-1), and in nearly circular orbits.

The planets and the Sun account for most of the matter in the Solar System. The Sun itself has a diameter of 864 thousand miles and contains more than 99 percent of all matter in the Solar System.

The four inner planets, Mercury, Venus, Earth and Mars, are relatively small, dense bodies. They are known as the "terrestrial" planets. The next four planets in distance from the Sun are Jupiter, Saturn, Uranus and Neptune. They are known as the major, or giant, planets. All four of these are relatively large bodies, believed to be composed principally of solid ice and rock cores. Very little is known of the planet Pluto, which is farthest from the Sun. Besides the Sun, the planets, and their moons, the Solar System also contains asteroids, comets, meteors and interplanetary dust.

Asteroids

The asteroids are a group of bodies or planetoids that orbit between Mars and Jupiter. It is estimated that there are hundreds of thousands

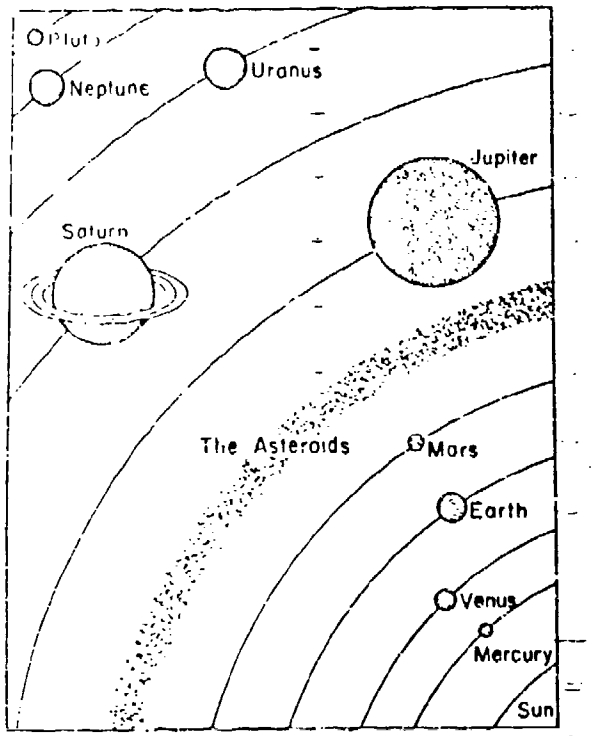


Fig. 2-1. The solar system./3/ (From Space Handbook: Astronautics and its Applications, courtesy of the RAND Corporation)

of these asteroids. They are believed to be evidence of a planet that never quite coagulated or one that disintegrated.

Most of the asteroids observable from Earth have dimensions of only several miles, but a few are 100 miles in diameter. The largest asteroid, Ceres, is nearly 500 miles in diameter. Some of the smaller asteroids have orbits passing quite close to Earth.

Comets

Comets are loosely bound collections of matter that sweep into the inner regions of the solar system from outer space. They have orbits that vary in eccentricity and direction around the Sun. On each trip around the Sun, the comet is partially distended by light pressure and leaves a "wake" or tail of small solid particles. Comet tails can be extremely long, at times even exceeding 100 million miles. It is estimated that typical comet masses, including the tails, have a magnitude of 10^{12} tons.

Meteorites and Micrometeorites

Meteorites and micrometeorites, also known as interplanetary dust, are believed to be the debris resulting from the disintegration of comets or asteroid collisions./6/ Meteors and micrometeors range in size from 20 microns to a few meters.

A layer of micrometeorites extends from the Sun to far beyond the Earth's orbit, and is concentrated in the plane of the Earth's orbit. The particles follow a path that spirals in toward the Sun.

Meteorites generally have highly elliptical orbits around the Sun, distributed along the orbits of the comets. A typical meteor orbit is shown in Fig. 2-2. Estimates, based on various assumptions, of the total amount of meteoric material that enters the Earth's atmosphere each day range from 25 to 1 million tons. Russian satellite data indicate an estimate of 800,000 to one million tons per day./7/ Meteorites enter the Earth's atmosphere at extremely high velocities, ranging from 8 miles per second to 50 miles per second, with their average speed being 30 miles per second. Most of the meteoritic material burns up when it enters the Earth's atmosphere, causing a drifting of dust particles to the Earth's surface. Data on the probability of flight vehicles encountering meteors and micrometeorites are covered in Chapter 3.

Temperature

The temperature of the solar corona near the Sun is probably about 1,800,000 F (1,000,000 C); near the Moon it is about 396,000 F (220,000 C)./8/ Temperatures of space bodies are largely dependent upon the Sun's radiation. If a space body does not receive any solar radiation or any reflected planet radiation, the space body's temperature may reach absolute zero. For example, Mercury's dark side receives no solar illumination and its temperature is probably close to absolute zero. Figure 2-3 shows the temperature of a spinning sphere as a function of its distance from the Sun. The sphere receives heat only from solar radiation. The

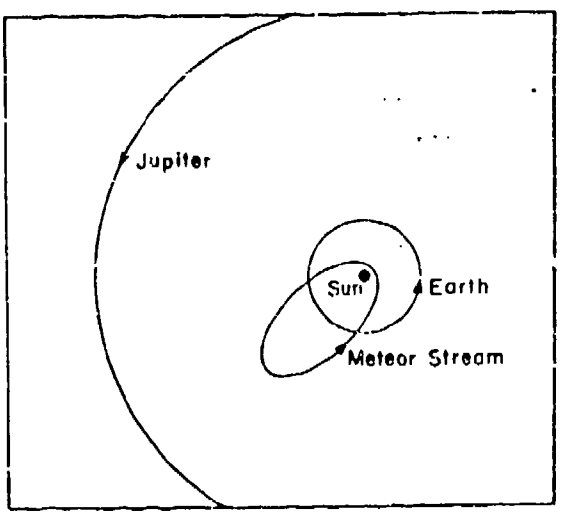


Fig. 2-2. Meteor orbit./6/

ratio of the sphere's absorptivity of solar radiation to emissivity of its own radiation is α/ϵ. The estimated average temperatures of the planets are also shown. If the body is near one of the planets, account must be taken of the reflected solar radiation from the planet, of radiation from the planet itself, and of the elimination of solar radiation if the body is in the planet's shadow./6,8/

Radiation

Radiation in space includes x-rays, steady ultraviolet and solar radiation and cosmic rays. Explorer IGY satellites, Explorer IV and Sputnik III indicate that radiation intensity increases by a factor of several thousand between 180 and 975 miles above the Earth, reaching as much as 10 roentgens per hour. Tentative data from the Pioneer I probe indicate a rapid decay of radiation intensity with increasing distance beyond 17,000 miles from the Earth. In addition to its steady radiation, the Sun delivers additional short outbursts of solar radiation during solar flares. During these periods, radiation levels may be 1000 times greater than normal./6/

SUN

With the exception of atomic and thermonuclear energy, the Sun is the ultimate source of all usable forms of energy on the surface of the Earth and other planets of the Solar System. More than 99 percent of the Solar System mass is concentrated in the Sun. Its diameter is 864,000 miles; approximately 13 million times larger than the Earth. The Sun's density averages one fourth that of the Earth, but at the Sun's center the density is several times that of the Earth./2,3/

A pressure of a billion tons per square inch and a temperature of about 360 million F (200 million C) probably exist at the Sun's center. In this atomic furnace, nuclei collide with tremendous velocities, and enormous energies are released. This energy goes to the Sun's surface, where it is radiated into space.

Some of the known physical properties of the Sun are listed below:/3,4/

Mean diameter	864,000 miles
Mass	2.1×10^{27} tons
Density (relative to water)	1.4
Period of rotation (average)	27 days
Inclination of equatorial axis	7° 10'

Atmosphere and Temperature

The Sun's surface, the photosphere, is a gaseous envelope about 200 miles thick. Its density is very low, being about a millionth the density of air on Earth. The pressure in the photosphere is only about one-fifth to one-tenth of the Earth's sea level pressure. Both the density and pressure decrease with distance away from the Sun's surface. The average temperature of the photosphere is very high, about 11,300 F (6300 C). The temperature decreases throughout the photosphere and reaches a low of 2550 F (1400 C) at its topmost region. This is the coolest region of the Sun./2,4/

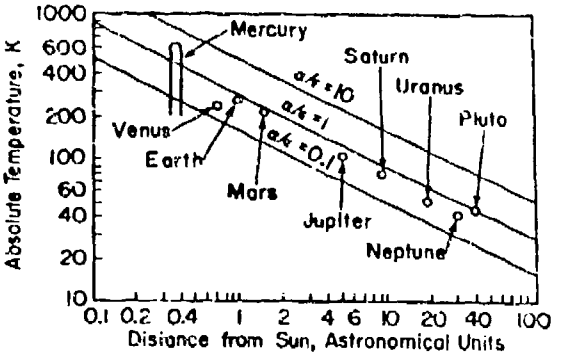


Fig. 2-3. Temperature of a spinning sphere as function of its solar distance and surface radiation characteristics./6/

Outside the photosphere is another layer called the chromosphere. This is the region of great solar storms and extreme turbulence. The chromosphere has a rarified atmosphere extending several thousand miles above the photosphere.

Above the chromosphere is a very faint corona region extending millions of miles into space. The temperatures in the corona are unexpectedly high and are believed to vary from 500,000 to 1,500,000 K in the outermost portion. Figure 2-4 shows the solar intensity distribution inside the Earth's atmosphere./2,3,4/

Solar Radiation

Energy leaving the Sun consists of electromagnetic radiation, and high speed protons and other particles. The energy output of light and heat is extremely constant, varying no more than about 0.5 percent from its average value. The output intensity of ultraviolet radiation, radio waves and charged particles, however, varies considerably due to solar flares, which appear to be associated with sun spot activity. /2,4/

The solar flares discharge immense energies in a few minutes. It is believed that this release of energy is due to a sudden instability in the Sun's chromosphere./2/

Magnetic Field

The Sun's magnetic field is only slightly stronger than that of the Earth, except during sunspot activity, at which time local north and

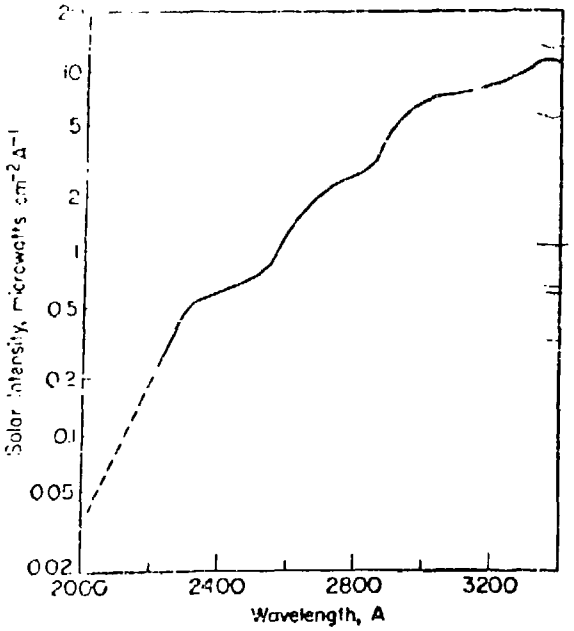


Fig. 2-4. Solar intensity distribution outside Earth's atmosphere./13/ (From "The Space Environment -- A Preliminary Study," appearing in Electrical Manufacturing, October 1958, courtesy of Conover Mast Technical Publications Corp.)

south magnetic poles in the sunspots cause magnetic moments to reach values 10^6 times those of the Earth. At such times, the Sun's magnetic field may reach 5000 gauss and would be expected to extend well beyond Mercury and almost to Venus. However, the solar corona, which is an excellent electrical conductor, nullifies the sunspot fields in outer space./5,6,8/

EARTH

The Earth is the third planet in distance from the Sun. The average density of the Earth is taken in relation to the average weight of an equal volume of water; the density of its crust varies from 2.67 at its outer surface to 2.90 at its lower extent. The crust is composed of igneous, metamorphic and sedimentary rock, with varying discontinuities down to its core, which is composed of liquid nickel-iron./9/

The topography of the Earth is unique among the planets due to its vast oceans and widespread vegetation. Mountains rise to 29,000 feet and ocean depths reach 35,000 feet. Other physical properties of the Earth are listed below./1,4,10/

Equatorial diameter	7920 miles
Polar diameter	7907 miles
Volume	259.9×10^9 cubic miles
Mass	6.586×10^{21} tons
Density (mean, relative to water)	5.5
Surface gravity (45 degree latitude)	32.1724 feet/sec^2
Escape velocity	6.86 miles/second
Albedo (fraction of total reflected sunlight)	0.29
Maximum distance from Sun (July)	94.6×10^6 miles
Minimum distance from Sun (January)	91.4×10^6 miles
Orbital speed (average tangental velocity)	18.517 miles/second
Orbit Eccentricity (departure of orbit from the circular: circle eccentricity = 0)	0.017
Inclination of the axis (mean)	23° 17'

The Earth's atmosphere, temperature, weather conditions and types and quantities of radiation are described below.

Atmosphere

The Earth's atmosphere can be divided into four zones: the troposphere, stratosphere, mesosphere and thermosphere. A representation of these zones is given in Fig. 2-5. The

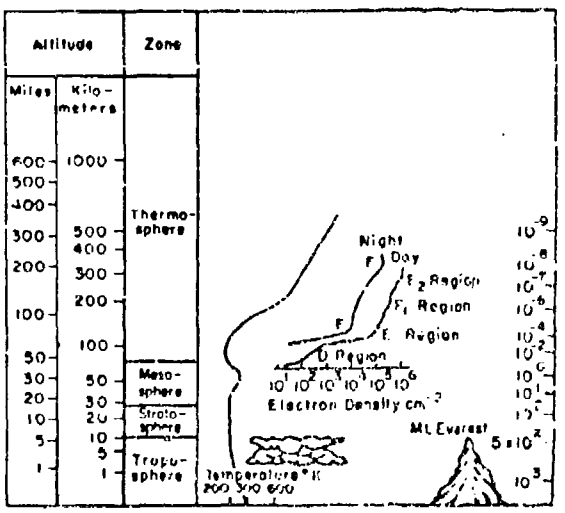


Fig. 2-5. Atmospheric zones./11/

Earth's weather is confined to the troposphere, which is the domain of high winds and cirrus clouds. The temperature decreases in the troposphere as a function of altitude, and is considered constant at 6.5 C per kilometer.

The stratosphere is considered an isothermal region. It is thickest over the poles and thinnest, or may even be considered absent, over the equator. Stratospheric temperatures are on the order of arctic winter temperatures. The lower regions of the stratosphere contain the meandering jet streams and are turbulent./11/

The mesosphere contains the first temperature maximum of 271.3 K at a height of 30 miles. At the top of the mesosphere is the atmospheric temperature minimum of 205 K. The mesosphere also contains the Dionic layer, which reflects very low frequency radio waves. There is considerable turbulence in the mesosphere, and it is also the region where most meteors disappear./1,12/

The thermosphere is the domain of the aurorae and magnetic storms. It is also a region of rising temperatures and heavy ionic densities, which exist in various layers. These layers are known collectively as the ionosphere. The ionic layers are the D, E, F_1 and F_2 layers. Their heights and electron concentrations vary with time of day, season of year and sunspot cycle. The lowest layer, the D layer, is found at a height of about 30 miles during the day. At night it disappears and the bottom of the ionosphere rises to about 70 miles. The top of the ionosphere is not well defined but is assumed to be at a height of 250 miles. The heavy electron densities (Fig. 2-5) cause refraction and reflection of radio signals.

Composition

The principal composition, by volume, of the dry atmosphere below 50 miles is:

nitrogen	78.088%
oxygen	20.949%
argon	0.93 %
carbon dioxide	0.03 %

The remaining constituents amount to less than 0.003%. The vertical distribution of the major atmospheric constituents is shown in Fig. 2-6./4,11

Ozone

Ozone, O_3, is a form of molecular oxygen. Any high-energy input to O_2 can cause the formation of O_3. In the Earth's high atmospheric regions, ozone is produced by interaction of the ultraviolet radiation with oxygen. The amount of ozone in the atmosphere is a function of altitude, latitude, season of year and solar activity. The maximum concentration occurs at a height

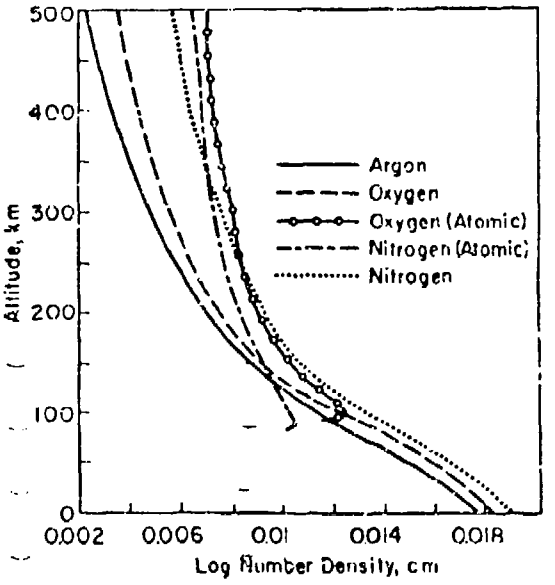


Fig. 2-6. Vertical distribution of major atmospheric constituents./11/

of about 90,000 to 110,000 feet, and is about eleven parts per million of air./11,13,14,15/

The concentration of ozone as a function of altitude at various latitudes is given in Fig. 2-7. Seasonal variations at Flagstaff, Arizona are shown in Fig. 2-8. The ozone concentrations are expressed in terms of "cm O_3 (STP) per kilometer." This is the thickness of a pure ozone layer, at standard temperature and pressure, contained in a vertical column of air one kilometer in height./4/

Table 2-1 shows maximum ozone concentration as a function of altitude. As shown, the concentration in parts-per-million of air is high at 130,000 feet. This is due to the changes in the density of air that occur in the ozone region. The data presented indicate that ozone should be considered as an environment only between 30,000 and 150,000 feet./15/

Atmospheric Electricity and Lightning

A difference in electrical potential exists between the Earth and the atmosphere. The difference averages about 120 volts per meter, but varies with location, season, hour and weather conditions. In good weather, the potential gradient is about 100 to 120 volts per meter, while during thunderstorms it may become 10,000 volts per meter or even higher./10/

A lightning discharge can occur between two charged regions, either within a thundercloud or between a cloud and the ground. The frequency

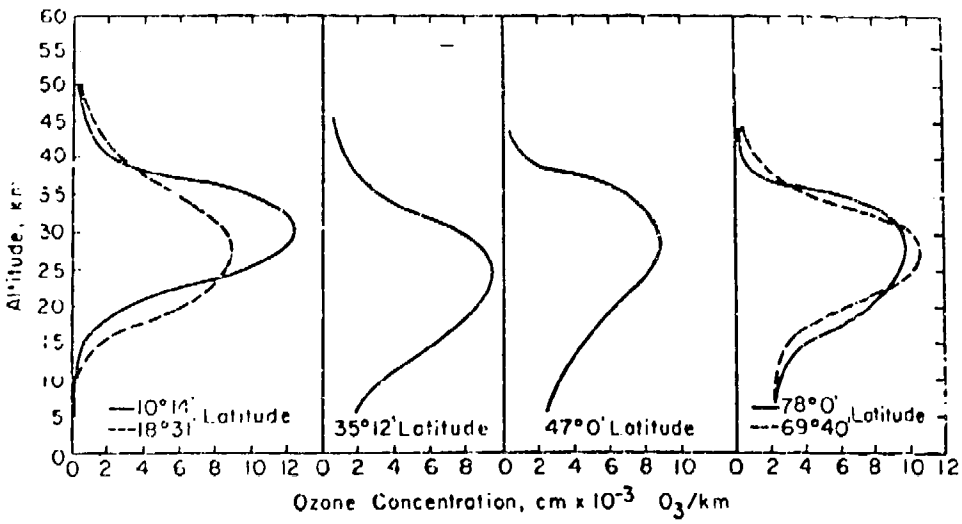


Fig. 2-7. Latitudinal variation of ozone concentration./4/

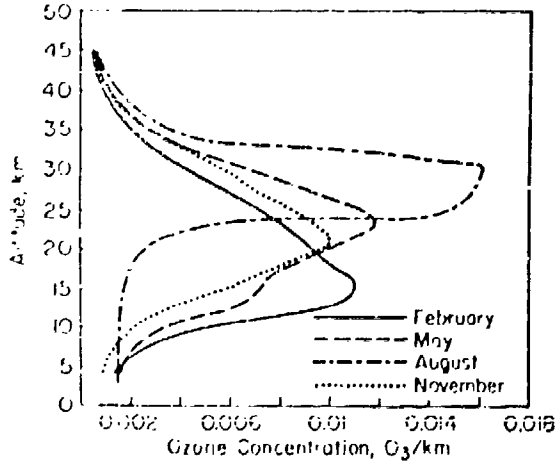


Fig. 2-8. Seasonal variation of ozone concentration at Flagstaff, Arizona./4/

Table 2-1. Maximum Ozone Concentration

Altitude (feet)	Ozone concentration (cm/km)	Relative density of air	Ozone (parts per million)
Sea level	0.005	1.000	0.05
30,000	0.010	0.375	0.3
50,000	0.030	0.153	2.0
70,000	0.040	0.059	7
90,000	0.024	0.022	11
110,000	0.009	0.0084	11
130,000	0.002	0.0034	6
150,000	0.0005	0.0015	4

From "The Space Environment -- A Preliminary Study," appearing in Electrical Manufacturing, October 1958, courtesy of Conover-Mast Technical Publications Corp.

of discharge within a cloud is four times greater than discharges from cloud to ground. However, before a lightning discharge can take place, the potential gradient must exceed the sparking value, normally considered to be about 1,000,000 volts per meter at normal air density. Under severe conditions, such as high ascending air currents, which distort the electric field, the sparking value may be as low an 3000 volts per meter. 4,14/

There are two forms of lightning strikes or discharges. The first is the steep-wave-front, high-current, short-time form, which produces explosive effects because of the sudden release of high energy. The second form is the continuous, low-current, long-time type, which releases large amounts of heat during a long period of current flow./14/ A study of lightning strikes by British European Airways showed the following distribution of strikes in the various cloud forms:

Cumulus	28.5%
Cumulus and cumulo-nimbus	13.5%
Cumulo-nimbus	16.0%

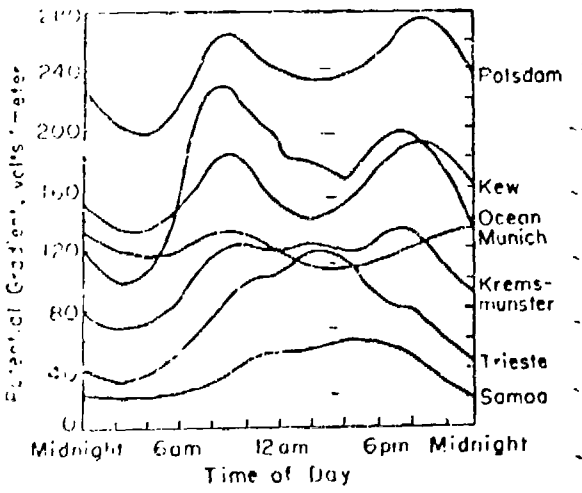


Fig. 2-9. Daily variation of atmospheric potential gradient for locations with different altitudes above sea level./16/

Cumulus and stratus	9.5%
Stratus	32.5%

The daily variation of atmospheric potential gradient changes with location and altitude, as shown in Fig. 2-9. The vertical potential gradient in the atmosphere varies through the lower layer of the troposphere. Above the troposphere, the decrease is less rapid and gradually diminishes to a relatively small value. The potential difference between the atmosphere and the Earth is shown in Fig. 2-10.

Density

Density distribution above 150 kilometers (95 miles) had been based, until recently, on indirect methods of computation. Ideas concerning high altitude density had been greatly influenced by an isolated measurement of density at an altitude of 219 kilometers (135 miles), obtained during the Viking flight of August 7, 1951 at White Sands, New Mexico. This flight gave a value of 1×10^{-5} grams per cubic centimeter at 219 kilometers. However, the three Russian satellites launched in 1957 reported the following density values at heights from 125 to 195 miles: 17

Satellite	Altitude	Absolute density
Alpha 2	220 km	4.5×10^{-13} gm/cm^3
Alpha 1	220 km	5.7×10^{-13} gm/cm^3
Beta	233 km	2.2×10^{-13} gm/cm^3

There is some doubt about the densities derived from Alpha 1 and Beta, since the densities were arrived at using estimates of the size and mass of the satellites. Although there is some spread of the computed densities, the estimated mean values of densities derived from all rocket and satellite data tend to lie on a smooth curve. This curve is shown in Fig. 2-11./18/ If conditions appear critical, additional information is available through IGY World Data Center A, Rockets and Satellites, National Academy of Sciences, IGY Satellite Report Series. This series can be obtained from the following source: Printing and Publishing Office, National Academy of Sciences, 2101 Constitution Avenue, NW., Washington 25, D.C./6,19/

The average densities in slugs per cubic foot at various altitudes from sea level to 100,000 feet are given in Tables 2-2 and 2-3. The densities shown in the tables are for each ten degrees of latitude over North America for the months of January and July, respectively. Included in Tables 2-2 and 2-3 are the standard deviation from the average densities for the altitudes shown.

Cold, hot, polar and tropical atmospheres provide useful climatic extremes. The climatic atmospheres for density-height data in the Northern Hemisphere are shown in Table 2-4. As shown in Tables 2-2, 2-3, and 2-4, an increase in temperature or a decrease in pressure generally results in a decrease in density. Since temperature and pressure vary from day

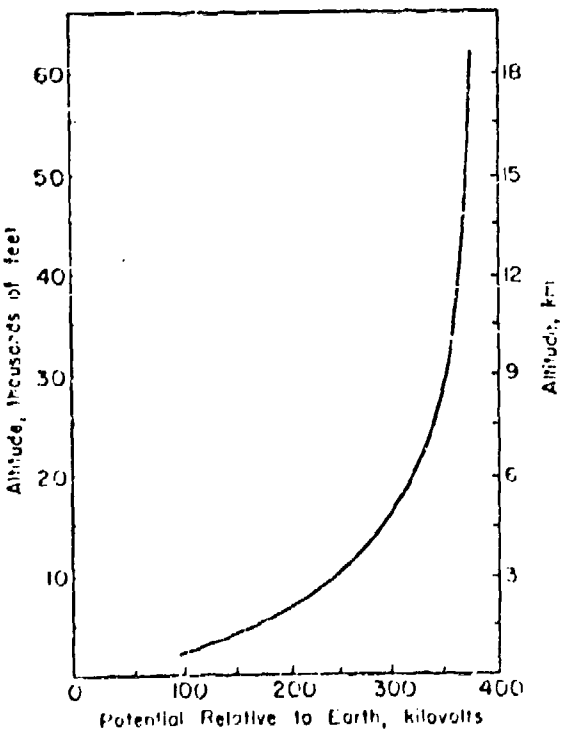


Fig. 2-10. Potential difference between Earth and atmosphere./14/

to night and from place to place, density will vary accordingly. These variations of density

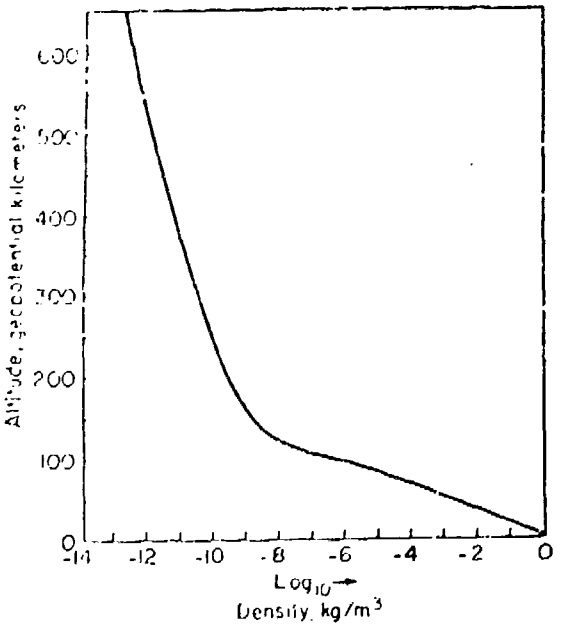


Fig. 2-11. Density as function of height./18/

are not certain; but they do exist and must always be taken into account./20/

Pressure

Atmospheric pressure can be defined as the force per unit area exerted by the weight of the atmosphere. Pressure is usually given in millibars (mbs), inches of mercury (Hg), pounds per square inch or pounds per square foot. To convert millibars into pounds per square foot, multiply the millibars by 2.089, and conversely, to convert pounds per square foot into millibars, multiply the pounds per square foot by 0.4788.

The standard atmospheric pressure at sea level is 1013.2 mbs. The extremes of atmospheric pressure that may be experienced by equipment during ground operations are: 1062 mbs maximum and 506 mbs minimum. These extremes represent altitudes of 1300 feet below sea level and 18,000 feet above sea level, respectively, at standard conditions./21/

Atmospheric pressure has its lowest values at the highest altitudes, and it is important to know the variation of pressure as a function of altitude from a geographical, seasonal and climatic standpoint. Figure 2-12 gives the pressure as a function of height from sea level to 500 km. Average pressures, as well as the standard deviation of pressure, for altitudes between 10,000 and 100,000 feet for various latitudes over North America are shown in Table 2-5 for the month of January. The same data

Table 2-2. Average Density of a Standard Level Surface and Standard Deviation for Month of January /4/

Altitude (feet)	Density for Month of January (slugs/cu ft x 10^{-4})													
	Latitude (degrees north)													
	20		30		40		50		60		70		80	
		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -
10,000	16.57	0.214	17.34	0.348	17.65	0.544	17.96	0.758	18.18	0.814	18.37	0.699	18.43	0.622
20,000	12.49	0.174	12.62	0.270	12.56	0.466	12.68	0.659	12.68	0.699	12.62	0.563	12.68	0.504
30,000	8.86	0.174	8.92	0.270	9.17	0.389	9.61	0.466	8.45	0.465	8.30	0.407	8.24	0.370
40,000	6.15	0.137	6.06	0.214	5.81	0.252	5.50	0.270	5.28	0.270	5.13	0.233	5.04	0.214
50,000	4.01	0.096	3.85	0.137	3.61	0.137	3.42	0.115	3.29	0.137	3.17	0.115	3.03	0.115
60,000	2.44	0.059	2.35	0.078	2.25	0.078	2.11	0.078	2.06	0.096	2.00	0.078	1.88	0.059
70,000	1.42	0.059	1.42	0.059	1.36	0.059	1.32	0.059	1.28	0.059	1.22	0.059	1.14	0.037
80,000	0.855	0.037	0.855	0.037	0.835	0.059	0.814	0.037	0.777	0.037	0.777	0.037	0.659	0.037
90,000	0.522	0.025	0.563	0.034	0.522	0.034	0.522	0.034	0.504	0.034	0.448	0.025	0.426	0.025
100,000	0.329	0.012	0.329	0.019	0.329	0.022	0.329	0.019	0.311	0.019	0.292	0.016	0.233	0.012

Table 2-3. Average Density of a Standard Level Surface and Standard Deviation for Month of July /4/

Density for Month of July (slugs/cu ft x 10^{-4})														
Altitude (feet)	Latitude (degrees north)													
	20		30		40		50		60		70		80	
		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -
10,000	16.97	0.115	17.06	0.155	17.03	0.233	17.25	0.329	17.37	0.370	17.53	0.407	17.53	0.389
20,000	12.43	0.115	12.43	0.137	12.53	0.214	12.71	0.311	12.53	0.348	12.53	0.370	12.53	0.348
30,000	8.86	0.096	8.89	0.137	8.89	0.193	8.86	0.252	8.80	0.270	8.76	0.292	8.73	0.252
40,000	6.22	0.076	6.28	0.096	6.25	0.137	6.00	0.174	5.75	0.174	5.69	0.174	5.58	0.155
50,000	4.10	0.059	4.07	0.078	3.95	0.078	3.73	0.078	3.61	0.078	3.51	0.059	3.52	0.059
60,000	2.48	0.037	2.46	0.037	2.41	0.037	2.31	0.037	2.25	0.059	2.23	0.059	2.25	0.037
70,000	1.45	0.037	1.45	0.037	1.44	0.037	1.40	0.037	1.42	0.037	1.40	0.037	1.42	0.037
80,000	0.562	0.019	0.581	0.022	0.640	0.022	0.640	0.022	0.659	0.022	0.755	0.022	0.833	0.019
90,000	0.348	0.012	0.370	0.012	0.389	0.016	0.407	0.016	0.426	0.016	0.485	0.016	0.544	0.012
100,000	0.214	0.006	0.233	0.006	0.270	0.009	0.252	0.009	0.282	0.009	0.310	0.009	0.348	0.006

Table 2-4. Density-Height Data for Cold, Hot, Polar and Tropical Atmospheres /21/

Altitude (thousands of geopotential feet)	Density (slugs/cu ft x 10^{-4})			
	Climatic atmospheres			
	Cold	Hot	Polar	Tropical
10	16.5	16.5	18.39	16.90
20	12.8	12.1	12.78	12.45
30	8.6	8.6	8.56	8.95
40	5.9	5.7	5.33	6.49
50	4.4	3.5	3.31	4.22
60	2.7	2.2	2.05	2.53
70	1.4	1.4	1.27	1.43
80	0.7	0.8	0.78	0.86
90	0.5	0.5	0.47	0.52
100	0.3	0.3	0.29	0.32

for the month of July are shown in Table 2-6. Atmospheric pressures for cold, hot, polar and tropical atmospheres are given in Table 2-7.

Temperature

The daily variation of the Earth's air temperature is fairly regular when variations due

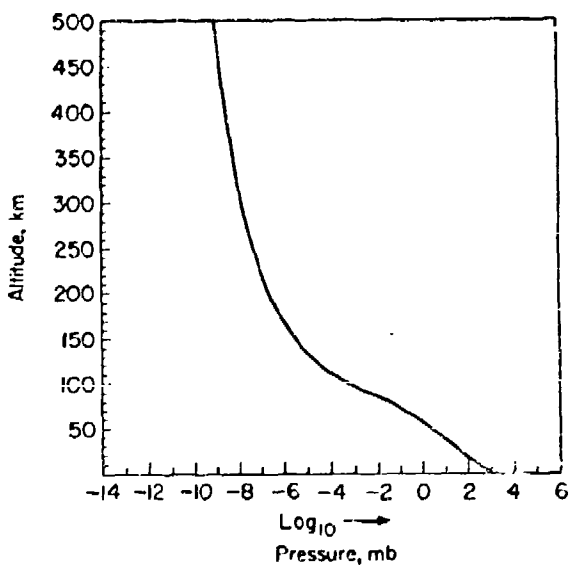


Fig. 2-12. Pressure as function of height./6/

to phenomena such as thunderstorms and fronts are excluded. Factors affecting the temperature of the Earth-air interface are:

1. Short-wave solar radiation and long-wave terrestrial and atmospheric radiation, such as albedo and color.
2. Mean wind speed.
3. Type of soil and ground cover.
4. Roughness of the Earth's surface.

Table 2-5. Average Pressure at Given Altitudes and Standard Deviation for Month of January /4/

Pressure for Month of January (millibars)														
Altitude (feet)	Latitude (degrees north)													
	20		30		40		50		60		70		80	
		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -
10,000	707	3	705	5	694	8	680	11	669	13	662	12	662	9
20,000	483	3	477	6	463	9	447	12	435	14	425	12	425	10
30,000	314	3	308	6	307	8	282	10	273	10	265	9	262	7
40,000	199	3	195	5	186	6	177	6	171	6	165	5	160	4
50,000	122	3	119	4	114	4	110	4	106	4	102	3	97	2
60,000	73	2	72	2	71	2	68	2	66	2	63	2	59	1
70,000	44	1	44	2	43	2	42	2	41	2	38	1	35	1
80,000	27	1	27	1	27	2	26	1	25	1	24	1	20	1
90,000	17	0.7	18	1.0	17	1.0	17	1.0	16	0.9	14	0.7	13	0.8
100,000	11	0.4	11	0.6	11	0.7	11	0.6	10	0.6	9	0.5	7	0.4

Table 2-6. Average Pressure at Given Altitudes and Standard Deviation for Month of July /4/

Pressure for Month of July (millibars)														
Altitude (feet)	Latitude (degrees north)													
	20		30		40		50		60		70		80	
		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -
10,000	711	2	715	2	708	4	701	5	694	6	691	7	688	6
20,000	487	2	488	2	485	4	476	6	466	7	461	7	458	6
30,000	319	2	319	3	316	4	307	5	299	5	295	6	293	5
40,000	203	2	204	2	202	3	196	3	191	3	188	3	188	3
50,000	125	2	126	2	125	2	122	2	120	2	119	2	120	2
60,000	75	1	76	1	76	1	76	1	76	1	76	1	77	1
70,000	46	0.6	46	0.7	46	0.8	47	0.8	48	0.8	48	0.7	49	0.6
80,000	18	0.6	19	0.6	21	0.7	22	0.7	23	0.7	26	0.6	29	0.6
90,000	12	0.4	12	0.4	13	0.5	14	0.5	15	0.5	17	0.4	19	0.4
100,000	7	0.3	8	0.3	9	0.3	9	0.3	10	0.3	11	0.3	12	0.3

The Earth's albedo varies with angle of incidence of the radiation, the type of surface and the amount of cloudiness. It is usually thought of as the ratio of reflected-to-incoming radiation. Its average value is about 29 percent./22/

In arctic regions, where periods of darkness and light extend for several months, the daily variation of temperature is controlled primarily by the prevailing cloudiness and surface wind speed. In summer months, the maximum temperature seldom exceeds 32 F (0 C).

In tropical regions, the daily and annual temperature is controlled by the effects of air mass changes, wind direction shifts and frontal passages. The intensity of these weather disturbances generally decreases towards the equator.

Table 2-7. Pressure-Height Data for Cold, Hot, Polar and Tropical Atmospheres /21/

Altitude (thousands of geopotential feet)	Pressure (lbs/sq ft)			
	Climatic atmospheres			
	Cold	Hot	Polar	Tropical
10	1414	1487	1412.3	1486.2
20	888	1013	915.3	1016.8
30	553	664	575.6	674.7
40	376	403	56.2	432
50	261	248	219.7	265
60	156	158	135.1	56.5
70	86	98	82.7	94.3
80	45	62	50.6	58.4
90	26	40	30.8	36.6
100	18	27	18.5	23.3

It can be assumed that, in tropical regions, the daily variation of temperature is practically constant from day to day and seldom exceeds 43 F (6 C)./23/

To illustrate the daily and annual temperature variations for tropical, subtropical, desert, temperate, subarctic and arctic regions, yearly records from six climatological stations are shown in Fig. 2-13.

A few official temperature extremes around the world are listed below./24/

World's lowest temperature	-117 F (-83 C), Antarctica
World's highest temperature	136 F (57 C), Libya
World's lowest average annual temperature	-30 F (-34.4 C), Antarctica
World's highest average annual temperature	88 F (31 C), Somalia
Alaska's lowest temperature	-76 F (-60 C)
Greenland's lowest temperature	-87 F (-66 C)
U.S. lowest temperature	-70 F (-56.7 C), Montana
U.S. highest temperature	134 F (57 C), California

Upper-level average temperatures for the months of January and July for various altitudes up to 100,000 feet are shown in Tables 2-8 and 2-9, respectively. The temperatures shown in these two tables are for each 10 degrees of latitude over North America. Standard deviations are included to provide an indication of the maximum and minimum seasonal changes that can be expected.

Cold, hot, polar and tropical atmospheres provide extreme minimum and maximum temperature-height data as well as other useful criteria. These climatic atmospheres are shown in Table 2-10. The temperature-height curves for Table 2-10 are presented in Fig. 2-14./21/ Figure 2-15 gives the temperature as a function of height from sea level to 500 km. Temperature data up to about 150 km are fairly certain. Above 150 km, however, the increase of temperature with height may be much more rapid than that shown in Fig. 2-15./6/

It should be noted that although temperature is a measure of the average translational kinetic energy of the particles that make up the atmosphere, it has different consequences at high altitudes than it does at the lower levels of the atmosphere. The lower atmosphere consists of molecules and may be considered a continuum. At higher altitudes, the mean free path of the molecules increases and dissociation takes place. And, although the kinetic energy of these particles is high, an object placed in this region

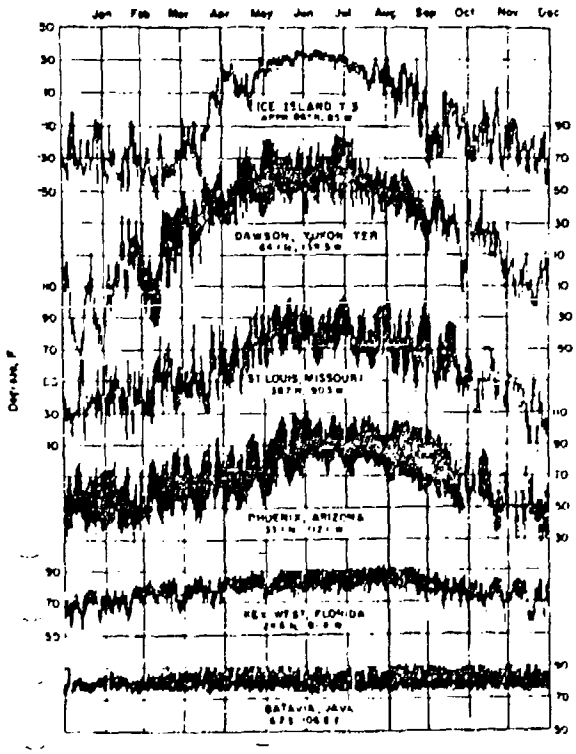


Fig. 2-13. Daily climatic extremes of temperature./4/

Table 2-8. Average Temperature and Standard Deviation for Month of January /4/

Average Temperature for Month of January (C)														
Altitude (feet)	Latitude (degrees north)													
	20		30		40		50		60		70		80	
		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -
10,000	9	2	2	4	-7	5	-17	7	-24	7	-29	5	-30	5
20,000	-10	2	-17	4	-24	5	-35	7	-41	6	-45	4	-47	4
30,000	-31	3	-40	3	-47	4	-52	5	-54	5	-57	4	-58	4
40,000	-54	3	-56	4	-57	5	-55	5	-55	6	-56	6	58	6
50,000	-69	1	-65	4	-60	4	-55	5	-55	6	-56	7	-57	6
60,000	-71	3	-66	3	-60	3	-56	4	-57	6	-60	5	-61	5
70,000	-64	3	-62	3	-58	3	-57	2	-58	4	-62	4	-65	4
80,000	-58	2	-57	2	-55	3	-55	4	-58	4	-64	4	-67	3
90,000	-51	2	-53	3	-52	3	-54	4	-58	4	-65	4	-69	4
100,000	-45	2	-48	3	-49	3	-53	4	-57	4	-65	4	-70	4

Table 2-9. Average Temperature and Standard Deviation for Month of July /4/

Average Temperature for Month of July (C)														
Altitude (feet)	Latitude (degrees north)													
	20		30		40		50		60		70		80	
		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -		+ or -
10,000	10	1	10	2	8	3	2	4	-3	4	-6	4	-8	4
20,000	-8	1	-8	2	-11	2	-20	3	-22	4	-24	4	-26	4
30,000	-29	2	-30	2	-33	2	-39	4	-43	3	-45	3	-46	3
40,000	-54	2	-53	2	-54	3	-52	4	-49	5	-46	4	-45	4
50,000	-67	2	-64	3	-60	3	-52	4	-47	4	-44	3	-43	3
60,000	-68	2	-65	2	-60	3	-50	3	-45	4	-42	4	-41	4
70,000	-60	2	-58	2	-56	2	-47	2	-43	3	-41	3	-40	3
80,000	-53	2	-53	2	-52	2	-43	2	-40	2	-40	2	-40	2
90,000	-47	2	-48	2	-48	2	-40	3	-38	3	-39	3	-39	3
100,000	-41	2	-43	2	-44	2	-37	2	-36	3	-37	3	-38	3

would come to a rather low temperature determined largely by radiation, since the air is so thin that conduction has a very small effect on the heat balance.

Weather Conditions

The circulation of air within the Earth's atmosphere is largely responsible for weather conditions; and the energy to sustain this circulation comes mostly from the Sun. The tropical and subtropical regions of the Earth absorb more solar radiation than they re-radiate, while the rest of the Earth radiates more than it receives. As a result, the air warmed in the tropics moves toward the poles. This fundamental movement sets up a global circulation system that is largely responsible for the weather conditions, such as temperature, humidity and rainfall, of the entire Earth.

Table 2-10. Temperature-Height Data for Cold, Hot, Polar and Tropical Atmospheres /21/

Altitude (thousands of geopotential feet)	Temperature (C)			
	Climatic atmospheres			
	Cold	Hot	Polar	Tropical
10	-26.1	18.9	-24.4	11.7
20	-47.7	-1.7	41.2	-8.7
30	-55.0	-22.2	-55.3	-29.0
40	-65.0	-42.8	-56.7	-49.4
50	-62.8	-40.3	-58.2	-69.8
60	-87.2	-39.1	-59.6	-73.3
70	-71.9	-37.5	-61.1	-60.0
80	-72.1	-33.7	-62.5	-52.7
90	-74.4	-29.9	-63.0	-45.4
100	-76.7	-26.1	-63.0	-38.0

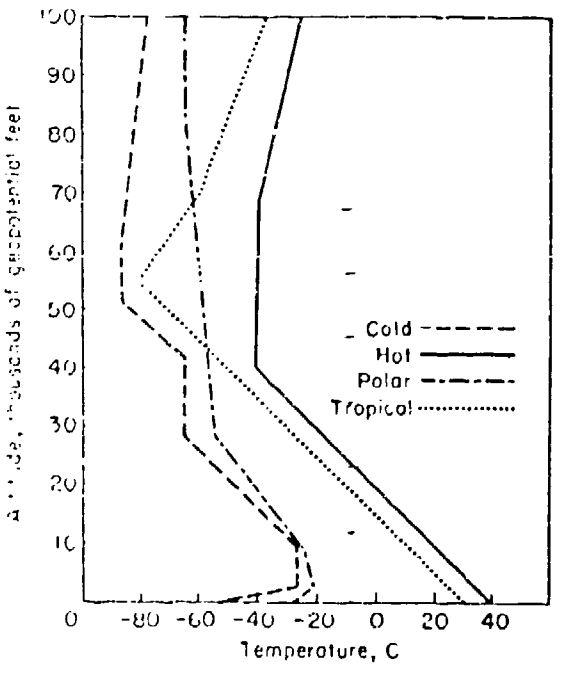


Fig. 2-14. Temperature vs altitude for hot, cold, polar and tropical atmospheres./21/

Wind

Wind direction is usually dependent on latitude, season and altitude, but local conditions may cause extreme variations. Normally, wind direction shifts with height. These shifts in direction are due to Earth surface effects and changes in the horizontal pressure patterns of the atmosphere; cold air weakens and warm air strengthens the wind direction shift. In the lower 3000 feet of the atmosphere, a maximum wind is encountered in midafternoon, and a minimum in the early morning hours. The average total shifting in this altitude range is 20 to 40 degrees./4/

Winds above 30,000 feet have the greatest variability. In low latitudes and in Newfoundland and Greenland maximum variability is encountered in the summer and minimum in the winter. In middle latitudes (20 to 60 degrees) the wind direction is most variable in spring and least variable in autumn. The prevailing wind is westerly in winter at all altitudes, becoming easterly above 60,000 feet. It then remains easterly up to between 300,000 and 400,000 feet./25/

The wind speed in middle latitudes increases from the Earth's surface to the tropopause, about 35,000 feet, and then decreases with altitude to about 80,000 feet. A second maximum is reached around 150,000 to 170,000 feet. This pattern exists in both summer and winter./4,25/ Very little is known about wind in the polar zone, from 60 to 90 degrees latitude, except that it is similar to that of the middle latitudes,

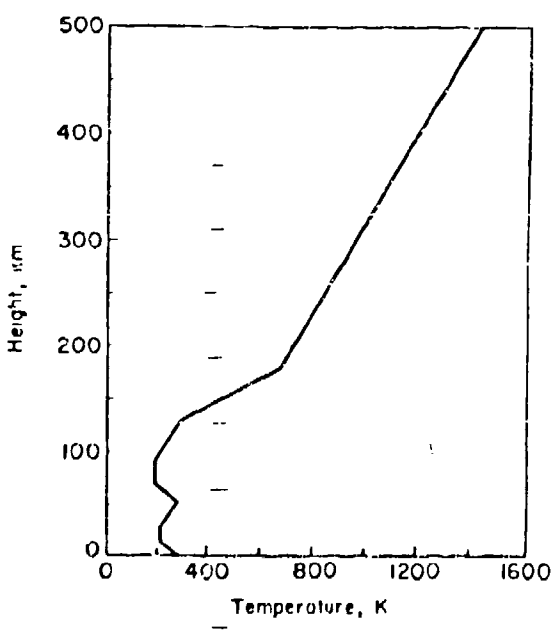


Fig. 2-15. Temperature as function of height from sea level to 500 km./6/

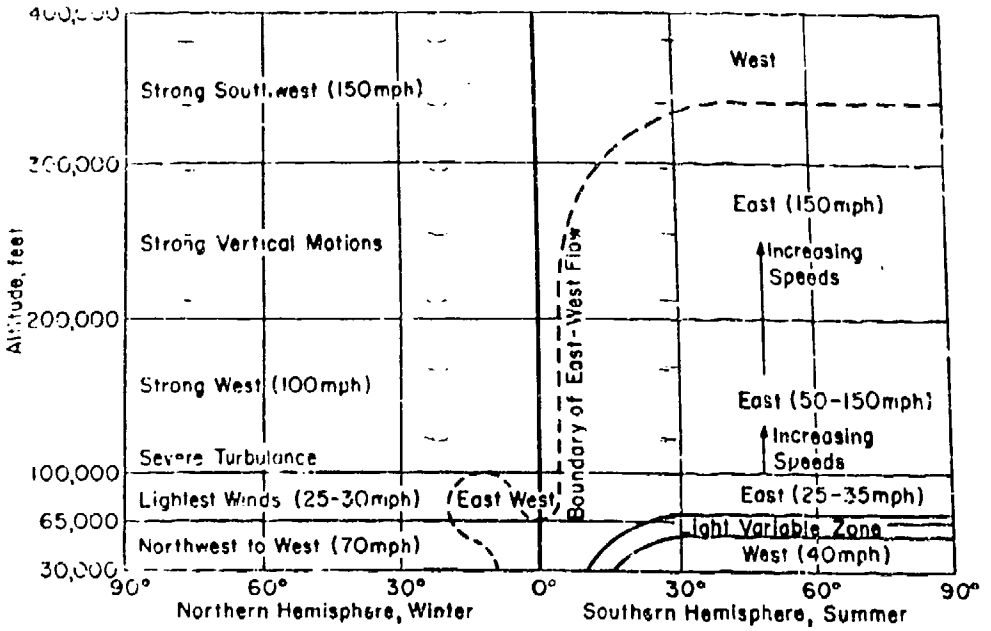


Fig. 2-16. Wind direction as function of altitude during winter and summer./25/

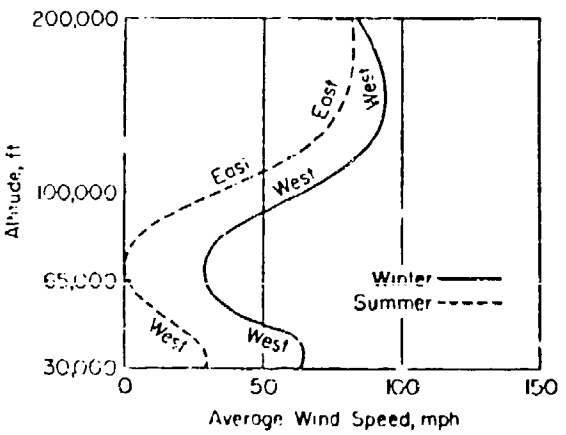


Figure 2-17. Average wind speed vs altitude during winter and summer in middle latitudes./25/

being westerly in winter and easterly in summer. Figure 2-16 is a simplified plot of wind direction as a function of altitude during winter and summer. Figure 2-17 shows the average wind speed plotted against altitude during winter and summer in the middle latitudes./25, 26/ Extreme change in wind speed with altitude will occur most frequently in wintertime. It should be noted that although extremely strong winds exist at altitudes higher than 290,000 feet, the density of air at these altitudes creates little force.

Maximum wind speed and peak shears that will be exceeded with given frequencies during the windiest season are shown in Fig. 2-18. Figure 2-18 indicates that maximum wind speeds and maximum wind shears occur between 30 and 40 thousand feet. Thus, a flight vehicle required to operate within this altitude range must cope with winds up to 300 mph and a shear of 45 fps.

Precipitation

Since world precipitation data are usually limited to average monthly, seasonal and annual totals, surface rates of precipitation cannot usually be obtained from climatological records. However, clock-hourly precipitation data present total precipitation on the hour every hour and are readily available for many stations in the United States and Europe. Periods of short and intense precipitation, called instantaneous rates of precipitation, have been computed for only a few stations.

Table 2-11 tabulates the percentage of time during an average year in which clock-hour and instantaneous rates of precipitation equal or exceed 0.06, 0.12 and 0.18 inch per hour at selected stations. The data in Table 2-11 considers precipitation as a whole. To obtain the rates of rainfall, the rates of snowfall equal to or exceeding 0.06, 0.12 and 0.18 inch per hour must be subtracted. It has been determined that 95 to

ten percent of all precipitation falling at rates equal to or exceeding 0.12 inch per hour will fall in the form of rain. About 85 percent of the precipitation falling at rates equal to or exceeding 0.06 inch per hour will be encountered at above freezing temperatures and will be in the form of rain. The remaining 15 percent will be encountered during the warmer months of winter and will be either rain or snow./4/

Precipitation extremes around the world are listed below./24/

U.S. greatest average annual precipitation--151 inches, Wynoochee, Wash.

U.S. greatest single season snowfall--884 inches, 1906-1907, Tamarack, Calif.

U.S. greatest 24-hour snowfall--76 inches, 14-15 April 1921, Silver Lake, Colo.

World's greatest 24-hour rainfall--46 inches, 14-15 July 1911, Baguio, Luzon.

World's greatest average annual precipitation--472 inches, Mt. Waialeale, Kauai, Hawaii.

World's lowest average annual precipitation--0.02 inches, Africa, Chile.

World's greatest rainfall per month--366 inches, July 1861, Cherrapunji, India.

Europe's greatest average annual precipitation--183 inches, Crkvice, Yugoslavia.

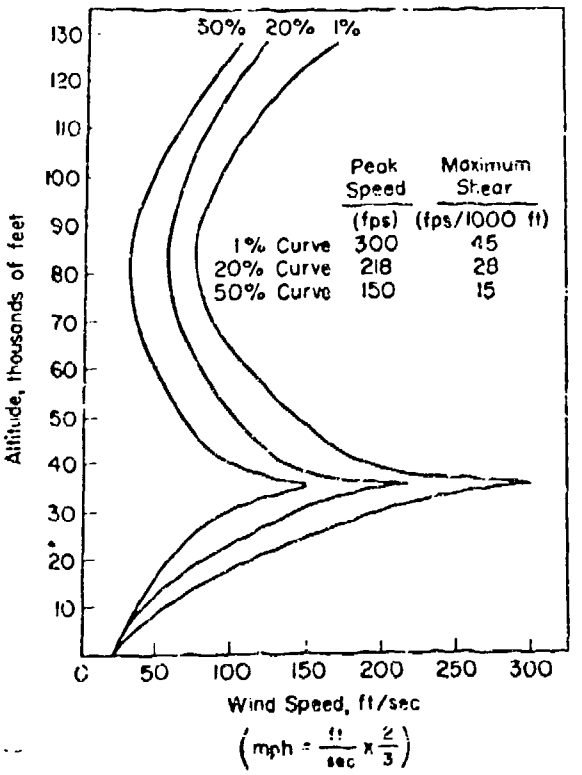


Fig. 2-18. Maximum wind speed and shears exceeded 1%, 20% and 50% of the time./4/

Table 2-11. Percentage of Time During Average Year in Which Clock-hour and Instantaneous Rates of Precipitation Equal or Exceed 0.06, 0.12 and 0.18 in./hr at Selected Stations /4/

Station	Location	Average annual precip. (inches)	Average annual no. days with measurable precipitation	Clock hour rates inches 1 hour			Instantaneous rates (in./hr.)		
				0.06 (%)	0.12 (%)	0.18 (%)	0.06 (%)	0.12 (%)	0.18 (%)
Athens	37°30'N, 23°43'E	15.70	98	0.94	0.24	0.08	0.85	0.23	0.08
Berlin	52°30'N, 13°25'E	22.88	169	0.84	0.16	0.03	0.76	0.15	0.03
Dublin	53°20'N, 6°15'W	27.37	218	0.76	0.13	0.01	0.70	0.12	0.01
London	51°25'N, 0°20'E	24.47	167	0.89	0.20	0.06	0.80	0.19	0.06
Moscow	55°45'N, 37°37'E	24.13	132	1.05	0.30	0.13	0.95	0.29	0.13
Paris	48°52'N, 2°20'E	22.62	160	0.84	0.16	0.03	0.76	0.15	0.03
Rome	41°45'N, 12°15'E	26.70	105	1.45	0.59	0.33	1.31	0.55	0.03
Tokyo	35°41'N, 139°46'E	61.40	149	2.22	1.13	0.72	2.00	1.06	0.72
Warsaw	50°14'N, 21°00'E	22.21	164	0.84	0.16	0.03	0.76	0.15	0.03
Washington	38°55'N, 77°00'W	42.20	124	2.11	0.90	0.60	1.90	0.85	0.60

Humidity

Humidity is expressed in many ways, some of the most common being: absolute humidity, relative humidity, specific humidity, vapor pressure, dew point and mixing ratio. These terms have the following meanings:

1. Absolute humidity is the mass of water vapor per unit volume of space. It is usually expressed in grams per cubic meter or grams per cubic foot.

2. Relative humidity is the ratio of the amount of water vapor actually present in the air to the amount required to saturate the air at that temperature and pressure.

3. Specific humidity is the weight of water vapor per unit weight of moist air. It is usually expressed in grams per kilogram.

4. Vapor pressure is the partial pressure of the water vapor in the atmosphere. It is expressed in the same units as atmospheric pressure.

5. Dew point is the temperature at which condensation would take place if the air were cooled at constant pressure.

6. Mixing ratio is the ratio of water vapor to dry air. It is usually expressed in grams per kilogram.

The highest possible absolute humidity is directly dependent upon temperature and it doubles for about each 10 C of temperature increase. The world extremes of absolute humidity occur in the coldest polar and hottest tropical air. Variations of atmospheric water vapor content closely follow the variations of temperature. Up to about 140,000 feet, absolute humidity decreases with altitude. It is limited by the cooler temperatures, which cannot support large amounts of vapor. For the very warm levels of the atmosphere, at altitudes between 140,000 and 200,000 feet and above 400,000 feet, the pressure is too low to permit liquid water.

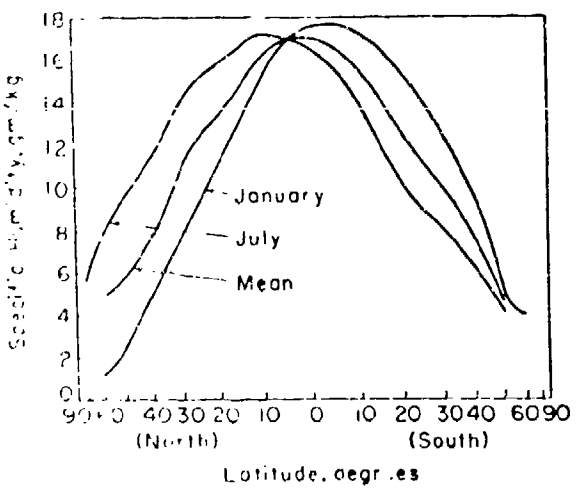


Fig. 2-19. Latitudinal distribution of specific humidity. /27/

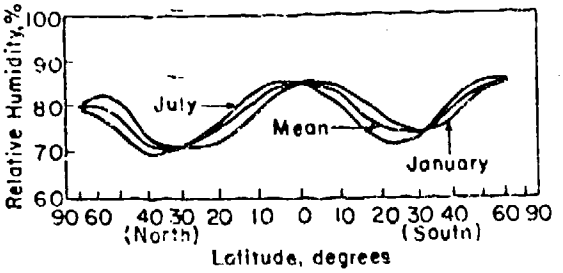


Fig. 2-20. Latitudinal distribution of relative humidity./27/

Figure 2-19 shows the latitudinal and seasonal variations of specific humidity. Specific humidity is greatest over the equator and decreases toward the poles. It is highest in the summer and lowest in the winter, and follows a daily cycle in accordance with temperature changes.

The geographical distribution of relative humidity (Fig. 2-20) is different from that of specific humidity. Relative humidity is highest at the equator and decreases toward the middle latitudes. From about latitude 30° toward the poles the relative humidity increases as a result of decreasing temperature. The seasonal distribution of relative humidity varies with latitude. From about 30° North to 30° South the average relative humidity is greater in summer than in winter, while at higher latitudes the reverse is true. The latter situation is caused by the low winter temperatures, especially those over land masses.

Although the relative humidity in the jungle occasionally drops to as low as 70 percent, it frequently averages more than 95 percent for months at a time. At the dry extreme, relative humidity rarely falls below 5 percent for longer than four hours, even in the hottest deserts.

Hail

Hail is formed only in well developed thunderstorms, and may be encountered in, under and near such storms. Hail reaching the ground occurs most often over mid-latitude mountainous areas, such as in Colorado and Wyoming. Seasonally, hailstorms are most numerous in summer, while diurnally they occur most frequently in the hours between mid-afternoon and early evening.

Thus, the probability of encountering hail is considerably increased when worst-location, worst-time conditions are assumed.

Hail may be encountered from the ground up to altitudes of about 50,000 feet. However, the probability of encounter increases with altitude up to approximately 15,000 to 16,000 feet, and then decreases rapidly at higher altitudes. Although thunderstorms are generally 5 to 10 miles in diameter, the areas in which hail is encountered are usually 1 to 3 miles in diameter.

The size of hailstones reaching the ground varies considerably. Frequency distribution by size is difficult to establish due to lack of data. The largest hailstone on record in the United States measured 5.4 inches in diameter and weighed 1.5 pounds. The most common size in the United States is about 0.25 to 0.75 inch in diameter./4,28,29,30/

Sand and Dust

Dust particles range in size from 0.1 to 50 microns in diameter, with the average size being somewhere between 0.5 and 1.5 microns. Dust is released from many natural and man-made sources, such as volcanic eruptions, salt sea spray, blowing soil, sand storms, plant pollen and bacteria, smoke and ashes of forest fires, and cosmic material. Dust is present in desert climates throughout the year. In the tropics it occurs only occasionally. Fine sand, silt, volcanic ash and soft rock form dust very quickly after a rain. Distribution of dust aloft varies with season, climatic area and time of day.

Sand particles range in size from about 50 microns upward, with the average size of wind-blown sand particles being about 150 and 300 microns./8,44/ Sand is seldom lifted more than five feet above the earth's surface, and the bulk of the movement takes place a few inches off the ground. A wind velocity of about 11 mph is necessary to set the grains of sand in motion. Wind-blown sand and sand storms are most frequent in desert regions, which have high daytime temperatures and low night-time temperatures, with little rainfall or moisture./4,14/

Magnetic Field

As a first approximation, the Earth's magnetic field resembles the field of a single, large magnetic dipole situated in the Earth's core, but not exactly at the center. The field is strongest near the magnetic poles, and decreases in strength towards the magnetic equator. The south magnetic pole is stronger than the north one, indicating that the effective center of the dipole is nearer that end of the Earth. The strength of the field at the south magnetic pole is slightly more than 0.7 oersteds. Above the Earth's surface, the strength of the geomagnetic field varies approximately as the cube of the distance to the center of the Earth. This relationship holds to an altitude of about 300,000 feet./13/

The direction of the Earth's magnetic field is expressed in terms of declination, which is the deflection of the field from north-south, and dip, which is the deflection of the field from the horizontal. The Earth's field is not fixed, but gradually changes with time. In the United States, the Coast and Geodetic Survey and the Navy Hydrographic Office are responsible for supplying up-to-date information on the geomagnetic field./31/

Radiation

Types of radiation are classified according to wavelength. The shortest known radiation type is cosmic rays, followed by gamma rays, x-rays, ultraviolet rays, visible light, infrared rays and radio, or hertzian rays. Figure 2-21 shows the radiation spectrum on a logarithmic scale. Radiation wavelengths are generally measured in terms of:

Angstom units (A) -- equal to 1×10^{-10} meter or 1×10^{-7} millimeter.

Millimicron (mμ) -- equal to 1×10^{-3} μ or 10 A.

Micron (μ) -- equal to 1×10^{-3} millimeter or 10,000 A.

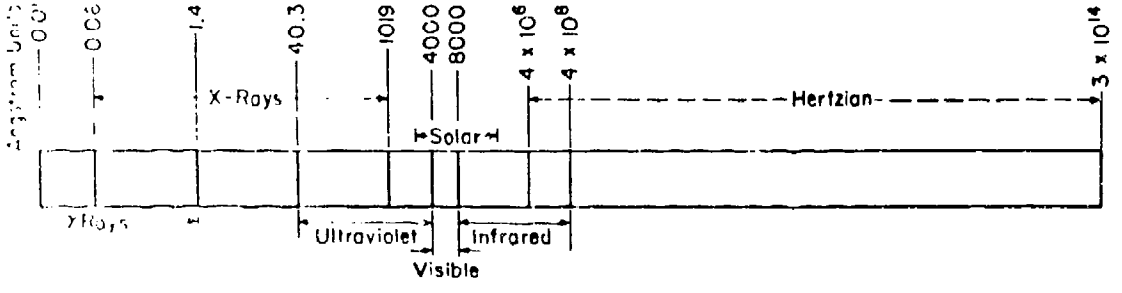


Figure 2-21. Radiation spectrum on logarithmic scale./14/

Solar radiation comprises infrared and ultraviolet radiation, as well as visible light. Solar radiation wavelengths are between 1500 and 1,200,000 A or 0.15 to 120 microns. Most of the solar radiation energy lies between the wavelengths of 1500 and 40,000 A. Half of this energy is in the visible region between 4000 and 7000 A, and the other half lies in the invisible ultraviolet and infrared range./14/ Figure 2-22 illustrates the solar spectrum from about 0.2 to 3 microns, or 2000 to 30,000 Angstrom units.

The most important factors determining the amount of solar energy received by any portion of the Earth's surface are the length of day and angle of the Sun's rays. Discounting the effects of variable elements, such as the Earth's atmosphere and cloud cover, all places on a given parallel receive the same amount of solar energy. However, different parallels of latitude receive varying amounts of energy. The amount of solar energy varies from almost zero at the poles to approximately 900 gram calories per square centimeter per day at the equator./14/ The amount of solar radiation absorbed by a vehicle will also be determined by the altitude of the vehicle. Much of the solar radiation entering the atmosphere is absorbed, scattered and reflected. Therefore, more radiation will reach a vehicle at the higher altitudes.

Cosmic Radiation

Cosmic radiation may be defined as radiation with sufficient energy to penetrate to the Earth's surface through the atmosphere. Cosmic ray energy levels are considered constant with time and have no preferred orientation./33/ Some cosmic rays can be identified as coming directly from the Sun during periods of violent solar activity. The rest arrive in equal numbers from all directions./34/ Nearly 10^{18} (a billion billion) cosmic-ray particles enter the Earth's atmosphere every second. Most of them possess energy of a few billion electron volts. A small fraction, however, have energies greater than 10^{11} electron volts./34/ Primary cosmic radiation penetrates the Earth's atmosphere to an altitude of 10 to 25 miles, where it interacts with protons and neutrons in the air to produce mesons. The mesons, in turn, travel

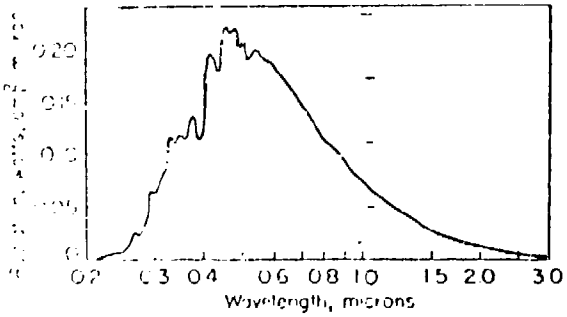


Fig. 2-22. Solar spectrum./6/

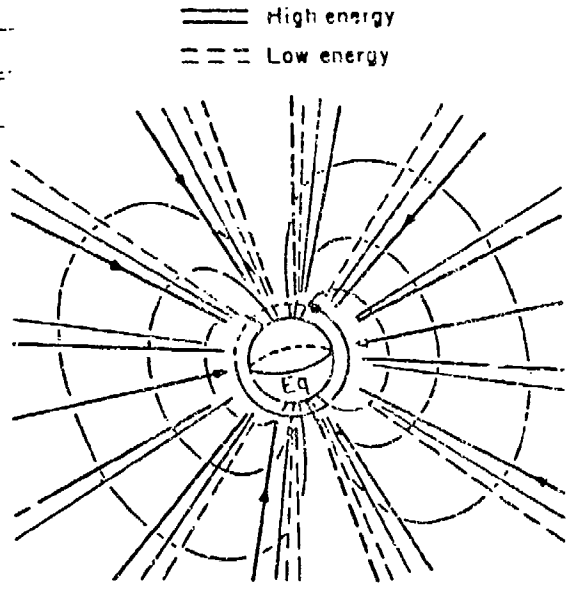


Fig. 2-23. Cosmic rays penetrating Earth's geomagnetic field./6/

through the atmosphere where they undergo energy loss. When the mesons decay, they emit electrons and uncharged particles. The atmosphere thus contains a mixture of primary and secondary radiations in proportions dependent on altitude. Many of the secondary cosmic rays interact to produce further secondary rays, thus producing a shower effect./4,14/

Before cosmic radiation particles reach the Earth's atmosphere, they have been drawn off their original course by the Sun's and Earth's magnetic fields. The Earth's magnetic field allows only high energy particles to reach the surface at the equator, and particles of low energy can enter only at the poles./6/ The geomagnetic field, as shown in Fig. 2-23, does not retard cosmic rays, but induces entry of the highest flux of particles at the poles.

Cosmic radiation increases with altitude from sea level until it reaches a maximum between 55,000 and 80,000 feet. Above this altitude, the combined primary and secondary cosmic radiation falls off rapidly to the primary component.

Van Allen Radiation Belt

Instrumented satellites and lunar probes Pioneer I and Pioneer III have shown the existence of a radiation belt around the Earth, known as the Van Allen radiation belt. This belt consists of charged particles trapped in

the Earth's magnetic field. The lower edge of the belt is approximately 1000 miles above the Earth's surface and extends into the atmosphere for a distance of several Earth radii. The radiation is most intense in the equatorial plane, decreasing in extent and intensity polewards.

A comparatively narrow inner core of high energy particles, formed from cosmic ray particles with energies of up to several hundred mev, exists several thousand miles above the Earth's surface. Surrounding this "hard belt" is a halo of lower energy particles that covers a much larger area.

Intensities of 5.5 roentgen per hr have been recorded by the Pioneer I probe at a distance of 3.8 Earth radii; the radiation intensity decreases to less than 0.2 roentgen per hr at a distance of 9 Earth radii./35/

MOON

The Moon is about 240,000 miles from the Earth. The most prominent feature of the Moon's surface is the dark plains, which are known as mares. These plains are usually circular and range in diameter from about 200 miles to over 700 miles.

Thousands of craters cover the Moon's surface. Clavius, which is the largest, has a diameter of over 150 miles and is 20,000 feet deep. Mountain ranges on the Moon are similar to those on Earth, ranging in size from 5000 feet to over 25,000 feet. It is believed that the Moon's surface is covered with pulverized rock and dust; however, at present, no definite statement can be made about the mineral composition or thickness of this upper layer. Probably, it is only several centimeters thick. Due to the continuous bombardment of meteors, the Moon's surface is very rough. Nothing is known about the small details, however, since the smallest formations that can be distinguished are several hundred feet in diameter.

Some of the Moon's physical features are listed below: /7,10,36/

Diameter	2160 miles
Volume	519.8×10^7 cubic miles
Volume (ratio to Earth)	0.02
Mass	810.1×10^{17} tons
Mass (ratio to Earth)	0.0123
Density	208.73 pounds/cubic foot
Density (ratio to Earth)	0.606
Density (ratio to water)	3.33
Surface gravity	5.1476 feet/sec^2
Surface gravity (ratio to Earth)	0.16
Escape velocity	1.50 miles/second
Albedo	0.07
Maximum distance from Sun	94.8×10^6 miles
Mean distance from Sun	93.0×10^6 miles
Minimum distance from Sun	91.2×10^6 miles
Maximum distance from Earth	252,948 miles
Mean distance from Earth	238,840 miles
Minimum distance from Earth	221,593 miles
Orbital speed	0.6 mile/second
Orbit eccentricity (eccentricity of circle = 0)	0.055
Orbit inclination	5° 8′
Inclination of axis	6° 3′
Length of time to complete one revolution around Earth	27.3217 Earth days
Length of day	27.3217 Earth days

Atmosphere

The moon has little if any observable atmosphere; its density being approximately 10^{-10} Earth atmospheres or less, which is more rarified than the F_2 region of the Earth's atmosphere. Argon is the most probable atmospheric constituent, although xenon, krypton, carbon dioxide, sulfur dioxide and water vapor may also be present.

Meteorites, cosmic dust and other celestial particles bombard the Moon at velocities ranging from 1.5 to about 4.4 miles per second. Since there is very little atmosphere, the meteoritic bodies will not disintegrate, and even the smallest particles will reach the Moons' surface intact./37,38,39/

Temperature

Since the Moon has practically no atmosphere to shield its surface and minimize radiation of its heat, the daily temperature variation is very large. At noon the temperature is about 240 F (115 C). At sunset the temperature reaches 32 F (0 C); it finally reaches a low of approximately -243 F (-153 C) at midnight. The great temperature ranges are partly due to the Moon's

low albedo value of 0.07, compared with that of the Earth, which has an albedo of 0.29. The Moon therefore radiates into space only seven percent of the solar heat received./36,37,38/

Radiation

Intense light and ultraviolet radiation from the Sun hit the Moon's surface. Due to its long exposure to solar radiation, the surface of the Moon probably has a simple molecular structure.

MERCURY

Mercury, an almost perfect sphere, is the innermost planet in our Solar System, and the smallest of the principal planets. Due to its small size and unfavorable conditions for observation, it is difficult to observe distinct surface markings. However, dark patches, similar to the Moon's plains, can be seen telescopically. Mercury's surface probably consists of mountainous and rocky terrain./1,10,36/

Mercury rotates on its axis only once in each trip around the Sun, thus always keeping the same side exposed to sunlight. The sunlit side is therefore extremely hot, and the dark side extremely cold. A day and a year are equal on Mercury, being the equivalent of 88 Earth days. Some of Mercury's physical features are listed below./1,3,10,36/

Diameter	3107 miles
Volume	155.9×10^8 cubic miles
Volume (ratio to Earth)	0.006
Mass	26.345×10^{19} tons
Mass (ratio to Earth)	0.04
Density	237.66 pounds/cubic foot
Density (ratio to Earth)	0.69
Density (ratio to water)	3.8
Surface gravity	8.6866 feet/sec^2
Surface gravity (ratio to Earth	0.27
Escape velocity	2.237 miles/second
Albedo	0.07
Maximum distance from Sun	43.4×10^6 miles
Mean distance from Sun	36.0×10^6 miles
Minimum distance from Sun	28.6×10^6 miles
Maximum distance from Earth	136.0×10^6 miles
Minimum distance from Earth	50.0×10^6 miles
Orbital speed (average)	29.76 miles/second
Orbit eccentricity	0.206
Orbit inclination	7° 0'
Inclination of axis	Unknown
Length of time to complete one revolution around Sun	87.9 Earth days
Length of day	88 Earth days
Number of moons	0

Atmosphere

Because of Mercury's small mass, high temperatures and small escape velocity, it is almost certain that it possesses only an insignificant atmosphere. None of the lighter atmospheric constituents, such as nitrogen, oxygen or water vapor, could be held for long. However, Mercury may contain a slight atmosphere of thinned out heavy gases, such as carbon dioxide. Recent observations indicate that Mercury's atmosphere may have a thickness about 0.0003 that of the Earth, and exert a pressure of one millibar per square centimeter, compared to the Earth's sea level pressure of 1013.2 millibars./3,10,36/

Temperature

Because of its relative nearness to the Sun, Mercury receives on the average about seven times as much heat per unit area as the Earth. However, the amount of heat received varies considerably due to the eccentricity of its orbit. Also, since Mercury has hardly any atmosphere, the temperature difference between the dark and sunlit sides is very large. On the dark side, the temperature is near absolute zero, and on the sunlit side, the temperature is about 784 F (412 C). Only twilight areas may have moderate temperatures./10,36/

VENUS

Of all the planets in our solar system, Venus most closely resembles the Earth in mass, size and density. As a result, Venus is often referred to as Earth's sister planet. Surrounding Venus is a dense cloud or haze layer that prevents observation of the surface. As a result, very little is known about Venus' surface. From all available information, it is believed that the surface of Venus is probably hot, dry and windy. The albedo of Venus is very high, 0.60, which means that 60 precent of the sunlight is reflected back into space. The major physical

characteristics of Venus are listed below. /3,10,36,40,41/

Diameter	7705 miles
Volume	239.1×10^9 cubic miles
Volume (ratio to Earth)	0.92
Mass	5.36472×10^{21} tons
Mass (ratio to Earth)	0.82
Density	306.54 pounds/cubic foot
Density (ratio to Earth)	0.89
Density (ratio to water)	4.86
Surface gravity	27.6083 feet/sec^2
Surface gravity (ratio to Earth)	0.86
Escape velocity	6.338 miles/second
Albedo	0.59
Maximum distance from Sun	67.8×10^6 miles
Mean distance from Sun	67.3×10^6 miles
Minimum distance from Sun	66.8×10^6 miles
Maximum distance from Earth	160×10^6 miles
Minimum distance from Earth	26×10^6 miles
Orbital speed	21.75 miles/second
Orbit eccentricity	0.007
Orbit inclination	3° 24'
Inclination of axis (approximate)	0°
Length of time to complete one revolution around Sun	225 Earth days
Length of day	8 to 46 Earth days
Number of moons	None

Atmosphere

The atmosphere of Venus is at least 20 miles thick, and denser than that of the Earth. Underlying Venus' atmosphere are either dust or water vapor clouds. The pressure near the cloud top lies between 1/6 and 4 Earth atmospheres. Above the cloud top, the pressure decreases by a factor of about 2 every 3 miles./40/ At higher altitudes, approximately 65 miles above the cloud layer, a region similar to the Earth's ionosphere and exosphere may exist. The temperature in this region may be more than 1500 K./36/

The only atmospheric gas that has been positively identified is carbon dioxide. Other gases, such as oxygen and nitrogen oxide, may also be present, but only in very minute quantities. In Venus' upper atmosphere, ionized atoms and molecules, as well as free electrons, probably exist due to absorption of short wavelength solar radiation./36,40/

Temperature

Venus receives about twice as much heat from the Sun as does the Earth. But, since Venus is covered with a dense atmosphere, and according to its albedo reflects about twice as much sunlight as does the Earth, the temperature on Venus is uncertain; however, it is undoubtedly higher than on Earth. The carbon dioxide found in Venus' atmosphere is very transparent to visible light and ultraviolet radiation. It is also an excellent absorber of the heat radiated from the planet's surface. As a result, if carbon dioxide is as abundant in the atmosphere as spectroscopic investigations indicate, the temperature on Venus' surface may be very high. The temperatures derived from various observations of Venus fall within the following ranges:/36/

Top of atmosphere	-38 F (-39 C) to 122 F (50 C)
Middle of atmosphere	54 F (12 C) to 117 F (47 C)
Surface of Venus	405 F (207 C) to 603 F (317 C)

As with Earth, daily and seasonal temperature variations occur over the surface of Venus, and the temperature range at the top of its atmosphere is very low.

Radiation and Magnetic Fields

There is evidence that Venus possesses a magnetic field similar to that of the Earth. The field around Venus, however, is about five times stronger than that surrounding the Earth./36/

The intensity of solar radiation just outside the Venus atmosphere is approximately 1.9 times the intensity outside the Earth's atmosphere, or 3.8 cal per cm^2 per min. It is also believed that the existence of a radiation belt, such as the Van Allen radiation belt surrounding the Earth, may exist on other planets with magnetic fields. Since Venus absorbs about twice as much radiation as the Earth, the radiation belt around Venus may be more intense than that surrounding the Earth./40/

MARS

More complete information is available concerning Mars than any other planet, with the exception of the Earth. However, details as to the exact surface conditions on Mars still are uncertain. Mars' surface is very flat, with no abrupt changes in elevation and no prominent mountains. Bright areas, covering more than half the surface, are believed to be dust-covered desert areas. In the bright areas, dark, narrow streaks, known as canals, have been observed. The dark areas show seasonal changes and may be areas of vegetation. The white polar caps are believed to be caused by a thin deposit of ice crystals. The "climate" on Mars is similar to that of a hypothetical desert on Earth about 11 miles high. Winds range up to 20 mph and dust storms are fairly frequent./1,36,42/ The major physical characteristics of the planet Mars are listed below./1,10,36,42/

Diameter (average)	4215 miles
Volume	389.85×10^8 cubic miles
Volume (ratio to Earth)	0.15
Mass	72.44864×10^{19} tons
Mass (ratio to Earth)	0.11
Density	241.1 pounds/cubic foot
Density (ratio to Earth)	0.70
Density (relative to water)	4.0
Surface gravity	11.9 feet/sec^2
Surface gravity (ratio to Earth)	0.37
Escape velocity	3.107 miles/second
Albedo	0.15
Maximum distance from Sun	154.9×10^6 miles
Mean distance from Sun	141.7×10^6 miles
Minimum distance from Sun	128.5×10^6 miles
Maximum distance from Earth	236.0×10^6 miles
Minimum distance from Earth	31.0×10^6 miles
Orbital speed	14.975 miles/second
Orbit eccentricity	0.093
Orbit inclination	1°51'
Inclination of axis	25°12'
Length of time to complete one revolution around Sun	687 Earth days
Length of day	1.026 Earth days
Number of Moons	2

Atmosphere

Mars' atmosphere has been studied for many years; yet much of the information gathered is speculative. The only gas identified in the Martian atmosphere is carbon dioxide, which, although only one percent by volume in the total atmosphere, is several times more abundant per square centimeter than in the Earth's atmosphere. The bulk of the Martian atmosphere consists of nonabsorbing gases, such as nitrogen, 95% by volume, argon, and only a trace of oxygen./3,10,42,43/

Mars' atmosphere has a variety of cloud types. "Yellow clouds" persist for weeks over large areas of the planet, and are believed to be dust clouds. Water vapor or mist clouds occur in the polar regions. All the clouds are below 20 miles. The Martian atmosphere is much thinner than that of the Earth. The surface pressure ranges from 50 to 100 millibars, and the pressure gradient up to 25 miles is only slightly less than the Earth's. Above 25 miles, the pressure decreases very slowly. The Martian atmosphere probably extends considerably farther into space than does the Earth's./36,42,43/

The weather in the lower regions of the Martian atmosphere is similar to that on Earth. However, the lack of appreciable amounts of water vapor causes a more uniform and simpler weather than exists on Earth. The atmospheric temperature decreases with height at an average rate of less than 3.7 K per 3200 feet, up to an altitude of approximately 16 miles. Above 16 miles, the variation of temperature with height is much smaller. Between 16 miles and 85 miles, the temperature is probably 180 K ± 50 K. /36,42,43/

Temperature

The daily, seasonal and geographic temperature variations on Mars are not completely known; however, they are currently being investigated. The following temperature information is therefore subject to change.

The average temperature on the surface of Mars is about -30 C (-22 F). The daily variation of temperature near the equator is approximately 30 C (86 F) at noon to -60 (-76 F) or -80 C (-112 F) at night. In the polar region, the average temperature is -70 C (-94 F). The large variations of temperature occur because of the relatively thin atmosphere and the absence of any large amount of water vapor./1,3,36,43/

Radiation

The average solar radiation incident on Mars is approximately one-half the amount received by the Earth, or about 0.87 gram-cal per cm^2 per min. Due to the eccentricity of Mars' orbit, however, this value may vary by as much as 20 percent during the Martian year. Mars' albedo is approximately 0.15, which indicates that the Martian atmosphere and surface absorb a large fraction of the solar radiation./42/

JUPITER, SATURN, URANUS, NEPTUNE AND PLUTO

The four major planets, Jupiter, Saturn, Uranus and Neptune have many characteristics in common. They are massive bodies of low density and large diameter. Because of their low densities, they are believed to possess sizeable solid cores surrounded by a thick shell of ice. The only gases in their atmospheres are ammonia and methane. Other gases may be present, but because of the low temperatures on these planets, the gases are probably in the liquid or possibly solid state./1,3,10,36/

Jupiter

Jupiter, the largest planet, has twelve moons. Jupiter spins so fast on its axis that it is flattened out at its poles. The major physical characteristics of Jupiter are listed below./2,3,10, 36/

Diameter (mean)	86,840 miles
Volume	342.55×10^{12} cubic miles
Volume (ratio to Earth)	1318
Mass	20.1×10^{23} tons
Mass (ratio to Earth)	318.3
Density	82.66 pounds/ cubic foot
Density (ratio to Earth)	0.24
Density (relative to water)	1.34
Surface gravity	84.93 feet/sec^2
Surface gravity (ratio to Earth)	2.64
Escape velocity	37.28 miles/ second
Albedo	0.44
Maximum distance from Sun	507.1×10^6 miles
Mean distance from Sun	483.9×10^6 miles
Minimum distance from Sun	460.7×10^6 miles
Maximum distance from Earth	600×10^6 miles
Minimum distance from Earth	367×10^6 miles
Orbital speed	8.45 miles/ second
Orbit eccentricity	0.048
Orbit inclination	1°18'
Inclination of axis	3°7'
Length of time to complete one revolution around Sun	11.86 Earth years
Length of day	9 hours 55 minutes
Number of moons	12

Saturn

Saturn is circled by three rings which consist of millions of small satellites. In addition, Saturn has nine moons. Titan, the largest and brightest of the moons, is considerably larger than our own Moon, and is the only satellite in the solar system known to have an atmosphere. /3/ The major physical characteristics of the planet Saturn are listed below./1,10,36/

Diameter (mean)	71,520 miles
Volume	211.29×10^{12} cubic miles
Volume (ratio to Earth)	736
Mass	6.28×10^{23} tons
Mass (ratio to Earth)	95.3
Density	44.78 pounds/ cubic foot
Density (ratio to Earth)	0.13
Density (relative to water)	0.715
Surface gravity	37.64 feet/sec^2
Surface gravity (ratio to Earth)	1.17
Escape velocity	22.37 miles/ second
Albedo	0.42
Maximum distance from Sun	936.8×10^6 miles
Mean distance from Sun	887.1×10^6 miles

Minimum distance from Sun	837.4 x 10^6 miles
Maximum distance from Earth	1025 x 10^6 miles
Minimum distance from Earth	745 x 10^6 miles
Orbital speed	5.965 miles/second
Orbit eccentricity	0.056
Orbit inclination	2°29′
Inclination of axis	26°45′
Length of time to complete one revolution around Sun	29.46 Earth years
Length of day	10 hours, 38 minutes
Number of moons	9

Uranus

Uranus has five satellites and an atmosphere composed almost entirely of methane, with only a trace of ammonia gas present. The major physical characteristics of Uranus are listed below./1,3,10,36/

Diameter (average)	31,690 miles
Volume	226.34 x 10^{11} cubic miles
Volume (ratio to Earth)	64
Mass	96.87 x 10^{21} tons
Mass (ratio to Earth)	14.7
Density	79.22 pounds/cubic foot
Density (ratio to Earth)	0.23
Density (relative to water)	0.92
Surface gravity	29.6 ft/sec^2
Surface gravity (ratio to Earth)	0.92
Escape velocity	13.05 miles/sec
Albedo	0.45
Maximum distance from Sun	1868.7 x 10^6 miles
Mean distance from Sun	1784.8 x 10^6 miles
Minimum distance from Sun	1700.9 x 10^6 miles
Maximum distance from Earth	1950 x 10^6 miles
Minimum distance from Earth	1615 x 10^6 miles
Orbital speed	4.225 miles/second
Orbit eccentricity	0.047
Orbit inclination	0°46′
Inclination of axis	98°
Length of time to complete one revolution around Sun	84.02 Earth years
Length of day	10 hours, 42 minutes
Number of moons	5

Neptune

Neptune is invisible to the naked eye and has two known satellites. Its atmosphere extends to perhaps 2000 miles, and the planet experiences external cold and only partial light. Other major physical characteristics of the planet Neptune are listed below./1,10,36/

Diameter (average)	31,070 miles
Volume	101.36 x 10^{11} cubic miles
Volume (ratio to Earth)	39
Mass	11.4 x 10^{22} tons
Mass (ratio to Earth)	17.3
Density	99.89 pounds/cubic foot
Density (ratio to Earth)	0.29
Density (relative to water)	2.22
Surface gravity	46.33 feet/sec^2
Surface gravity (ratio to Earth)	1.44
escape velocity	14.29 miles/second
Albedo	0.52
Maximum distance from Sun	2820.75 x 10^6 miles
Mean distance from Sun	2796.7 x 10^6 miles
Minimum distance from Sun	2772.65 x 10^6 miles

Maximum distance from Earth	2900 x 10^6 miles
Minimum distance from Earth	2700 x 10^6 miles
Orbital speed	3.355 miles/second
Orbit eccentricity	0.0086
Orbit inclination	1°47'
Inclination of axis	29°
Length of time to complete one revolution around Sun	164.8 Earth years
Length of day	15 hours, 48 minutes
Number of moons	2

Pluto

Very little is known about Pluto. Its mass is believed to be about one-tenth of the Earth's mass, and the eccentricity of its orbit is the greatest of all the principal planets in our solar system. The known physical characteristics of Pluto are listed below./3,10/

Diameter (average)	3600 miles (?)
Volume	24.43 x 10^9 cubic miles
Volume (ratio to Earth)	0.094 (?)
Mass	Unknown
Mass (ratio to Earth)	Unknown
Density	Unknown
Density (ratio to Earth)	Unknown
Density (relative to water)	Unknown
Surface gravity	Unknown
Surface gravity (ratio to Earth)	Unknown
Escape velocity	Unknown
Albedo	0.04
Maximum distance from Sun	4590.45 x 10^6 miles
Mean distance from Sun	3675.3 x 10^6 miles
Minimum distance from Sun	2760.15 x 10^6 miles
Maximum distance from Earth	4650 x 10^6 miles
Minimum distance from Earth	2700 x 10^6 miles
Orbital speed	2.98 miles/sec
Orbit eccentricity	0.249
Orbit inclination	17°19'
Inclination of axis	Unknown
Length of time to complete one revolution around Sun	247.7 years
Length of day	Unknown
Number of moons	0

SUMMARY OF PLANET DATA

A complete summary of all of the planets' characteristics is given in Table 12.

NATURAL AND INDUCED ENVIRONMENTS

In addition to the natural environments previously discussed, all flight vehicles are subjected to induced environments during operation. Some of these induced environments, such as acceleration and vibration, are brought about strictly by the operation of the system; others, such as aerodynamic heating, are caused by interaction of the system with its natural environment. In contrast to all the natural environments, induced environments do not exist without the system.

Some environments, such as temperature, can be both natural and induced. Their effects, however, are the same regardless of how they are produced. The reason for separating environments into the broad categories of natural and induced is that it simplifies the environmental analysis (Chapter 4) during equipment design.

Although the various environments are generally thought of individually, a flight vehicle never encounters them singly, but in combinations. The peaks, or extremes, of the environments may be encountered individually, but nevertheless other, less severe environments are present at the same time and must be considered. In addition, during its mission a vehicle will encounter a continuous gamut of changing environments, each of which may be affected by that which preceded it. The many combinations and sequences of environments that are possible include both the natural and induced types. Thus, adequate information on both natural and induced environments is mandatory if a vehicle is to be designed efficiently and economically for reliable operation. The natural environments have been covered in previous portions of this chapter. The induced environments are discussed in Chapter 3.

Table 2-12. Physical and Positional Properties of the Planets /10/

	Mercury	Venus	Earth	Moon	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Distance (minimum from Sun (mean miles x 10^6 (maximum	28.6 36.0 43.4	66.8 67.3 67.8	91.4 92.0 94.6	91.2 93.0 94.8	128.5 141.7 154.9	460.7 483.9 507.1	837.4 887.1 936.8	1700.9 1784.3 1868.7	2772.65 2796.7 2820.75	2760.15 3675.3 4590.45
Length of time to complete one revolution about Sun	87.97 days	224.7 days	365.26 days	--	687.0 days	11.86 years	29.46 years	84.02 years	164.8 years	247.7 years
Length of day	88 days	30 days	1 day	27.3217 days	1.026 days	9 hrs 55 min	10 hrs 38 min	10 hrs 42 min	15 hrs 48 min	Unknown
Orbital (speed, mi/sec)	29.76	21.75	18.517	0.6	14.975	8.45	5.965	4.225	3.355	2.98
(eccentricity)	0.206	0.007	0.017	0.055	0.093	0.048	0.056	0.047	0.0086	0.249
(inclination)	7°0'	3°24'	-	5°9'	1°51'	1°18'	2°29'	0°46'	1°47'	17°19'
Volume*	0.05	0.92	1	0.02	0.15	1318	738	64	39	0.094(?)
Mass*	0.04	0.82	1	0.0123	0.11	318.3	95.3	14.7	17.3	Unknown
Density*	0.62	0.89	1	0.606	0.70	0.24	0.13	0.23	0.29	Unknown
Surface Gravity*	0.27	0.86	1	0.16	0.37	2.64	1.17	0.92	1.44	Unknown
Escape velocity mi/sec	2.237	6.338	6.860	1.50	3.107	37.28	22.37	13.05	14.29	Unknown
Mean diameter, miles	3107	7705	7917.5	2160	4269	86,840	71,520	31,690	31,070	3600(?)
Oblateness	0.000	0.000	0.0034	0.000	0.0052	0.065	0.105	0.071	0.022	Unknown
Inclination of axis	Unknown	0°(?)	23°27'	6°30'	25°12'	3°7'	26°45'	98°	29°	Unknown
Albedo	0.07	0.59	0.29	0.07	0.15	0.44	0.42	0.45	0.52	0.04
Moons (known)	0	0	1	-	2	12	9	5	2	0
Distance from (max	135	160	-	0.252,948	236	600	1025	1950	2900	4650
Earth x 10^6 (min	50	26	-	0.221,593	21	367	745	1615	2700	2709

*Ratio to Earth

3. Speed - aerodynamic glide to orbital - 25,460 fps at 275,000 ft.
3. Speed range - re-entry - 25,460 fps at 275,000 ft.
Altitude range - 200,000 to 300,000 feet.

Propeller Driven and Jet Propelled Aircraft

Since conventional propeller driven and jet propelled aircraft depend upon aerodynamic forces for their operation, their entire flight path is confined within the Earth's atmosphere. As a result, they may be subjected to any of the natural environments previously discussed under "Earth." The probability of encountering any particular natural environment, as well as the severity of the environment, depends to a large extent on where the aircraft is operated. For example, flight conditions in polar regions are far different than flight conditions in tropical areas.

Altitude also significantly affects the presence and severity of natural environments. Figure 2-24 shows how some of these environments vary as a function of altitude. The information given in Fig. 2-24 is based on the ARDC Model Atmosphere, 1959 [13].

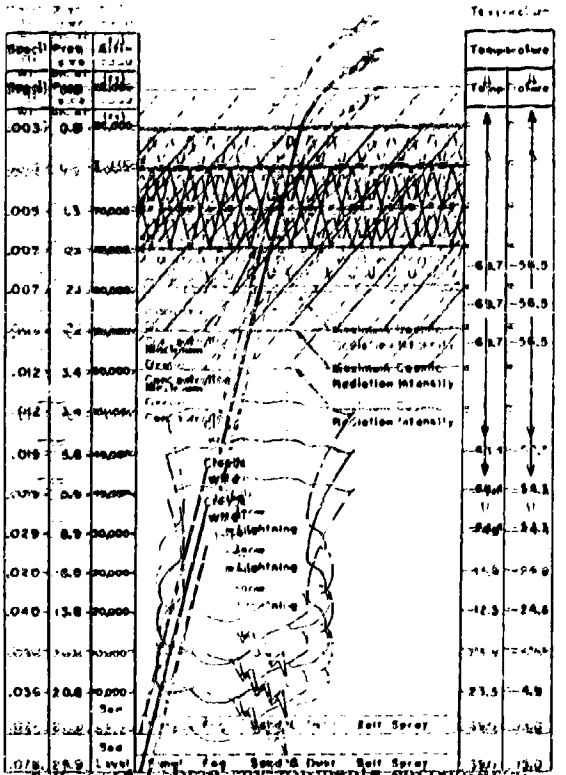


Fig. 2-24. Some environments encountered in aerodynamic flight regime.

Fig. 2-24. Some environments encountered in aerodynamic flight regime.

The type and severity of induced environments encountered by conventional aircraft depend primarily on the kind of aircraft and on its speed. The acceleration at takeoff of propeller-driven and turbo-prop aircraft is generally greater than that of pure jets. Once in the air, however, most jet aircraft experience greater accelerations than do the propeller-driven or turbo-prop types. In addition, aircraft that use some means of rocket assisted takeoff, plus those that employ aerodynamic braking, experience large accelerations.

The induced vibration caused by the engine is also different for various aircraft. In piston-engine aircraft, the vertical up-and-down motion of the pistons sets up low-frequency vibrations that are more severe during landing than during flight. In contrast, the turbines of jet aircraft cause high-frequency vibrations that are most severe during flight.

Aerodynamic heating of an aircraft surface, although always present to some degree during flight, becomes a consideration only under certain conditions of speed and altitude. Flight in the lower, denser layers of the atmosphere, and at high speeds is especially conducive to aerodynamic heating. This, however, is vastly different than the reentry environment of ballistic missiles, satellites and similar vehicles.

Supersonic and Hypersonic Ramjet and Rocket-Powered Vehicles

In general, the natural environments encountered by supersonic and hypersonic ramjet and rocket-powered vehicles are the same as those previously discussed for conventional aircraft. Some of these environments, however, such as low atmospheric pressure and density, are more severe for ramjet and rocket-powered vehicles because of their greater altitude range.

The induced environments and flight paths of hypersonic ramjet and rocket-powered aircraft are closely related to those of the super-aerodynamic rocket glider. They are discussed jointly in the following paragraphs.

Rocket-Powered Super-Aerodynamic Glide Vehicles

Rocket-powered super-aerodynamic glide vehicles use the centrifugal force created by near orbital speeds and a minimum of aerodynamic lift to provide an equilibrium flight path while circumnavigating the Earth in an approximate great circle. During the boost phase, a glide vehicle will experience a severe noise environment. The principal noise source during this phase is the rocket engine, which generates a power level at the exhaust of nearly 200 db at the low ranges of the frequency band. As the vehicle rises, the sound pressure level may drop to about 150 db at the
the booster or at the vehicle

Vibrations during boost
range from 20 to 4000 cps
than 15 g's. During the sus
of the boost phase, vibratio
less than 2.5 g's, and from
about 8.5 g's are likely.
accelerations from the lu
rocket engine are expecte
9 g's. During boost or sepa
order of 50 to 200 g's fo
milliseconds are probable.
tures due to aerodynamic h
to 700 F (260 to 370 C)./44/

The super-aerodynamic
which glide vehicles opera
from the aerodynamic reg
density rather than flight s
tical purposes, in the aero
air is dense enough to be
uum. However, at the hig
quired by the extreme spee
glide vehicles, the air is
ceases to act as a continuu
problem of aerodynamic he
high altitudes, above 500,
layer cannot be formed a
operates at this height its
determined essentially by
irradiation. This results
between the skin temperat
side of the vehicle and on t

The thin atmosphere at
has the effect of converting
of individual molecules, w
pinge on the skin of the
"sputtering" phenomenon t
ting and erosion of the sur

During flight, hyperson
super-aerodynamic vehicl
the physical dimensions a
which depend upon the blu
airfoil leading edges. Den
he shock wave, and in ba
ture and dynamic viscosit
higher than in front.

An induced environment
affect both the glide vehicl
zero gravity. This condit
vehicle's orbital phase.
brief periods during certa

The trajectory of a pro
shown in Fig. 2-25, toget
natural environments ex
hicle's altitude range. I
the atmosphere the natur
countered by a glide vehi
those for other manned
discussed. The environm
ciated with reentry of a
denser portions of the Ea
covered in a later paragra

solar and terrestrial
in large differences
dres on the daylight
he shaded side.

these high altitudes
the air into a stream
hich, when they im
ehicle, can cause a
at may result in pit-
ace.

c aerodynamic and
s set up a shock wave,
d dissipation rate of
nthesis of the nose or
ity increases across
ck of it the tempera-
y of the air are much

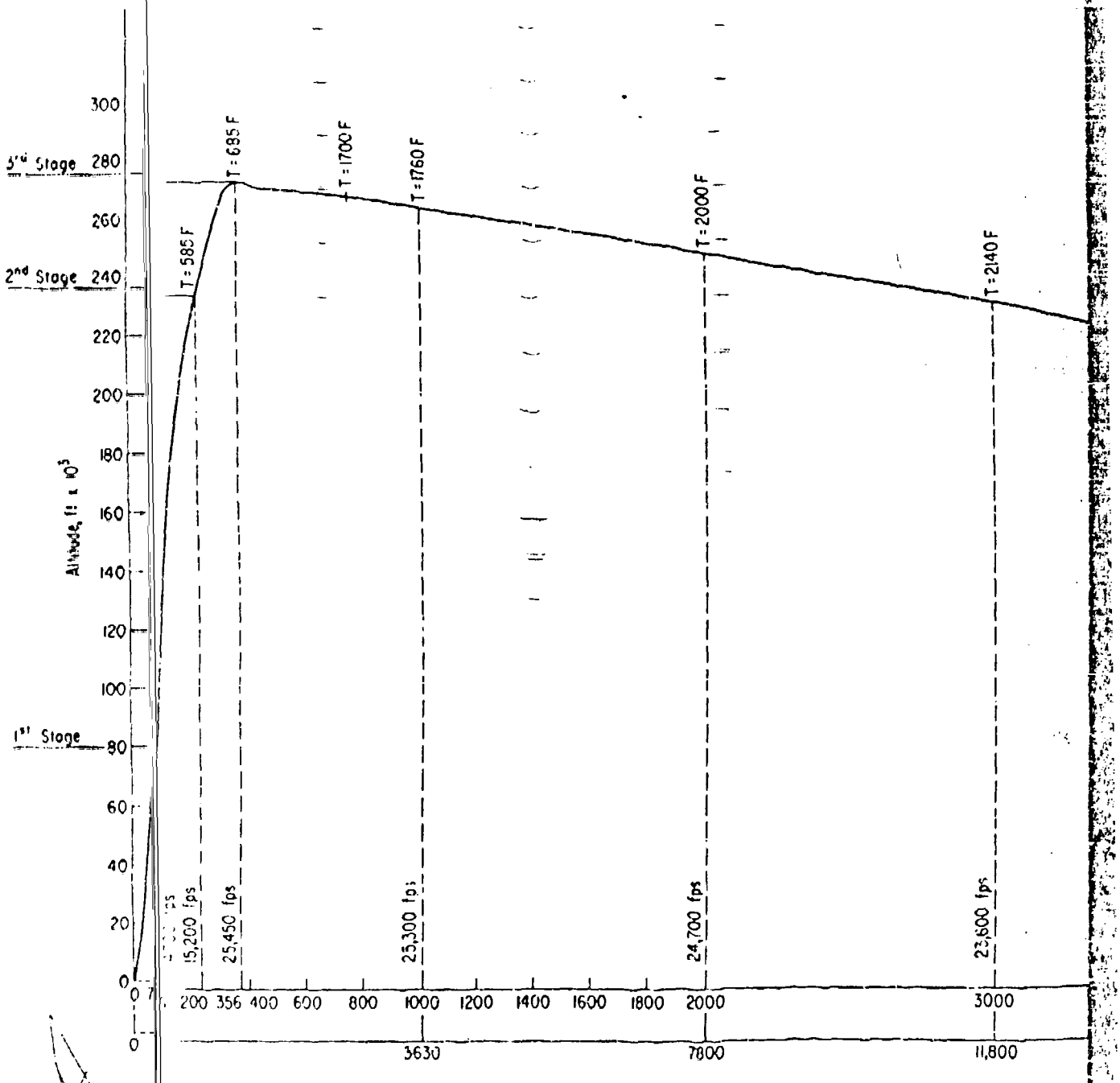
that may seriously
and its occupants is
ion exists during the
t can also occur for
h other maneuvers.

posed glide vehicle is
er with many of the
sting within the ve-
the lower regions of
al environments en-
cle are the same as
vehicles, previously
ental problems asso-
lide vehicle into the
th's atmosphere are
ph.

ipitation data present
hour every hour and
many stations in the
Periods of short and
compared for only a

percentage of time
which clock-hour and
ipitation equal or ex-
h per hour at selected
nple 2-11 considers
o obtain the rates of
fall equal to or ex-
inch per hour must be
etermined that 95 to

ple 2-11 considers
every hour and
percent of time


Altitude, ft x 10³
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
5th Stage
2nd Stage
1st Stage
T = 685 F
T = 1700 F
T = 1760 F
T = 2000 F
T = 2140 F
T = 585 F
15,200 fps
25,450 fps
25,300 fps
24,700 fps
23,600 fps
0
200
356
400
600
800
1000
1200
1400
1600
1800
2000
3000
3630
7800
11,800

T = 2160 F
T = 1900 F
T = 1340 F
20,200 fps
19,700 fps
18,800 fps
17,100 fps
10,900 fps
3000
4000
5000
6000
Time from Launching, seconds
11,900
15,500
18,600
20,900
Distance, nautical miles

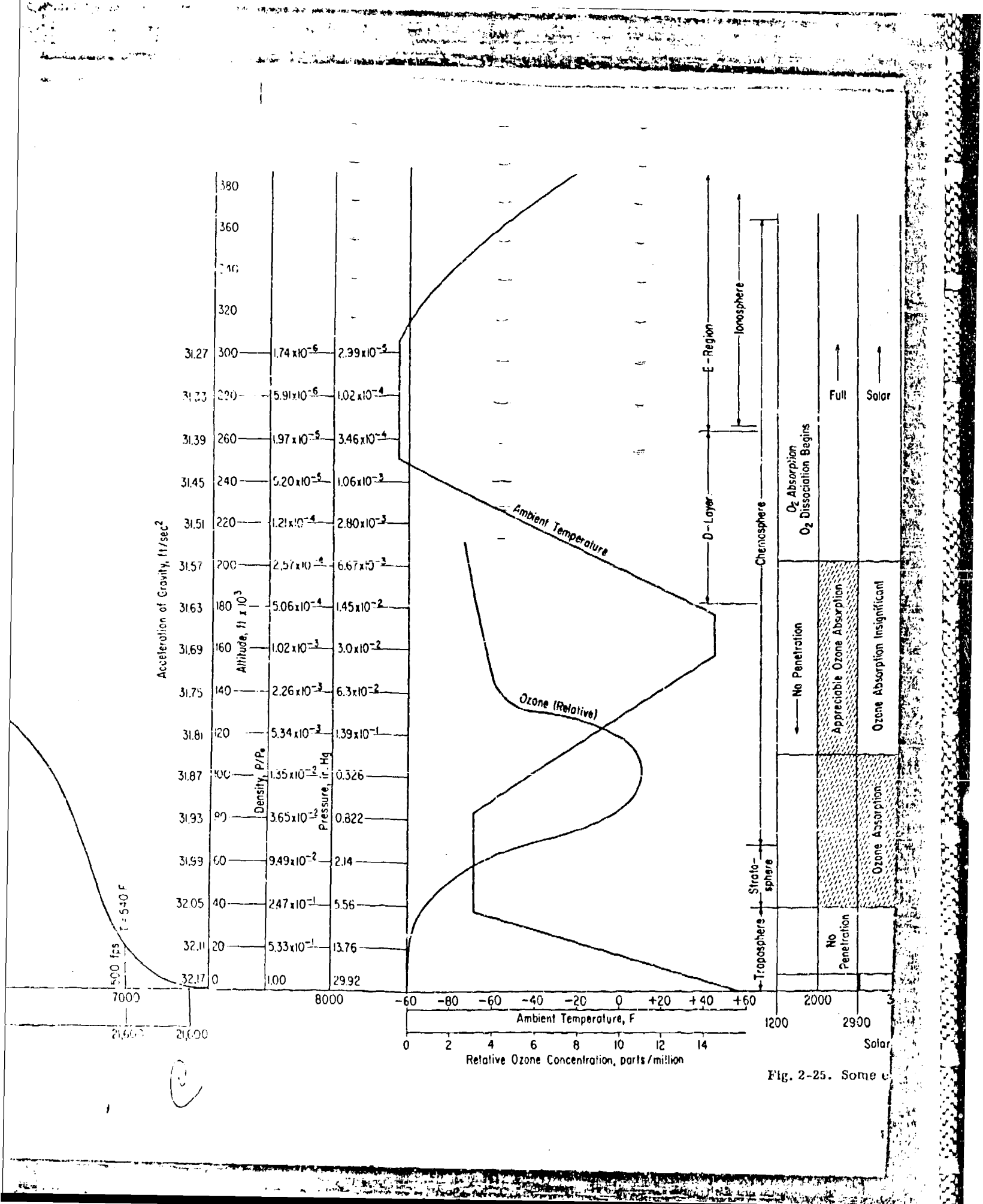


Fig. 2-25. Some c

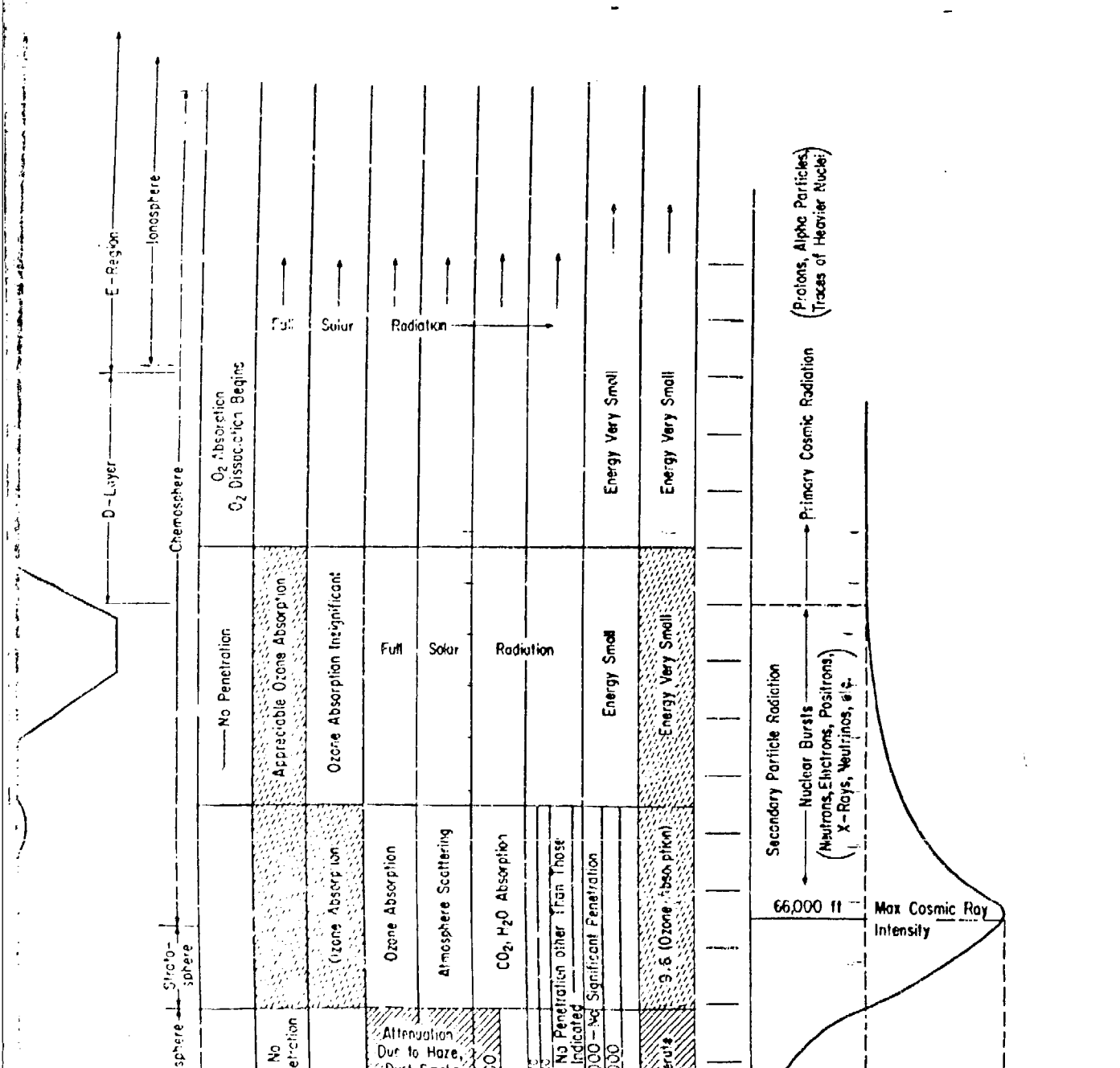


Fig. 2-25. Some environments encountered in super-aerodynamic glide vehicle regime./44/

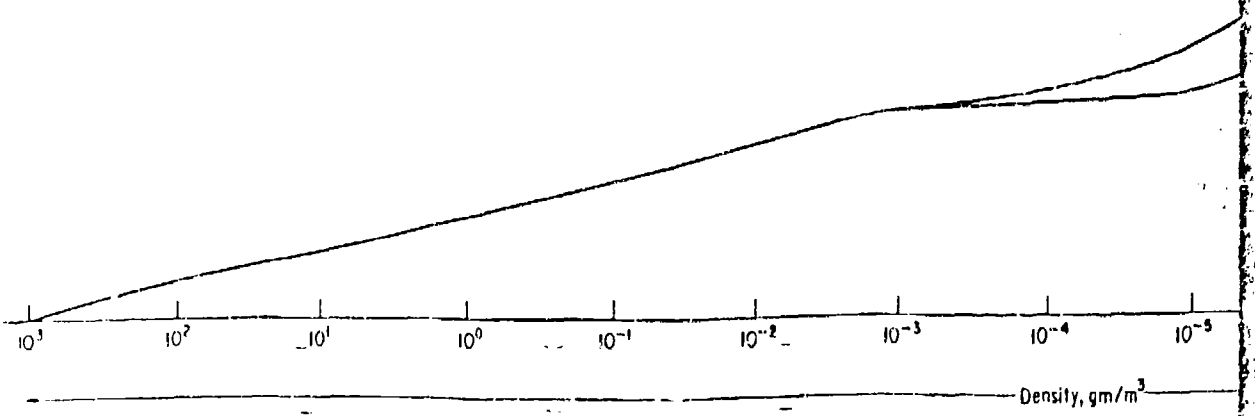
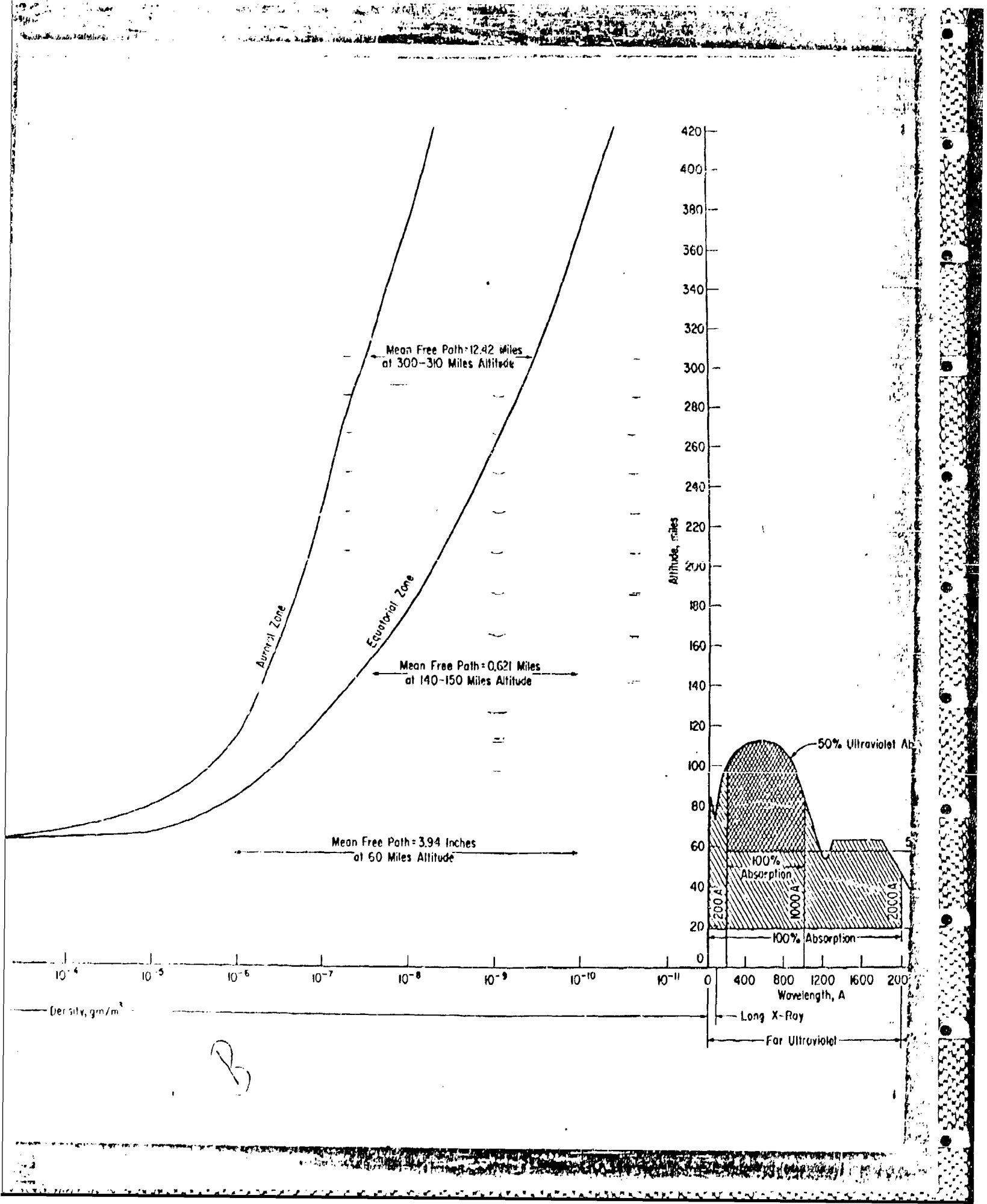
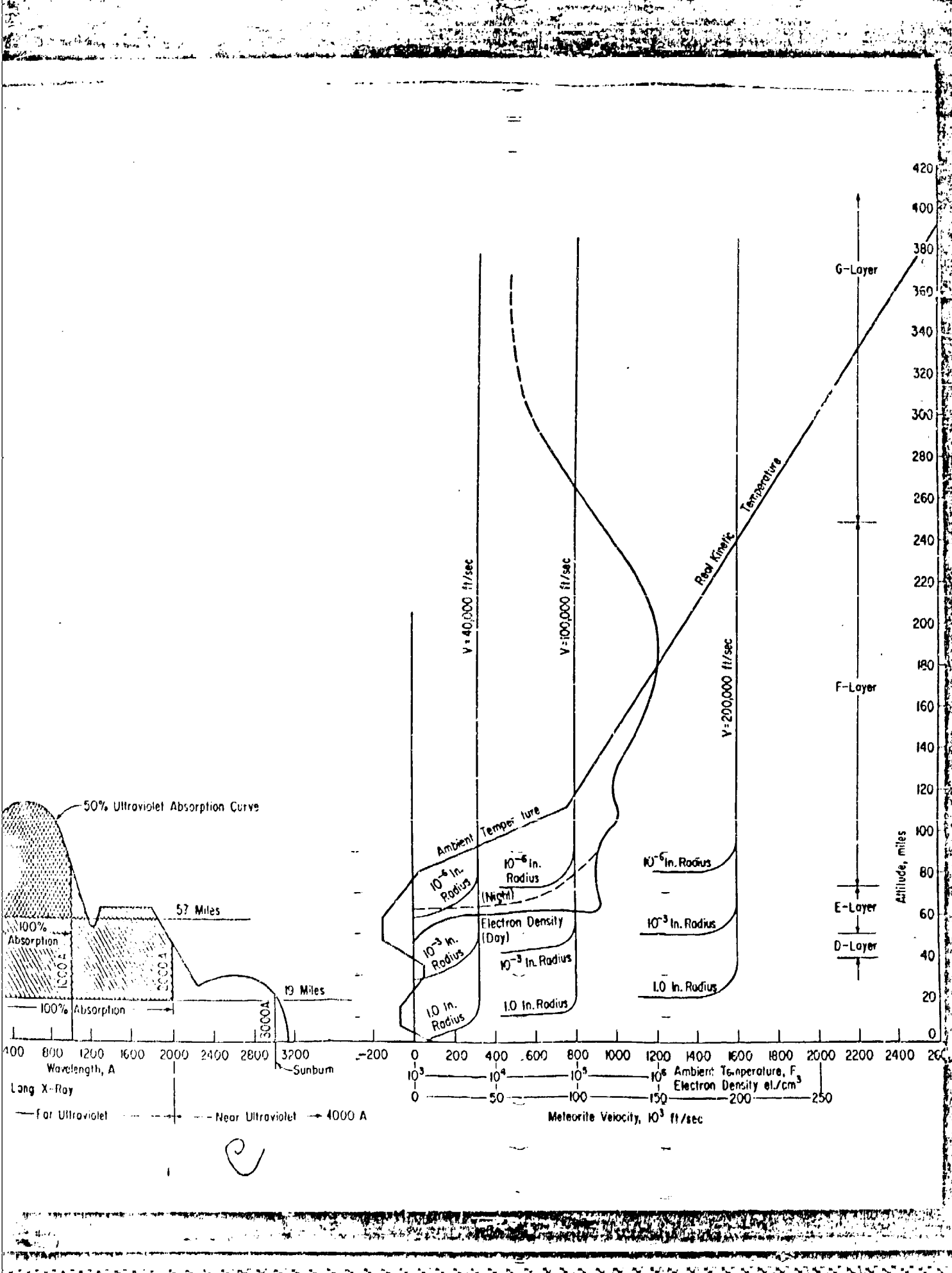
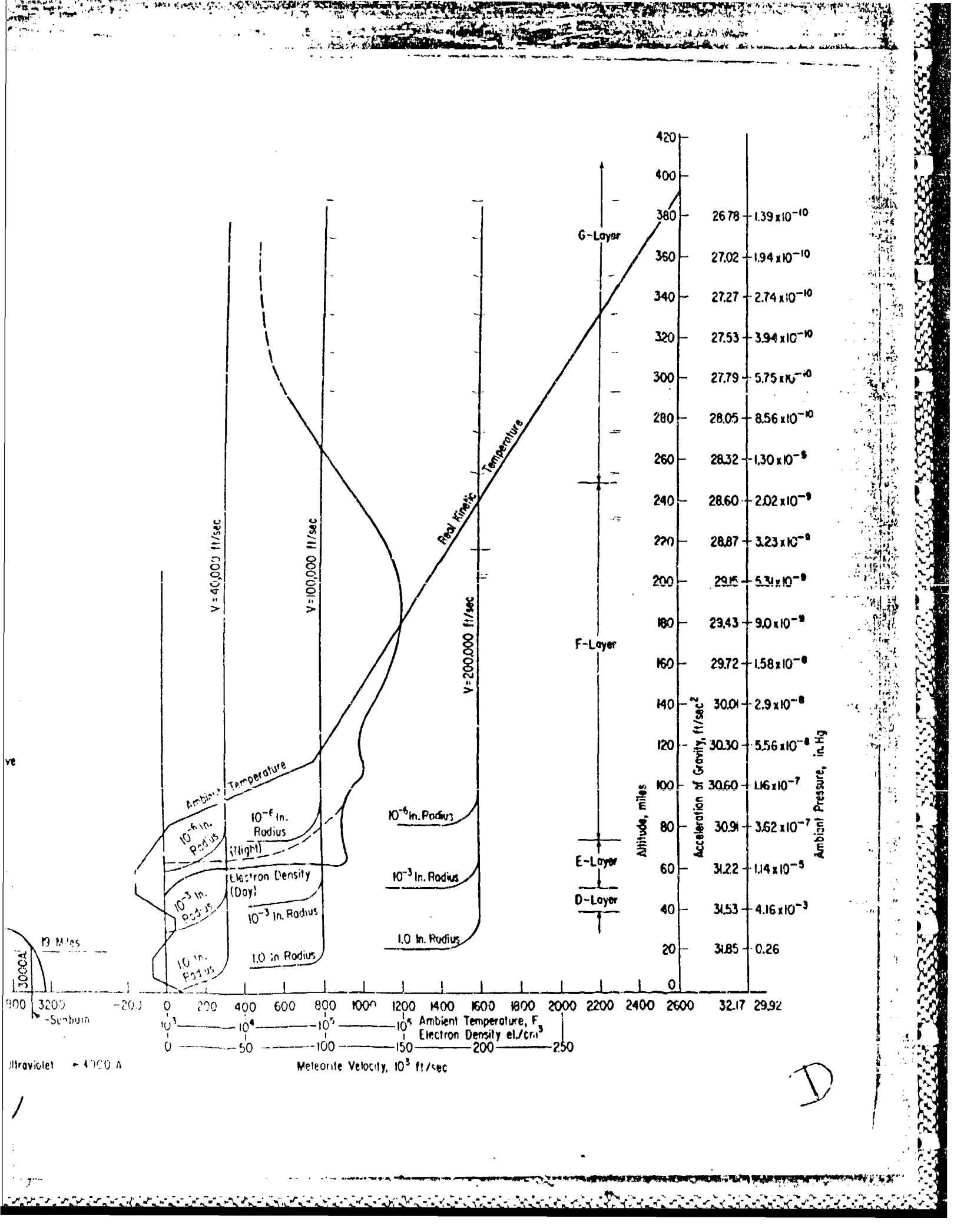


Fig. 2-26. Natural environments up to 420 miles./44/


Mean Free Path = 12.42 Miles
at 300–310 Miles Altitude
Auroral Zone
Equatorial Zone
Mean Free Path = 0.621 Miles
at 140–150 Miles Altitude
Mean Free Path = 3.94 Inches
at 60 Miles Altitude
Altitude, miles
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
50% Ultraviolet Ab
100% Absorption
200 A
1000 A
2000 A
100% Absorption
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Density, gm/m³
0
400
800
1200
1600
200
Wavelength, A
Long X-Ray
Far Ultraviolet


50% Ultraviolet Absorption Curve
57 Miles
100% Absorption
1000 A
2000 A
19 Miles
100% Absorption
3000A
Sunburn
Wavelength, A
Long X-Ray
Far Ultraviolet
Near Ultraviolet
4000 A
V = 40,000 ft/sec
V = 100,000 ft/sec
V = 200,000 ft/sec
Real Kinetic Temperature
Ambient Temperature
10⁻⁶ In. Radius
10⁻⁶ In. Radius (Night)
Electron Density (Day)
10⁻³ In. Radius
10⁻³ In. Radius
1.0 In. Radius
1.0 In. Radius
10⁻⁶ In. Radius
10⁻³ In. Radius
1.0 In. Radius
G-Layer
F-Layer
E-Layer
D-Layer
Altitude, miles
Ambient Temperature, F°
Electron Density el./cm³
Meteorite Velocity, 10³ ft/sec


V = 40,000 ft/sec
V = 100,000 ft/sec
V = 200,000 ft/sec
Real Kinetic Temperature
Ambient Temperature
G-Layer
F-Layer
E-Layer
D-Layer
10⁻⁶ In. Radius
(Night)
Electron Density (Day)
10⁻³ In. Radius
1.0 In. Radius
Altitude, miles
Acceleration of Gravity, ft/sec²
Ambient Pressure, in. Hg
Ambient Temperature, F
Electron Density el./cm³
Meteorite Velocity, 10³ ft/sec
Ultraviolet
Sunburn
3000 A
13 Miles

MISSILES

Missiles may be divided into the following categories:

1. Pilotless conventional aircraft.
2. Pilotless high-supersonic and hypersonic ramjet and glide missiles.
3. Ballistic missiles.

Of the three, only ballistic missiles will be covered, since the mission profiles and accompanying environments of the other two are similar to manned aircraft.

For long-range ballistic missiles, the flight path consists of three sections: (1) powered ascent path, (2) elliptic trajectory, and (3) reentry path. The types and extremes of environments encountered in each of these sections varies. However, a common feature of all the environments encountered is the extreme rapidity with which they change, due to the high velocities attained. Generally, the overall flight time of a ballistic missile is less than an hour, even for ranges as large as half the circumference of the Earth.

Powered Ascent Path

The powered path of a ballistic missile consists of a brief period of intense acceleration during which the missile gains the momentum necessary to carry it along its trajectory. This portion of the flight path begins with engine ignition at launching and ends at the departure point, which is the point at which the rocket engines cutoff and the missile enters the ballistic trajectory towards its destination. For long-range missiles, the departure point lies at an altitude somewhere between 400,000 and 700,000 feet.

Along the lower portion of its powered ascent path, a ballistic missile may encounter any of the natural environments previously discussed. Some of the natural environments present along the upper portion of the powered ascent path are shown in Fig. 2-26.

Some induced environments experienced by a missile include: acceleration, shock, vibration and aerodynamic heating. The acceleration is especially severe, since it is important to propel the missile through the dense, lower layers of the atmosphere as quickly as practicable in order to keep gravitational losses to a minimum.

Elliptic Trajectory

The flight path of a ballistic missile following the powered ascent is a section of an elliptic orbit whose track lies partly below the surface of the Earth. For the purpose of this discussion, the elliptic trajectory can be defined as that part of the flight path between the departure point and the start of reentry.

While traveling in its elliptic trajectory a missile may be disturbed by atmospheric effects or gravitational anomalies. However, for missiles with a range greater than about 200 nautical miles these disturbances are small. Other natural environments that exist along the elliptic trajectory are shown in Fig. 2-26. Long-range ballistic missiles with lofty trajectories may also encounter the Van Allen radiation belt.

An important induced environment encountered by a ballistic missile along its elliptic trajectory is zero gravity. For a missile of the Jupiter range (IRBM), this can last for as long as 11 minutes; for an ICBM it is even longer.

Reentry Path

The reentry path of a ballistic missile starts where the missile enters the aerodynamically relevant atmosphere. The most severe natural environment encountered is the abrupt increase in atmospheric density, which in turn induces deceleration and aerodynamic heating of the missile. As the temperature rises rapidly, an ion sheath is formed around the vehicle. This sheath is bounded by the shockwave and the vehicle and causes communications interference and possibly complete blackout during reentry. /44/ The severity of the induced environments experienced during reentry depends on many factors: the height of the missile trajectory and hence the reentry velocity; the angle of reentry; and the shape of the missile. These are discussed in a latter paragraph.

EARTH SATELLITES

Depending upon the altitude at which they operate, Earth satellites may be divided into two categories: satelloids, and true satellites. The satelloid orbits at comparatively low altitudes, and, because of the existing aerodynamic drag, requires thrust power to overcome the drag and keep the velocity constant. Without this thrust power, the satelloid would be unable to complete even one revolution. The true satellite, on the other hand, orbits at high altitudes where the atmosphere is extremely thin, and thus requires no sustaining thrust power.

Satelloids

The satelloid represents a transition from an aerodynamic vehicle to a true space vehicle. It operates within an altitude range of 60 to 150 nautical miles; too low for a satellite, and generally too high for a glide vehicle. Inasmuch as it operates under sustaining power, the satelloid resembles an aircraft and may be subjected to many of the same induced environments as aircraft, such as vibration, noise, etc.

At low altitudes, the most critical environmental factor affecting satelloid operation is skin temperature resulting from aerodynamic heating. Above about 70 nautical miles, the

amount of skin heating is determined to an increasing extent by solar radiation, and, as a result, large differences exist between the skin temperatures on the lighted and shaded sides of the vehicle. Other natural environments encountered by satelloids are shown in Fig. 2-26.

As a satelloid's orbital lifetime is extended, a certain amount of pitting and erosion of the skin will take place as a result of impact by atmospheric molecules, micrometeorites and other particles. Another important environment encountered by a satelloid, as well as by true satellites, is zero gravity or weightlessness, which prevails for the orbital lifetime.

Satellites

Depending upon the distance at which they orbit the Earth, satellites may be divided into two categories: terrestrial and cislunar. Many of the environments experienced by each are unique and therefore they will be treated separately.

As shown in Fig. 2-27, terrestrial space begins at an altitude of approximately 100 nautical miles, below which true satellite operation is impossible, and extends out to about 10 to 14 Earth radii. From an environmental standpoint, the major considerations in terrestrial space are: (1) atmospheric gases, (2) gravitational anomalies and (3) the geomagnetic field.

The density of the atmosphere, and hence the drag on the satellite, decreases continuously with increasing altitude (Fig. 2-26). The increased orbital lifetimes made possible by the rarified atmosphere increase the exposure time of the satellite to meteoric material. Meteors and micrometeorites are especially concentrated in the plane of the Earth's orbit, and a satellite with a polar or near polar orbit is therefore least susceptible to bombardment.

Satellites operating in terrestrial space encounter gravitational anomalies caused by the asphericity of the Earth, especially its oblateness, and the inhomogeneity of its mass distribution. From an environmental standpoint, the gravitational anomalies are of significance only in that they cause precession of satellite orbits, and this precession changes the satellite's duration of exposure to sunlight. The disturbing force on satellite orbits due to the Earth's oblateness is inversely proportional to the cube of the distance. At ten Earth radii, or approximately 40,000 miles, the perturbation due to the Earth's oblateness equals that induced by the Moon. Thus, beyond this distance the perturbation caused by the Moon gradually becomes more dominant. Gravitationally speaking, therefore, terrestrial space ends at a distance of approximately ten Earth radii.

The geomagnetic field is environmentally important in terrestrial space because it traps incoming solar and cosmic radiation to form the Van Allen radiation belt (Chapter 2). Measurements made with Explorer IV, Pioneer III and Pioneer IV have shown that the radiation belt is oriented symmetrically around the magnetic equator and contains two zones of radiation, separated by a gap about 5000 nautical miles wide. According to the latest available data, the region of maximum radiation in the inner zone extends from about 1400 to 3400 nautical miles and that of the outer zone from about 8000 to 12,000 nautical miles./44/ Thereafter, the intensity gradually diminishes, reaching the level of ambient cosmic radiation at about 15 Earth radii.

Cislunar space begins beyond the loosely defined limit of 10 to 14 Earth radii. No perceptible radiation, except for primary cosmic rays, has been detected in cislunar space by either the American or Russian Moon probes. The density of gases in this region is extremely low, being on the order of 1000 gas particles per cubic centimeter as compared to approximately 3×10^7 per cubic centimeter at an altitude of about 600 nautical miles.

Although not an environment in itself, the orbital lifetime of a satellite may be considered an environmental parameter. The longer the lifetime, the longer the satellite is exposed to the environment. Some of the many factors that affect orbital lifetime are altitude, orbit eccentricity, atmospheric density, abundance of charged particles, and the shape and density of the satellite. Orbital lifetime and supporting data for satellites launched from 1957 through 1959 are listed in Table 2-13. The data for the

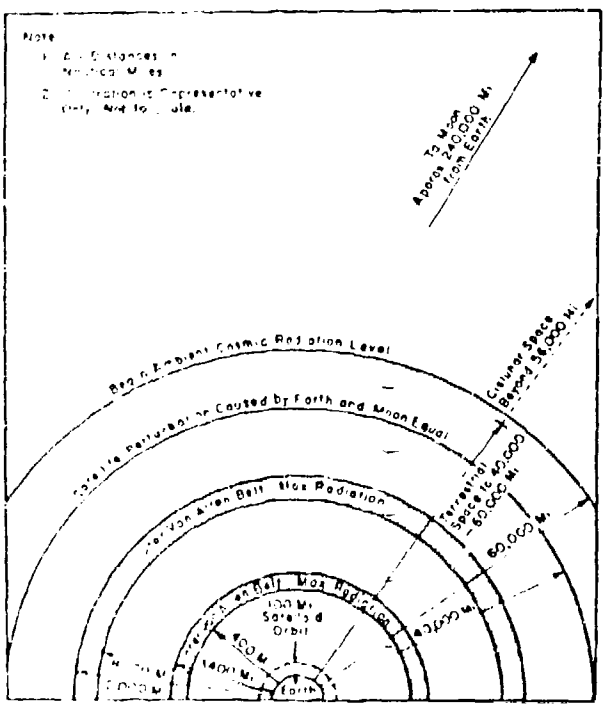


Fig. 2-27. Terrestrial and cislunar space.

Table 2-13. Satellite Data /45/

Satellite	Weight (lbs)	Shape	Dimensions	Perigee (mi)	Apogee (mi)	Initial orbital period (min)	Lifetime
Sputnik I	>184	sphere	dia - 22.8"	142	588	96.17	180 days
Sputnik II	>1120	complex	?	140	1,038	103.7	155 days
Explorer I	30.8	cylinder	length - 80" dia - 6"	224	1,573	114.8	3-5 years
Vanguard I	3.25	sphere	dia - 6.4"	409	2,453	?	200-1000 years
Explorer III	31	cylinder	length - 80" dia - 6"	121	1,746	115.87	94 days
Sputnik III	>2925	cone	length - 11.75' base dia - 5.67'	135	1,176	106.	1.25 years
Explorer IV	38.4	cylinder	length - 80.39" dia - 6.25"	163	1,380	110.27	450 days
Atlas-Score	8750	cylinder	length-85' dia-10'	110	920	101.46	34 days
Vanguard II	20.74	sphere	dia - 20"	347	2,064	125.85	~10 years
Discoverer I	1300	cylinder	length - 10.2' dia - 5'	99	605	95.9	~5 days
Discoverer II	1610	cylinder	length - 19.2' dia - 5'	142	220	90.5	~13 days
Explorer VI	142	spheroid, with flattened bottom and 4 solar vanes or paddles	dia - 26" depth - 29" vanes - 18" x 18"	156	26,357	12.5 hrs	>year
Discoverer V	1700	-	length - 27" dia - 33"	136	450	94	34 days
Discoverer VI	1700	-	length - 27" dia - 33"	139	537	94	62 days
Vanguard III	100	sphere, with tapered tubular extension	sphere dia - 20" extension - 26"	319	2,329	?	30-40 yrs
Explorer VII	91.5	2 truncated cones joined at base	base dia - 30" length - 30"	342	680	101.33	~30 years
Discoverer VII	1700	-	length - 27" dia - 33"	100	520	?	launched Nov. 20, 1959
Discoverer VIII	1700	-	length - 27" dia - 33"	130	1,035	?	~14 days
Atlas-Able	372	spheroid, with 4 solar vanes or paddles	length - 39" depth - 55" vanes - 24" x 24"	-	-	-	launched Nov. 26, 1959 altitude unknown

Discoverer satellites may not be representative, since the ejection of a recoverable capsule may have led to unpredictable disturbances of the satellites' orbits.

Launching and Reentry Environments of Satellites and Satelloids

During launching, the environments encountered by satellites and satelloids are similar to those encountered by a ballistic missile during powered ascent. In addition, satellite type vehicles may be subjected to a severe shock environment upon being "boosted" into orbit. The environments experienced during reentry are discussed in a later paragraph.

SPACE STATIONS

Space stations are inhabitable Earth satellites. They are placed in orbit in a manner similar to instrumented satellites and encounter essentially the same environments. In contrast to an instrumented satellite, however, a space station cannot orbit at any arbitrary altitude. Unless it is heavily shielded, the station must orbit either above or below the high intensity regions of the Van Allen radiation belt. To stay above the belt, it is expected that the orbital distance must be greater than about 15 Earth radii, and at the present time this is not technically practical. The highest altitude at which the station can orbit and remain below the belt is about 350 nautical miles. For permanent stations, a lower altitude limit of about 200 nautical miles is set by the atmosphere. Thus, a relatively narrow corridor between 200 and 350 nautical miles is left for the operation of space stations. More detailed data on the natural environments existing in this corridor, especially corpuscular radiation, must be obtained before a permanent manned space station can be established.

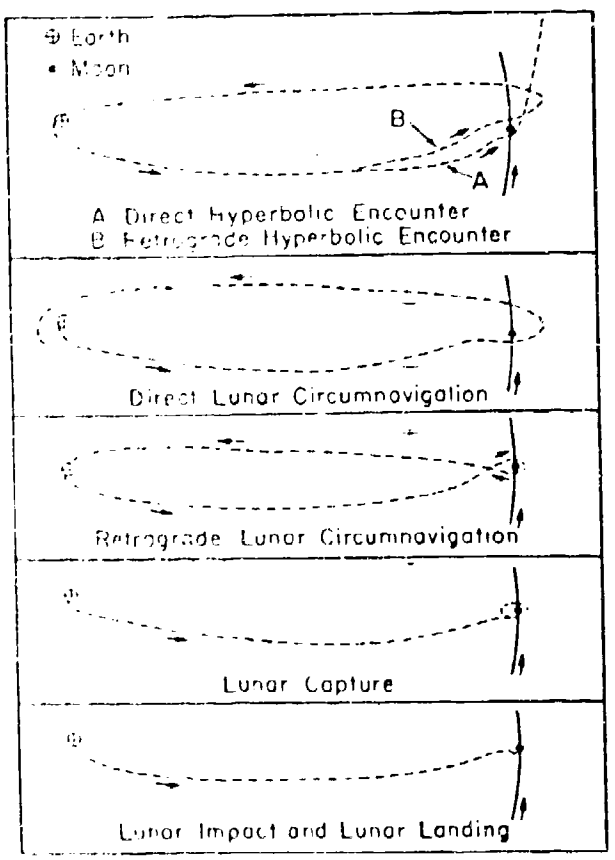


Fig. 2-28. Possible flight paths of Lunar vehicles.

LUNAR VEHICLES

Based on their intended missions, Lunar flights can be divided into the following groups:

1. Hyperbolic encounter.
2. Lunar circumnavigation.
3. Lunar capture (lunar satellite).
4. Lunar impact (hard landing).
5. Lunar landing (soft landing).

The flight paths followed by vehicles in each of these groups are shown in Fig. 2-28. It should be noted that Fig. 2-28 is purely schematic and is included for explanation purposes only. It does not show true Lunar vehicle paths as they exist in space.

The environments encountered by Lunar vehicles before they reach the vicinity of the Moon have already been discussed. Once the vehicle approaches the Moon, the type and severity of environments experienced depend upon its flight path. Vehicles that land on the Moon as well as those that become lunar satellites, will be subjected to temperature shock due to the extreme temperature difference between the light and dark sides of the Moon. Also, Lunar vehicles that ignite an auxiliary propulsion system to exercise a powered maneuver near the Moon will be subjected to acceleration or deceleration, as well as shock and vibration. For Lunar impact vehicles, which fall to the Moon's surface under the force of gravitational attraction, the most severe environment encountered is the extreme shock at impact.

The surface of the Moon must also be considered from an environmental standpoint, although it is not known for sure whether it consists of a hard crust or is covered with a thick layer of dust-like material. In addition, the almost nonexistent atmosphere of the Moon will provide vehicles with little shielding from the intense bombardment of meteoric material and solar radiation.

Another natural environment that will be encountered on the Moon is low gravitational acceleration. Its value at the Moon's surface is only about 16 percent of the value on Earth.

INTERPLANETARY VEHICLES

For the purposes of this discussion, interplanetary vehicle refers to a space vehicle traveling between the Earth and another planet. A flight path sequence that might be followed by a vehicle traveling from Earth to Mars is shown in Fig. 2-29. The vehicle is placed into a low-altitude orbit around the Earth when both planets are at (A). A suitable departure position is reached when the planets are at (B), and the vehicle is then boosted out of its Earth orbit. It coasts out of the Earth's relevant gravitational field and comes under the influence of the Sun's gravitational field. If undisturbed, the vehicle would travel in an elliptical orbit around the Sun, with its orbit crossing that of Mars at (C). However, both Mars and the vehicle arrive in the vicinity of (C) at the same time, and the vehicle is "captured" by the planets gravitational field. A powered maneuver is then required if the vehicle is either to land or become a satellite of Mars. Similar types of flight paths may be followed by vehicles traveling to planets other than Mars.

Many environments encountered by interplanetary vehicles depend upon whether thay are travelling toward or away from the Sun. With increasing distance from the Sun, corpuscular radiation, as well as solar light and heat, decrease in intensity. Conversely, for a vehicle traveling nearer to the Sun, these environments become more severe. The asteroid belt, which is concentrated between the orbits of Mars and Jupiter, becomes an environment for vehicles traveling to Jupiter and the more distant planets. Other environments that may be encountered by vehicles in interplanetary space are dust, meteoric material and comets.

Upon arriving at a particular planet, a vehicle will be subjected to many environments. Atmosphere, magnetic field, gravitational acceleration and surface characteristics vary from planet to planet. Mars, for example, has an extremely thin atmosphere, while that of Venus is relatively dense. Similarly, some planets are believed to have fairly weak magnetic fields, while it appears that Venus possesses a powerful one, and consequently, a radiation belt similar to the Earth's Van Allen belt, but far more intense. A detailed discussion of planetary environments is contained in previous portions of this chapter.

REENTRY ENVIRONMENTS

Reentry occurs when a vehicle returning from space enters the Earth's relevant atmosphere. The kinetic energy of the returning vehicle is enormous, and the relatively rapid dissipation of this energy results in severe aerodynamic heating and deceleration.

Aerodynamic Heating

Aerodynamic heating, caused by the intense friction between the vehicle's skin and the air molecules, is the most destructive reentry

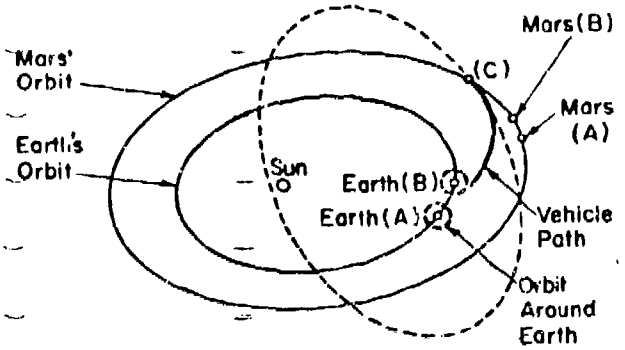


Fig. 2-29. Possible flight sequence between Earth and Mars.

environment encountered. The high air density and high speeds involved can cause the skin temperature of the entering vehicle to go as high as 3200 R. Factors that determine the severity of aerodynamic heating include: (1) speed of reentry, (2) reentry angle, which is measured with respect to the local horizon, and (3) shape of the vehicle.

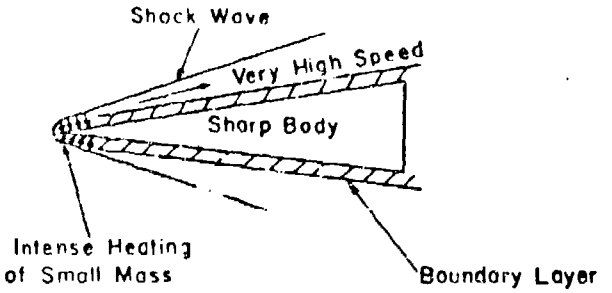
Lower reentry speeds decrease aerodynamic heating by reducing the friction between atmosphere and vehicle. Smaller reentry angles also decrease aerodynamic heating, since the vehicle passes more gradually through the atmosphere, thus allowing more heat to be dissipated into the atmosphere than into the skin.

The shape of the vehicle, especially its bluntness, has an important effect on aerodynamic heating. Slender and sharp, or pointed, bodies have more surface area exposed to the air flow, and therefore build up a thicker boundary layer (see Fig. 2-30). The shock wave at the pointed nose, or edge, is generally not as steep, and hence weaker than that of a blunt body; and the air flow velocity behind the shock wave, as well as the boundary layer friction, is much higher. This results in less energy being dissipated into the air by the shock wave and more into the boundary layer and skin. Consequently, severe aerodynamic heating takes place at sharp or pointed edges.

The shape of the vehicle also affects aerodynamic heating by influencing the reentry velocity and angle. A super-aerodynamic glider, for example, possesses some degree of aerodynamic lift, which enables it to maintain a small reentry angle for a longer time than would otherwise be possible. It should be noted, however, that for a vehicle employing lift, the reentry time is greatly increased. And, although peak skin temperature is reduced, the total quantity of heat that enters the vehicle is generally greater than for a non-lift producing vehicle.

Deceleration

As shown in Fig. 2-31, the deceleration experienced by a vehicle during reentry is primarily determined by the reentry angle. This angle, measured with respect to the local horizon, is negative in a downward direction. It can be



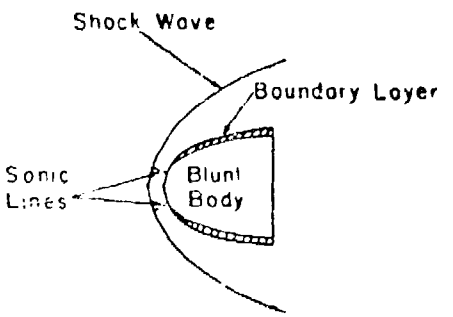


Fig. 2-30. Aerodynamic heating as a function of shape.

seen that the g-load increases rapidly for reentry angles greater than two degrees. This is especially dangerous as far as human transportation is concerned, since small errors in the reentry angle result in large changes in the deceleration environment.

The drag parameter, $C_D A/W$, which is a function of the vehicle's shape and mass, has almost no effect on the deceleration environment other than to change the altitude at which the peak g-load occurs. Similarly, the reentry velocity has little affect on deceleration. A velocity reduction of as much as 30 to 40 percent of circular velocity causes only relatively small changes in g-load.

Communications Interference

Extreme temperatures exist behind the shock wave set up by a reentry vehicle with a blunt shape. At these temperatures and the accompanying low pressures, air molecules are dissociated and to some extent ionized. This hot plasma surrounding the vehicle has a high degree of absorption for radio signals with frequencies up to about 15,000 mc; and since frequencies between 20,000 and 30,000 mc and between 40,000 and 60,000 mc are attenuated by atmospheric water vapor and oxygen, only a limited portion of the spectrum can be used for radio communication with a reentering vehicle.

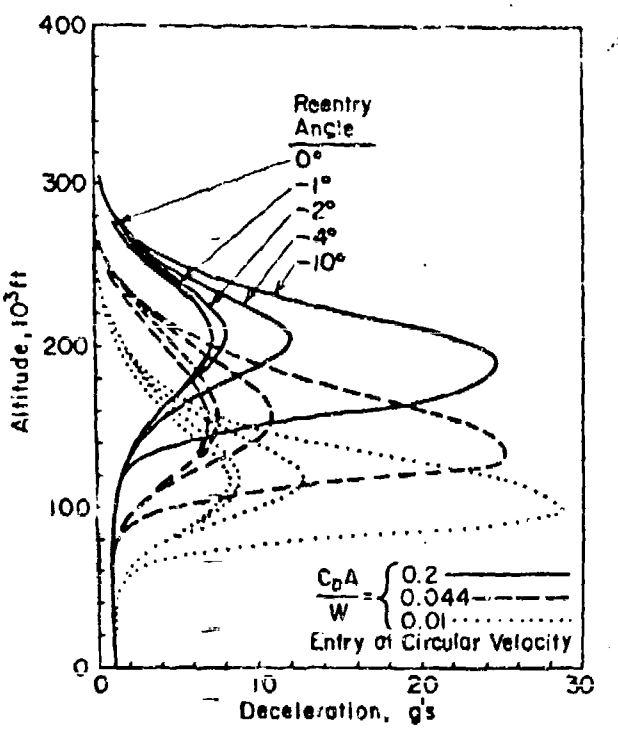


Fig. 2-31. Variation of deceleration with altitude, reentry angle and drag parameter.

REFERENCES

1. Space Handbook: Astronautics and its Applications, Staff Report of the Select Committee on Astronautics and Space Exploration, United States Government Printing Office, Washington, D.C., December 1958.

2. Stever, H. G., "Our Interest in Space and its Technology," IRE Transactions, Volume MIL-2, Number 1, December 1958.

3. Baker, R.H., An Introduction to Astronomy, 5th Edition, D. Van Nostrand Company, Inc., Princeton, N.J., 1957.

4. Handbook of Geophysics, Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, U.S. Air Force, 1957.

5. Bucheim, R. W., S. Merrick, E. H. Vestine and A. G. Wilson, Edited by Peter Swerling "Some Aspects of Astronautics," IRE Transactions, Volume MIL-2, Number 1, December 1958.

6. Gazley, C., Jr., W. W. Kellogg and E. H. Vestine, Space Vehicle Environment, RAND Corporation, Report No. P-1335, 1700 Main Street, Santa Monica, California, 7 July 1958.

7. Nazarova, I. W., Rocket and Satellite Investigations of Meteors, presented at the fifth meeting of the Comite Speciale de l'Annee Geophysique Internationale, Moscow, August 1958.

8. Vestine, E.H., Physics of Solar-Terrestrial Space: Lunar Flight, RAND Corporation, Report No. P-1344, 1700 Main Street, Santa Monica, California, 24 February 1958.

9. Moore, R. C., Introduction to Historical Geology, McGraw-Hill Book Co., New York, 1949.

10. Arthur, G. F., Physical and Positional Properties of the planets, WADC TN 58-347, ASTIA Document No. AD 206671, Project No. 1309, Task No. 13001, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1 December 1958.

11. Gerson, N.C., The Atmosphere, Number 73, AFCRC TN 55-216, Geophysics Research Directorate, Air Force Cambridge Research and Development Command, Cambridge, Mass., September 1955.

12. Kaplon, J., G.G. Schilling and K.K. Kallmon, Methods and Results of Upper Atmosphere Research, Report No. 3, Institute of Geophysics, University of California, Los Angeles, California, 30 November 1954.

13. Di Taranto, R. A. and J. J. Lamb, "The Space Environment," Electrical Manufacturing, October 1958.

14. Riley, F.C., Jr., and P.F. Walker, Atmospheric Contaminant, Radiation, and Electricity Criteria for Aircraft and Airborne Equipment, Booz, Allen and Hamilton, WADC TN 55-118, ASTIA Document No. AD 92498, Air Force Contract No. 33(616)-2689, Project No. 1111, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

15. Di Taranto, R. A. and J. J. Lamb, Preliminary Investigation of Hyper Environments and Methods of Simulation, Part 1, Natural and Induced Environments Above 75,000 Feet, Defense Electronics Products, Radio Corporation of America, Camden, N. J., WADC TR 57-456, ASTIA Document No. AD 142002, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, July 1957.

16. Climatic and Environmental Criteria for Aircraft Design, Prepared for Munitions Board by Aircraft Committee, ANC-22, ASTIA No. ATI 187921, June 1952.

17. Whipple, F. L., T. E. Sterne and G. F. Schilling, Some Preliminary Values of Upper Atmosphere Density from Observation of USSR Satellites, Special Report No. 3, Project No. 30.10, NSF Grant No. Y/30-10/167, ASTIA No. AD 148174, Smithsonian Institution, Astrophysical Observatory, Cambridge, Mass, November 1957.

18. Minzner, R. A., K. S. W. Champion and H. L. Pond, The ARDC Model Atmosphere, 1959, AFCRC-TR-59-267, Air Force Surveys in Geophysics No. 115, Geophysics Research Center, Air Research and Development Command, Bedford, Massachusetts, August 1959.

19. Greenfield, S. M., Availability of Upper Atmospheric and Other Selected Data from the I.G.Y., RAND Corporation, Report No. RM-2309-ARPA, 1700 Main Street, Santa Monica, California, 7 January 1959.

20. Kellogg, W.W., Scientific Exploration in the Fringe of Space, RAND Corporation, Report No. P-1350, 1700 Main Street, Santa Monica, California, 4 February 1958.

21. Climatic Extremes for Military Equipment, Military Standard-210A, Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C., 2 August 1957.

22. Shackleton, H. R. and A. L Quirk, A Contribution to the Measurement of the Earth's Albedo, Scientific Report No. 3, ASTIA No. AD 71613, Contract No. AF 19(122)-249, Department of Physics, Upper Air Research Laboratory, Engineering Experiment Station, University of Rhode Island, Rhode Island, 29 July 1955.

23. Riehl, H, Tropical Meteorology, McGraw-Hill Book Company, Inc., New York City, N.Y., 1954.

REFERENCES (continued)

24. Weather Extremes Around the World, M-183, Environmental Protection Research Division, Quartermaster Research and Development Command, Natick, Mass.

25. Jenkins, C. F., A Survey of Available Information on Winds Above 30,000 Feet, Air Force Surveys in Geophysics No. 24, ASTIA Document No. AD 3275, Operation Branch, Geophysics Research Directorate, Air Force Cambridge Research Center, December 1952.

26. Greathouse, G. A. and C. J. Wessel, Deterioration of Materials, Reinhold Publishing Company, 1954.

27. Riley, C.F., Jr. and P.F. Walker, Moisture Criteria for Aircraft and Airborne Equipment, Booz, Allen and Hamilton, WADC TN 55-97, Contract No. AF 33 (616)-2689, Project No. 1111, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

28. Byers, H. R. The Thunderstorm, U.S. Government Printing Office, Washington 25 D. C., 1949.

29. Lemons, H., "Semi-Monthly Distribution of Hail in the United States," Monthly Weather Review, July 1943.

30. Arthur, Gilbert F., Hail as a Flight Hazard, Environmental Criteria Branch, Directorate of Laboratories, ASD, Wright-Patterson Air Force Base, Ohio, 22 April 1959.

31. Howell, Benjamin F., Jr., Introduction to Geophysics, McGraw-Hill Book Company, 1959.

32. Johnson, F. S., J. D. Purcell, R. Tousey and M. Wilson, "The Ultraviolet Spectrum of the Sun," Rocket Exploration of the Upper Atmosphere, Pergamon Press, London, 1954.

33. Montgomery, D. J. K., Cosmic Ray Physics, Princeton University Press, Princeton, N.J., 1949.

34. Rossi, Bruno, "High-Energy Cosmic Rays," Scientific American, Vol. 201, No. 5, November 1959.

35. Van Allen, J. A., "Radiation Belts Around the Earth," Scientific American, Vol. 200, No. 3, March 1959.

36. Kiess, C. C. and K. Lassovzsky, The Known Physical Characteristics of the Moon and the Planets, ARDC TR 58-41, ASTIA No. AD 115617, Contract No. AF 18(600)-1770, U.S. Air Force, ARDC, Andrews Air Force Base, Washington 25, D.C., July 1958.

37. Vestine, E. H., "Evolution and Nature of the Lunar Atmosphere," RAND Corporation, Report No. RM-2106, ASTIA Document No. AD150683, 1700 Main Street, Santa Monica, California, 29 January 1958.

38. Freiday, D., "Engineering for the Moon," Mechanical Engineering, Vol. 8, Number 12, December 1958.

39. Ritchie, C. A., "The Moon's Supply of Atmosphere and Water," A.S.N.E. Journal, August 1958.

40. Dale, S. H., The Atmosphere of Venus, RAND Corporation, Report No. P-978, 1700 Main Street, Santa Monica, California, 12 October 1956.

41. Shaw, J. H. and N. T. Bobrovnikoff, Natural Environment of the Planet Venus, WADC TN-847-2, Contract No. AF 33(616)-5814, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, February 1959.

42. Shaw, J.H., Natural Environment of the Planet Mars, WADC TN-847-1, Contract No. AF 33(616)-5914, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, February 1959.

43. Hess, S. L., "The Atmosphere of the Planet Mars," Transactions of the New York Academy of Sciences, Serial II, Vol. 19. No. 4, ASTIA No. AD 133165, February 1957.

44. Wacholder, B. V., and E. Fayer, Critical Environments Encountered by High-Altitude Vehicles, Proceedings of Institute of Environmental Sciences, April 1960.

45. Project Mercury-Man in Space, Senate Report No. 1014, 86th Congress, 1st Session, U.S. Senate, December 1959.

BIBLIOGRAPHY

Bobrovnikoff, N.T., Natural Environment of the Moon, Phase Technical Note 847-3, Contract No. AF 33(616)-5914, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June - 1959.

Dale, S. H., The Atmosphere of Venus, The RAND Corporation, Report No. P-978, 1700 Main Street. Santa Monica, California, 12 October 1956.

Eggers, A. J., Jr., "The Possibility of a safe Landing," Space Technology, H. Seifert Edit., Chapter 13, John Wiley & Sons, Inc., New York, 1959.

Ehricke, K. A., A System Analysis of Past Manned Reconnaissance Missions to Venus and Mars, Convair-Astronautics, Report AZM-072, March 1959.

Ehricke, K. A., Basic Aspects of Operation in Cislunar and Lunar Space with Instrumental Satellites, American Rocket Society Paper No. 235A-55, November 1955.

Ehricke, K. A., "Interplanetary Operations," Space Technology, H. Seifert edt., Chapter 8, John Wiley & Sons, Inc., New York, 1958.

Ehricke, K. A., "On the Descent of Winged Orbital Vehicles," Astronautica Acta, Vol. II, Fasc. 1, pages 1-19, 1956.

Ehricke, K. A., "The Satelloid," Astronautica Acta, Vol. 2, Fasc. 2, Spring 1956.

Ehricke, K. A. and H. A. Pence, Reentry Characteristics of Recoverable Spherical Satellites, Satelloids and Lunar Vehicles, Convair-Astronautics, Report AZP-001, June 1957.

General Environmental Criteria for Guided Missile Weapon Systems, U.S. Air Force, Specification Bulletin No. 100A, 18 March 1957.

Hawthorne, R. and V. de Biasi, "Advancing the Vertical Frontier," Space Aeronautics, December 1958.

Heller, G., Temperatures of Explorer I, DV-TN-61-58, Thermodynamics Section, Research Projects Laboratory, Development Operations Division, Army Ballistic Missile Agency, Redstone Arsenal, Alabama, 15 April 1958.

Heary, I. G., "Lifetimes of Artificial Satellites of the Earth," Jet Propulsion, Vol. 27, No. 1, January 1957.

Hess, S. L., "The Atmosphere of the Planet Mars," Transactions of the New York Academy of Sciences, Ser. II, Vol. 19, No. 4, ASTIA No. AD 133155, February 1957.

Hogue, D. W., Temperatures of North America, Research Study Report RER-9, Environmental Protection Research Division, Regional Environments Research Branch, Headquarters Quartermaster Research and Engineering Command, U.S. Army, Quartermaster Research and Engineering Center, Natick, Mass., June 1956, Revised October 1957.

Imboersteg, R. A., Review of Outer Space Environment, Part 1. Radiation Environment in Space; Part 2. Thermal Environment in Space, General Electric Company, Light Military Electronic Department, Utica, New York.

Jaller, R. W., Evaluation of Northern Hemisphere Icing Probabilities, The American Power Jet Company, WADC TN 55-225, Directorate of Laboratories, Contract No. AF 33(616)-2605, Project No. 1111, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

Kemp, N. H. and F. R. Riddell, "Heat Transfer to Satellite Vehicles Reentering the Earth's Atmosphere," Jet Propulsion, Vol. 27, No. 2, pages 132-137, and 147, 1957.

Letta, H., What do Lunar Temperatures Tell Us Concerning the Nature of the Moon's Surface, ASTIA Document No. AD 78211, Translated by J. Gough, Jr., Translated for Geophysics Research Center, Cambridge, Mass., by the American Meteorological Society, Contract No. AF 19(604)-203, December 1955.

Lilley, A. E., "The Absorption of Radio Waves in Space," Scientific American, Vol. 197, No. 1, July 1957.

Manoogian, H. A., "The Challenge of Space," Electronics, McGraw-Hill Publishing Company, 24 April 1959.

McCoy, T. M., Hyperenvironment Simulation Part I -- Definition and Effects of Space Vehicle Environment -- Natural and Induced, WADD TR 60-785, Northrop Corp., Norair Division, Contract No. AF 33(616)-6679, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, September 1960.

Meigs, P. and F. de Percin, Frequency of Cold-Wet Climatic Conditions in the United States, Technical Report EP-25, Project Reference 7-83-03-008B, Environmental Protection Research Division, Regional Environments Research Branch, Headquarters Quartermaster, Research and Development Command, Quartermaster Research and Development Center, U.S. Army, Natick, Mass., July 1956.

O'Bryan, J. E., Mass Values of Humidity at Various Temperatures, Relative Humidity, and Sea Level Pressure, WCSPE TN 54-6, RDO No. 550-87, Environmental Criteria Branch, Systems Planning Office, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 14 April 1954.

Pauly, James, The Dust Environment and its Effect on Dust Penetration, Southwest Research Institute, WADC TR56-556, ASTIA No. AD110472, Contract No. AF 33(616)-3280, Project No. 1111, Task 11115, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, September 1956.

Pekeris, C. L. and H. Jarosch, The Free Oscillations of the Earth, ASTIA Document No. AD 132732, the Weizman Institute, Rehovot, Israel, November 1956.

Perkins, F. M., "An Analytical Solution for Flight Time of Satellites In Eccentric and Circular Orbits," Astronautica Acta, Vol. IV, Fasc. 2, Spring 1958.

Petersen, N. V., "Lifetimes of [illegible]tes in Near-Circular and Elliptic Orbits, [illegible]ropulsion, Vol. 26, No. 5, May 1956.

Rinehard, J. S., Meteor Distribution and Craterin[illegible], AFOSR TN-57-700, ASTIA Document No. AD 126693, Technical Report No. 3, Contract No. AF 18(600)-1956, Physics Division, Air Force Office of Scientific Research, ARDC, Washington 25, D.C., Smithsonian Institution Astrophysical Observatory Cambridge, Mass., 28 October 1957.

Shaw, J. W., Natural Environment of Interplanetary Space, Phase Technical Note 847-4, Contract No. AF 33(616)-5914, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, January 1960.

Thompson, W. E., The Mean Molecular Weight of the Upper Atmosphere, AFCRC TR-55-208, ASTIA Document No. AD 73446, Geophysical Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, May 1955.

Van Allen, J. A., G. H. Ludwig, E. C. Ray and C. E. McIlwain, The Observation of High Intensity Radiation by Satellites 1958 Alpha and Gamma, U.S. I.G.Y. Project 32.1 of the National Academy of Sciences and National Science Foundation, Department of Physics, State University of Iowa, Iowa City, Iowa.

Van Allen, J. A. and L. A. Frank, Radiation Measurements to 658,300 Kilometers with Pio[illegible], State University of Iowa, Iowa City, Iowa, August 1959.

Vestine, E. H., Evolution and Nature of the Lunar Atmosphere, The RAND Corporation, Report No. RM-2106, ASTIA No. AD 150683, 1700 Main Street, Santa Monica, California, 29 January 1958.

Vestine, E. H., Magnetic Storms, The RAND Corporation, Report No. P-1631, 1700 Main Street, Santa Monica, California, 6 March 1959.

Whipple, F. L., T. E. Sterne, B.M. Folkart and G. F. Schilling, An Interim Model Atmosphere Fitted to Preliminary Densities Inferred from USSR Satellites, ASTIA Document No. AD 156616, Special Report No. 7, IGY Project No. 30.10, NSF Grant Y/30.10/167, Smithsonian Institution, Astrophysical Observatory, Cambridge, Mass., 31 December 1957.

Whipple, F. L., The Meteoric Risk to Space Vehicles, Paper presented at the 8th International Astronautical Congress, Barcelona, October 1957.

Westbrook, J., High Temperatures at High Elevations, Research Study Report EA-9, Environmental Protection Research Division, Environmental Analysis Branch, Headquarters Quartermaster Research and Engineering Command, U.S. Army, Quartermaster Research and Engineering Center, Natick, Mass., January 1956.

Yarcho, W. B., Ambient Temperatures at High Altitude Airfields, WADC TN 55-386, ASTIA No. AD 67877, Environmental Criteria Branch, Product Control Office, Project No. 1111, Task No. 11118, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 24 July 1955.

Zwicky, F., Photometry of Galaxies Brighter than the 15th Photographic Magnitude with the 18" Schmidt Telescope on Palomar Mountain, California, Institute of Technology, Pasadena 4, Calif., 4 February 1955.

CHAPTER 3

ENVIRONMENTAL FACTORS AND EFFECTS

The effects of the various environments on flight vehicles, support equipment, components and materials are described in this chapter. Natural and induced environments are covered, both singly, and where information is available, in combinations.

To avoid excessive repetition, the environments are covered independently rather than in mission profile or flight path sequence. Information on which particular environments are likely to be encountered by flight vehicles following specific flight paths is given in Chapter 2.

Because of the interrelation between environmental effects and methods of protecting systems and equipment against these effects, some overlap exists between the information contained in this chapter and that contained in Chapter 5 (ENVIRONMENTAL PROTECTION). Thus, for maximum benefit these two chapters should be used in close conjunction.

ENVIRONMENTAL EFFECTS

Environmental effects fall into two general categories: operational and mechanical. An operational effect is one that does not actually cause the system to fail, but nevertheless prevents it from fulfilling its intended mission. As an example, interference caused by a severe electrical storm can make radio reception impossible, even though the receiving equipment is in good operating condition. A mechanical effect, on the other hand, is an actual defect that prevents the system from functioning properly. Examples of this are an antenna damaged by lightning and a frozen starter motor.

Table 3-1 is a list of natural environments showing whether the effect of each is operational or mechanical. The same information for induced environments is shown in Table 3-2. A more detailed table showing the portion of the mission profile during which the various environments will most likely be encountered, as well as whether their effects are operational or mechanical, is included in Chapter 4 (Table 4-2).

Table 3-1. Natural Environments and Their Effects

Environment	Effect	
	Operational	Mechanical
Albedo	X	
Altitude	X	
Clouds	X	
Cosmic rays		X
Density	X	X
Dew		X
Dissociated gases		X
Fog	X	
Frost	X	
Geomagnetism	X	
Gravity	X	X
Hail	X	X
High-speed particles		X
Humidity		X
Ice (freezing rain)	X	
Ionized gases		X
Lightning	X	X
Meteoroids		X
Ozone		X
Pollution, air	X	X
Pressure, air	X	
Rain	X	
Salt spray		X
Sand and dust	X	X
Sky brightness	X	
Sleet	X	
Snow	X	
Solar radiation		X
Temperature	X	X
Vacuum	X	X
Wind	X	X
Wind shear	X	X

TEMPERATURE

Fundamentally, temperature is a manifestation of the average translational kinetic energy of the molecules of a substance due to heat agitation. It should be distinguished from heat, which is a form of energy, while temperature is a factor affecting the availability of energy.

Every weapon system is exposed to many varied temperature extremes from production until the time of participation in a mission. Temperatures in a system are initially influenced by solar radiation and ambient air temperature. System operation creates additional heat sources that contribute to surface and compartment tem-

Table 3-2. Induced Environments and Their Effects

Environment	Effect	
	Operational	Mechanical
Acceleration		X
Acoustics		X
Aerodynamic heating	X	X
Atmospheric electricity		X
Explosion		X
Icing	X	X
Moisture	X	X
Nuclear blast (near miss)	X	X
Nuclear radiation		X
Shock		X
Sonic boom	X	X
Temperature	X	X
Turbulence	X	X
Vapor trails	X	
Vibration		X
Zero gravity		X

peratures. At supersonic speeds, aerodynamic heating becomes the predominating factor, followed by electronic and propulsion equipment heating, and then by solar radiation.

Heat Producing Sources

Flight vehicle surface and compartment temperatures are brought about by one or more of the four following major heat sources:

1. Ambient air temperature.
2. Solar radiation.
3. Aerodynamic heating.
4. Heat-producing equipment.

Ambient Air Temperature./1/ On the ground, ambient air temperature is influenced by many factors, some of which are: the nature of the Earth's surface, geographical latitude, incidence of solar radiation, season, prevailing winds, and atmospheric conditions. Temperatures over the entire Earth range from about -117 F (-83 C) to 136 F (57 C). For short periods, both the low and high temperatures can be exceeded.

Solar Radiation. Direct absorption of solar energy can increase aircraft and compartment temperatures well above ambient air temperature. Solar radiation is of particular importance on flight vehicles parked in the open and on equipment stored without protective coverings.

Depending upon the material surface and temperature, solar radiation is reflected or absorbed in varying degrees. Once the radiation is absorbed by the outer surface of a flight vehicle, its effects on temperature are dependent on the thermal capacity and heat transfer characteristics of the skin and on the flight vehicle structure. If the flight vehicle's thermal capacity and heat transfer capabilities are high, the absorbed heat will be stored in the material or distributed around the body with moderate temperature changes. If the thermal capacity is small, temperatures will rise more rapidly./2/

Aerodynamic Heating./3/ The heat produced by the compression and friction of air sliding past a moving object is generally referred to as aerodynamic heating. Since this heating effect is proportional to the square of the Mach number, substantial increases in temperature can be produced at high flight vehicle speeds.

Figure 3-1 shows a speed-temperature relationship at 40,000 feet for velocities up to Mach 10. The information is based on the assumption of a 0.9 recovery factor, no solar radiation and

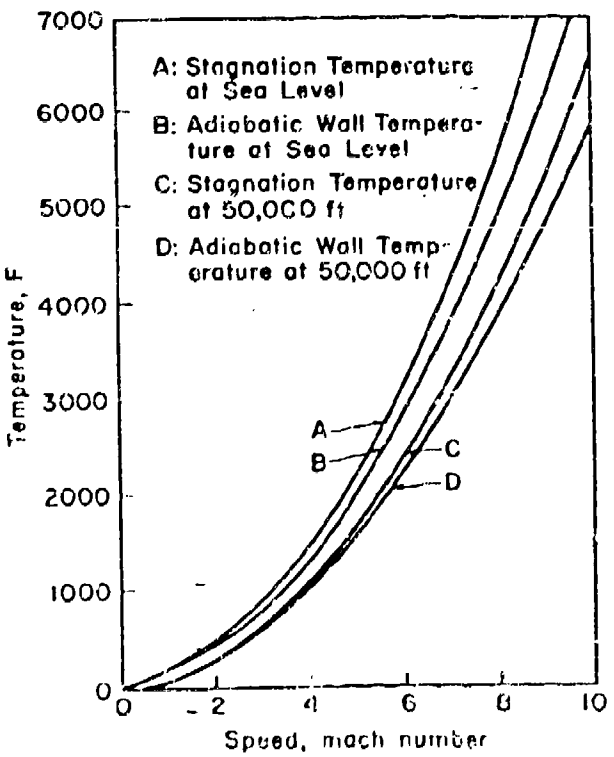


Fig. 3-1. Temperature versus speed to Mach 10./3/

standard atmospheric temperatures. This illustration graphically shows the dangerously high temperatures that are reached at speeds exceeding Mach 2.

Heat-Producing Equipment. At low speeds, the principal source of flight vehicle heat is the equipment within the vehicle itself. Electronic equipment, electrical rotating equipment, power plants and several other types of airborne equipment can produce sufficient heat to raise compartment temperatures appreciably.

Although the heat produced by any piece of equipment could be critical, electronic and electrical equipment are generally considered the major internal heat sources. The trend toward miniaturization and greater power output also accentuates the local flight vehicle heat intensity problems.

Power plant heating is a critical factor in compartments surrounding the engine. Although thermal insulation is generally used, sufficient heat is transferred to those areas immediately adjacent to the engine to restrict severely the installation of other equipment.

Temperature Effects on Materials

Heat and Cold./4/* Heat and its correlative cold, or the absence of heat, act as agents of chemical and physical deterioration for two basic reasons. First the physical properties of almost all known materials are greatly modified by changes in temperature; and second, the rate of almost all chemical reactions is markedly influenced by temperature. For chemical reactions, a familiar rule-of-thumb is that the rate of most reactions doubles for every rise in temperature of 10 C. Most chemical activity is stepped up by heating and slowed down by cooling.

All chemical and physical agents of deterioration exhibit mutually interrelated actions, and it is not always easy to distinguish between the two except in the most superficial way. The effect of heat and cold on materials is modified by the presence or absence, or by the relative intensity of other agents like moisture, sunlight and oxygen.

Physical Effects. Aside from the fact that many materials undergo a change of state with the required increase or decrease in temperature (that is, solids melt, liquids freeze or boil away into gases, and gases condense to liquids), perhaps the most important physical effect of addition or removal of heat on materials is that of change in dimensions. With very few exceptions, all known materials expand on heating and contract on cooling, and different materials expand and contract at different rates. Parts do not usually fit together at one temperature in the same way as they do at another. Thus, changes in the temperature of certain assemblies can result in some components being forced apart while others are unduly compressed. The coefficients of expansion for some commonly used materials are listed in Table 3-3.

Moreover, most materials, for lack of perfect heat conductivity, do not ordinarily heat up or cool off uniformly throughout their volume but do so by a series of temperature gradients. Hence, the several portions of a single piece may expand or contract at different times and different rates. The result in most cases is a complex system of internal stresses that the material may or may not be able to withstand.

Chemical Effects. As temperatures increase, most materials not only show a change in physical properties of one kind or another, but they are also more likely to undergo chemical changes. These changes take place within the material or by chemical reaction with other elements of the environment. Chemical reactions proceed more readily at high temperatures than at low ones.

Table 3-3. Linear Coefficients of Expansion for Some Commonly Used Materials/3/

Material	Coefficient of expansion (per deg F x 10^{-6})
Porcelain	2.0
Carbon	3.0
Chromium	3.4
Wood (average)	3.5
Glass (average)	4.5
Titanium	4.7
Steel, soft rolled	6.3
Iron	6.5
Nickel	7.4
Copper	9.2
Zinc	9.4 - 22
Bronze	10.0
Brass	10.4
Silver	10.9
Tin	13.0
Aluminum	13.3
Magnesium	14.0
Cadmium	16.6
Rubber	42.8

*From Deterioration of Material -- Causes and Preventive Techniques, by Glen A. Greathouse and Carl J. Wessel, courtesy of Reinhold Publishing Corporation, Book Division.

On exposure to elevated temperatures many organic materials, especially those of complex structure, undergo internal chemical changes such as rearrangement, polymerization, cleavage and pyrolysis. Certain plastics, for example, experience continued polymerization under the influence of temperature; others undergo splitting of polymer chains. And finally, increases in temperature encourage the reaction of many materials with water (hydrolysis) or with oxygen (oxidation), or both.

Low-Temperature Effects./3/ The effects of low temperatures on materials are as follows:

1. Lubricants become more viscous, loosing lubrication and flow qualities.

2. Rubbers, particularly carbon based types, stiffen, become brittle and eventually crack. Rubber shock mounts lose their resilience, and load-carrying rubber parts such as tires, lose strength or become temporarily deformed.

3. Most plastics become brittle and fracture. However, some thermoplastics, such as Teflon and polyethylene, maintain satisfactory pliability. Electrical characteristics of plastics are not altered appreciably.

4. Most hydraulic fluids thicken, and the system becomes stiff.

5. Most structural metals exhibit a decrease in impact properties.

6. Leather becomes stiff, and cracks and tears easily under tension, torsion or impact.

7. Heavy fabrics, like canvas, become so inflexible they cannot be folded or unfolded without danger of breaking or tearing.

8. Some materials, notably glass and wood, are not appreciably affected.

High-Temperature Effects. The effects of high temperatures on materials are as follows:

1. Greases become thin, break down and oxidize. The oil base evaporates and the soap base chars under the increased frictional heat. Lubricating oils evaporate or oxidize, forming sludge.

2. When in contact, lubricants, hydraulic fluids and various metals undergo a complex chemical reaction that leads to (1) a decrease in lubricant life and (2) corrosion of the metal. Metals affected this way include cadmium, cadmium alloys, lead, lead alloys, magnesium, copper and silver. Steel, aluminum and titanium are not affected appreciably.

3. Rubbers, both natural and synthetic, become gummy, take on a permanent set, and decrease in tensile strength. The temperatures at which various types of rubber become unusable are shown in Table 3-4.

Table 3-4. Degradation of Rubber by High Temperatures /3/

Type of rubber	Highest usable temperature F (C)
Silicone	500 (260)
Polyacrylic	350 (177)
Buna-N	340 (171)
Neoprene	315 (157)
Butyl	300 (149)
Buna-S	280 (138)
Natural	260 (127)
Thiokol	250 (121)

4. Organic materials deteriorate, and long-range aging processes are accelerated. The heat distortion of most thermoplastics is below 203 F (95 C), and cellulose begins to deteriorate at about 212 F (100 C).

5. Hydraulic fluids evaporate, break down and oxidize.

6. The strength of most flight vehicle structural materials decreases.

Thermal Shock. Thermal shock refers to sudden changes in temperature, which result in high temperature gradients. Depending upon the severity of the thermal shocks and the resulting stresses, the effects can vary from little or no damage to complete rupture.

Thermal shock will be encountered most frequently when flight vehicles that have been exposed to low temperatures for long periods are quickly brought up to maximum speeds./3/

Temperature Effects on Components

Extreme temperatures are frequently the cause for the failure of component parts. The general effects of temperature on various components are described in the paragraphs that follow. Electronic, electromechanical and mechanical components are discussed under separate headings.

Electronic Components /5/

Resistors. The types of resistors presently employed in military equipment generally perform satisfactorily at low temperatures, although large resistance variations in high value composition resistors can be expected. High temperatures cause most resistors to fail rapidly. Both reversible and irreversible resistance changes take place.

Within the temperature range of -67 to +77 F (-55 to +25 C), the resistance of wire wound resistors usually varies less than 1 percent. The actual extent of the resistance change for any particular resistor depends upon its nominal value and the resistance material used. Use of dissimilar metals for control shafts and shaft bearings of continuously variable resistors (potentiometers and rheostats) can result in excessive tightness or looseness of shafts at low temperatures. Binding of the shafts can also result if proper lubricants are not used in the bearings. The torque required to rotate the movable arm of some units operated at -67 F (-55 C) can sometimes be more than 50 times as great as the turning effort needed at room temperature. Temporary electrical discontinuity in variable wire wound resistors, due to ice formation or hardening of the lubricant on the resistance element, have been reported at -67 F (-55 C)./6/

Composition resistors, both fixed and variable, can show resistance variations of from 10 to 50 percent as the temperature varies from -67 to +25 F. The larger changes take place in resistors of higher nominal values. During thermal cycle tests performed between -67 and +25 F, numerous cracks in the plastic insulating tubes of certain fixed composition resistors developed Although the cracks do not alter the resistance characteristics immediately, they tend to shorten the life of the affected units. Variable composition resistors are subject to the same torque and discontinuity difficulties mentioned in connection with wire wound resistors. In addition, high temperatures cause the lubricants used in all variable resistors to dry up, ooze out, or migrate from the bearings to other surfaces.

Capacitors. Most capacitors are capable of satisfactory operation at temperatures as low as about -40 F (-45 C) and often lower. The behavior of electrolytic and wax impregnated paper capacitors becomes critical at temperatures between +32 and -40 F (0 and -40 C). Some types, such as tantalum, can operate at the lower temperatures, but under several limitations.

Electrolytic capacitors exhibit large reductions in effective capacitance at low temperatures, the extent depending upon the electrolyte, type of foil, voltage rating and manufacturing technique. The series resistance, and consequently the impedance, of electrolytic units increases greatly at sub-zero temperatures. Variations in reactance and resistance with temperature become greater at higher frequencies. Low temperatures result in two favorable effects: the dielectric breakdown voltage increases and the direct current leakage values show an extreme decrease. Storage of electrolytic capacitors at temperatures as low as -67 F (-55 C) results in no permanent harm and may even inhibit deterioration due to aging.

Mica capacitors perform satisfactorily at sub-zero temperatures. Capacitance and loss factor variations with temperature are quite small at temperatures down to -67 F (-55 C) and lower. If potting compounds of those types housed in ceramic or molded castings crack, or if molds split under thermal shock, relatively large and permanent changes in capacitance as well as a-c losses may occur if moisture enters the affected units.

Oil-impregnated paper capacitors function well at cold temperatures. As ambient temperatures are lowered from +77 to -67 F (+25 to -55 C) and below, a general reduction in capacitance takes place, although this property may show a slight increase down to about -4 F (-20 C) for certain types of oils. The capacitance reduction from room temperature to -67 F (-55 C) may vary 5 percent for mineral oil impregnants.

Wax-impregnated paper capacitors are subject to extensive cracking of the impregnate below -4 F (20 C). This results in permanent changes in capacitance, insulation resistance, and a-c losses, especially if moisture enters. In general, the capacitor's properties become impaired, with the dielectric failing ultimately.

Air capacitors (including vacuum and insert gas types) are relatively stable with respect to capacitance and losses as temperatures are varied. In some instances, variable types may require considerable increases in torque to rotate the movable plates, probably as a result of improper low temperature lubricants.

In general, high temperatures cause decomposition and dielectric failure in electrolytic and paper capacitors. In addition, temperature rises result in increased d-c leakage current in electrolytic capacitors. This causes increased heating and drying out of the electrolyte. Rapid failure of the capacitor inevitably follows. High temperatures can also lead either to rupture of the electrolyte or rupture of the container, both of which result in capacitor failure. Air capacitors are virtually immune to high temperature effects, while variable air capacitors may be affected by loss of lubricant in bearings and shaft seizure.

Transformers. Transformers can be expected to operate satisfactorily over the temperature range of +77 to -67 F (+25 to -55 C), provided precautions have been taken in their design to prevent mechanical damage due to thermal contraction. Coil winding resistance decreases sharply with decreasing temperature. The d-c resistance for copper wire of any gauge at -67 F (-55 C) is about 70 percent of its value at 77 F (25 C). Cracking of potting compounds and terminal bushings can also occur, especially if the temperature drops rapidly.

In general, high temperatures reduce the life of a transformer, Insulation deteriorates and the resistance of the windings increases, possibly resulting in changes in transformer characteristics.

Electron Tubes. Low temperatures have no serious effects on tubes. Below 32 F (0 C), tube cathode heating time takes longer. Also, if the

condensed-mercury temperature in a mercury-vapor rectifier tube is below the minimum value of the operating range, arc-back can occur. This will damage the tube. Low temperatures can also cause tube basing cement to crack.

High temperatures can result in grid emission and release of gas from other tube elements. Electrolysis of leads coming through the glass envelope can also occur. As the bulb temperature increases, the life of a tube is markedly decreased. Figure 3-2 shows average life test survivals of typical tubes as a function of bulb temperature./7/

Semiconductors. In general, semiconductor devices give satisfactory performance at sub-zero temperatures. Changes from room temperature operation can be readily compensated for, should any low-temperature effect be undesirable.

As the temperature rises, semiconductor devices become increasingly unreliable. Transistors, for example, should not be operated in ambient temperatures over 185 F (85 C).

Other Electronic Components. Additional electronic components include terminal boards, connectors, wire, sockets and pilot lamps. Low temperatures do not normally affect these components seriously. Possible low-temperature effects are: (1) phenolic sockets may crack, (2) wire requiring the ability to flex may stiffen as the cold affects the insulation, and (3) connectors may freeze and become difficult to separate.

Generally, high temperatures adversely affect sockets, terminal boards, connectors and the insulation of wires. Unless the temperature is high enough to soften the glass, pilot lamps are not affected by high temperatures.

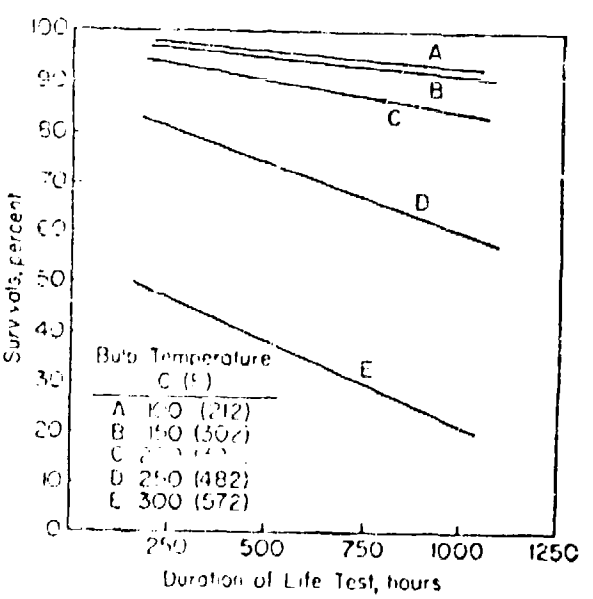


Fig. 3-2. Average life test survivals of typical tubes vs bulb temperatures./7/

Electromechanical Components/5/

Electromechanical components are items such as relays, magnetic and thermal circuit breakers, switches, electrical indicating instruments and rotating devices (motors, generators, dynamotors, resolvers, synchros, gyros).

Relays. Relays operated under cold temperature conditions generally perform their intended functions, provided the mechanical problems encountered at low temperatures are taken into account. The decrease in winding resistance tends to alter relay operating characteristics, particularly if small or critical currents are involved, as is the case with sensitive relays. At low temperatures, operating (closing) margins are improved and nonoperating (release) margins are impaired. Variations in spring stiffness and magnetic properties can also change these characteristics. Ice formation on operating parts and contacts can cause trouble at low temperatures. In addition, lubricants and dashpot oils, where used, tend to congeal.

Magnetic and Thermal Circuit Breakers. Magnetic circuit breakers with silicone oil damping perform well at sub-zero temperatures. As the temperature drops, the time required for the breaker to trip under overload or short circuit conditions tends to increase. Thermal circuit breakers are affected at reduced temperatures by the increased heat transfer away from the bimetallic actuating elements, with a resultant change in operating characteristics. The tripping time at temperatures near -67 F (-55 C) can be about double the time required at 77 F (25 C) for a given overload current.

At high temperatures, both magnetic and thermal circuit breakers trip at lower currents than at room temperature. Thermal circuit breakers are affected more by high temperature than are magnetic types.

Switches. Exposure to low temperatures can cause the molded body or plastic wafers of a switch to contract and thus be stressed sufficiently to cause cracking. This is especially true in the proximity of attached metal parts, which may contract more severely or more rapidly than the phenolic, plastic or ceramic body of the switch. A cracked body or wafer may allow entrance of moisture or other foreign matter that can cause a short circuit. The spacing of switch contacts, which may be a fraction of an inch, may decrease sufficiently to cause voltage breakdown or corona.

The chemical actions to which switches may be subjected are accelerated by high temperatures. Reactions that take place slowly at normal temperatures, may take place rapidly enough at high temperatures to impair switch operation. Insulation resistance between the

switch contacts and ground may be thousands of megohms at room temperature; but at elevated temperatures it may decrease to as low as 1 megohm. Another effect of high temperature is the increased speed of corrosion of contacts and switching mechanisms. Corrosion or expansion of materials at high temperatures results in stuck toggles or jammed detents.

Electrical Indicating Instruments. Most electrical indicating instruments operate satisfactorily at reduced temperatures; changes in indication may be less than 10 percent at -67 F (-55 C). Thermocouple and rectifier type meters normally have the greatest temperature errors. Temperature reduction can cause meters to read incorrectly by altering the properties of such basic meter movement parts as control springs, magnets, and coils, as well as range and function-changing accessories.

Rotating Devices. Motors and dynamotors will start and operate satisfactorily at temperatures as low as -67 F (-55 C), provided lubricants specially developed for low temperatures are used. In general, as the temperature is decreased from +77 to -67 F (+25 to -55 C), the final operating speed is lowered and the input power increases somewhat. Generators require greater power and have a higher voltage output because of the reduced resistance of the windings. Low temperatures change the electrical characteristics of resolvers, synchros and gyros, with the most important effect being a decrease in accuracy.

High temperatures cause lubricants to creep, ooze or evaporate, leading to bearing failure. Commutators and slip rings deteriorate more rapidly, and winding resistance increases, lowering the output voltage of dynamotors and generators. Synchros, resolvers and gyros exhibit a decrease in accuracy. In general, deterioration of insulation brings about ultimate failure of all rotating devices from an electrical point of view.

Mechanical Components. Mechanical components include items such as pumps, valves, hydraulic and pneumatic actuators, shock and vibration isolators, etc.

At low temperatures, differential contraction results in binding, fluid leakage and pump and actuator difficulties. Entrapped moisture freezes, clogging metering orifices. Stiffening of vibration mounts at cold temperatures increases their natural frequency, and thereby reduces isolation. The behavior of these components is greatly influenced by the material from which they are constructed and the type of lubricant used.

High temperatures similarly result in differential contraction. This causes a variety of malfunctions, such as binding of movable parts, loosening of joints, distortion of assemblies and rupture of seals. Valves, for example, may either bind or leak. Fuel leakage in check valves, boost pumps and selector valves, normally aggravated by the cyclical use of fuels of different aromaticity, will be increased at elevated temperatures.

Temperature Effects on Equipments/3/

The effects of temperature on equipment are dependent mostly on the components comprising the equipment. However, the design of the equipment determines to a great extent the temperatures that the components will be subjected to.

In electronic equipment, the proximity of heat producing components, such as tubes, transformers, and resistors, in confined spaces and enclosures raises the temperature and may lead to malfunction or early failure. The heat producing components themselves tend to operate hotter, compounding the deleterious effect high temperatures.

The trend toward miniaturization and greater power output also accentuates heat intensity problems in electronic equipment. Miniaturization, with its small space factor, leads to an increased concentration of thermal energy. This is particularly true since the total electrical power dissipated by a miniaturized unit is usually as great as, if not greater than, that dissipated by an equivalent unit of conventional construction.

The combined effect of miniaturization and increased power output has been to increase heat densities of subminiaturized electronic equipment to from 0.5 to 3.0 watts per cubic inch, with an average of about 1 watt per cubic inch. Experience has shown that degradation is likely to occur when the heat dissipating surface of a piece of equipment is required to dissipate, by natural means, more than 0.5 watt per square inch for a 122 F (50 C) rise in temperature.

Other effects of high and low temperatures on equipments are:

1. The shock and vibration environment of shock mounted equipment may increase in severity due to rubber shock mounts losing their resilience.

2. Freezing of collected water may cause equipment to malfunction by restricting the operation of, or damaging, gear trains, mechanisms, controls, etc.

3. Guns may freeze and become inoperable, either because of congealing of lubricants or condensation and freezing of moisture in armament mechanisms.

4. Battery operated equipment may malfunction at low temperatures due to reduced battery output, and at high temperatures due to battery deterioration and decomposition.

Equipment may malfunction at low temperatures due to binding of movable parts.

Temperature Effects on Guided Missiles

The thermal shock of going from a relatively low ground temperature to extremely high temperatures within a few minutes puts tremendous stress on guided missiles. Differential expansions and binding of mechanical parts, as well as malfunctioning of metering devices can occur quickly, leading to system failure. High ram-air and skin temperatures lead to compartment heating and constitute the most critical aspect of supersonic flight. The increase in ram-air temperatures with flight speed is shown in Table 3-5. From the figures in this table it is apparent that ram air will not be a suitable means of compartment cooling. In addition, compartment temperatures are increased to dangerously high levels because of the heat transferred to compartments from the hot skin of the missile./6/

Increased flight altitudes also increase compartment heating. The effect of this increase in altitude is to further decrease the cooling effect of a given volume of air, since the capacity of air to absorb heat is directly proportional to its density. The order of magnitude by which the heat absorbing capacity of air falls off with altitude as shown in Table 3-6.

Table 3-5. Increase of Ram-Air Temperatures With Flight Speed /6/

Altitude (feet)	Temperature in F for flight Mach number of:			
	1	2	3	4
0	160	470	990	1720
10,000	110	410	890	1570
20,000	80	350	790	1420
30,000	40	280	690	1270
37,000 to 265,000	10	250	640	1190

Table 3-6. Reduction of Heat Absorbing Capacity of Air With Altitude /6/

Altitude (feet)	Heat absorbing capacity of given volume of air as percentage of that at sea level
0	100
20,000	50
40,000	25
60,000	10
80,000	3
100,000	1

Compartment heating is also increased by solar radiation. The maximum compartment temperatures in guided missiles due to solar, radiation will depend on speed and altitude. For altitudes below 100,000 feet, the effects of radiation on the transient temperature distribution may be neglected regardless of Mach number, as the heat flux due to radiation is never more than approximately 8 percent of that due to convection. For altitudes above 100,000 feet, though, the effects of radiation should be taken into account.

In liquid-fuel missiles, the extremely low temperatures that exist ambient to liquid oxygen or liquid hydrogen lines can adversely affect nearby components and equipment. Temperatures as low as -300 F (-149 C) may be encountered.

Temperature Effects on Manned Aircraft

Most of the temperature effects on manned aircraft arise from the effects on materials, components and equipments, previously discussed. Additional effects are described in the following paragraphs. Temperature effects on humans, which must be considered for manned aircraft, are covered later in this chapter.

High Temperature Effects. High temperature conditions can effect virtually every system and part in an aircraft. Important high temperature effects are as follows:

1. The strength of most aircraft materials decreases as temperatures increase.

2. Differential expansion between the interior and exterior aircraft sturcture may set up reverse thermal stresses.

3. Hydraulic systems may malfunction due to degradation of hydraulic fluids.

4. If too much heat is absorbed by aircraft fuel as a result of aerodynamic heating, the vapor pressure of the fuel may exceed ambient pressure and the fuel will begin to boil, resulting in the loss of fuel.

5. Turbojet and after burner performance are adversely affected as a result of higher inlet temperatures.

6. At high speeds, aerodynamic heating becomes so severe that ram-air cooling cannot be used.

Low temperature Effects. Low temperature effects on manned aircraft include the following:

1. Hydraulic systems may spring leaks due to differential contraction. Also, hydraulic systems can become stiff as hydraulic oil thickens.

2. Moisture may freeze in pneumatic systems, clogging metering orifices and lines.

3. The starting of reciprocating engines is restricted by the congealing of oil.

4. Contamination of jet fuel can result from condensation following a change in temperature. Water may crystallize out at 0 F (-18C) and clog fuel metering passages.

Temperature Effects on Satellites and Satellite Vehicles/8/

There are two types of temperature environments encountered in satellite flight: aerodynamic heating and radiation heating. The first type occurs while satellite and vehicle are moving from the ground to orbit. The second type is encountered during orbital movement of a satellite at altitudes greater than 200 miles.

The satellite and vehicle travel at very high speeds to reach orbiting velocity. During this aerodynamic heating phase, which may last for two or more minutes, the induced temperature is of prime importance. The temperature increase creates a thermal shock that results in temperature gradients and stresses in the satellite and vehicle. The skin temperatures for this portion of flight range from 1700 to 2400 F (927 to 1335 C) and are highly dependent upon the altitude, speed of flight, and type of air flow about the vehicle. Turbulent flow creates temperatures higher than those obtained by laminar flow. Typical variations are shown in Fig. 3-3.

The temperature shock is felt directly by the skin and other external surfaces such as radomes. The skin-temperature shock problem can involve a change of 36 F (20 C) per second for 2 minutes. The internal equipment does not receive the same temperature shock since it receives the temperature change over a longer period due to the lag in thermal transmission.

The major effect of the high temperature is to cause equipment to become inoperative. Electronic equipment can cease to function. Seals may not seal properly due to expansion. Mechanical moving parts may expand and lose their strength. Properties of liquids and metals change. Hydraulic fluid may evaporate, solder may melt, resistance of wire will increase, and the properties of magnetic material will change.

Space Vehicles/9/

The primary means of heat exchange between a space vehicle and its environment is radiation. Radiation exchanges, plus any internal heat generation, thus determine the space vehicle's internal and surface temperatures. The amount of radiation absorbed by the vehicle depends on the spectral absorption characteristics of the surface material, while the amount of radiant energy emitted depends not only on the surface temperature but also on the spectral emission characteristics of the surface. The absorptivity and emissivity of a material depend, in turn, on the wavelength of the radiation and the chemical and mechanical character of the surface.

The absorptivity and emissivity of most polished metal surfaces increase approximately linearly with temperature, and the radiation equilibrium temperatures of such materials are

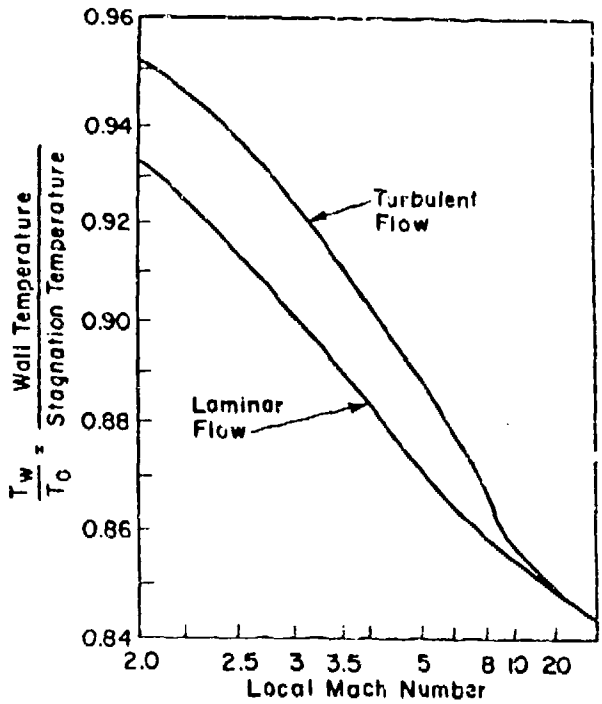


Fig. 3-3. Turbulent and laminar flow temperature variations as functions of Mach number./8/

relatively high. Non-metals, on the other hand, often exhibit the opposite trend, with absorptivity and emissivity decreasing with temperature. This results in a lower radiation equilibrium temperature. The absorptivity and emissivity of rough or oxidized metal surfaces are generally little affected by the temperature of the radiator.

Reentry Vehicles

Vehicles reentering planetary atmospheres are subject to extreme heating due to friction between the atmosphere and the skin of the vehicle. Although little is known about the effects of penetration into other planetary atmospheres, the effect of reentering the atmosphere of Earth has been the subject of considerable study.

Figure 3-4 shows the stagnation temperature as a function of altitude for reentry vehicles of typical ratios of mass to frontal area, with approach speeds ranging from 10,000 to 36,200 feet per second. The latter figure was chosen as a limiting case because it represents the so called "escape velocity" for a body leaving the Earth. The stagnation temperature refers to the temperature at the extreme forward part of the nose, where the air has zero velocity relative to the vehicle./10/

The heat at the reentry vehicle nose is so great that the nose will burn up unless: (1) it is made of heat resistance material, (2) it is coated to absorb the heat, (3) it is designed aerody-

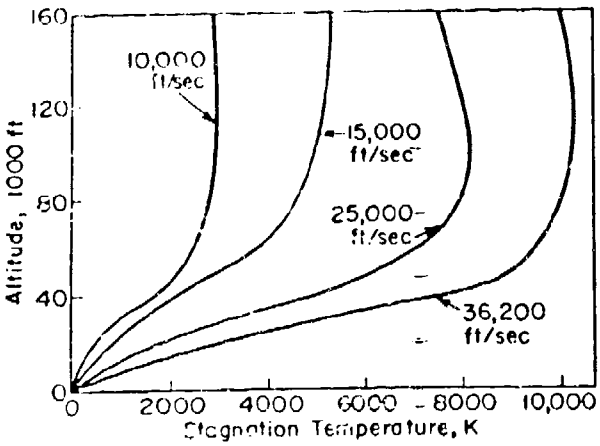


Fig. 3-4. Reentry vehicle altitude vs stagnation temperature with typical trajectories as parameters. Heat generated equals 100 Btu/ft²-sec./10/

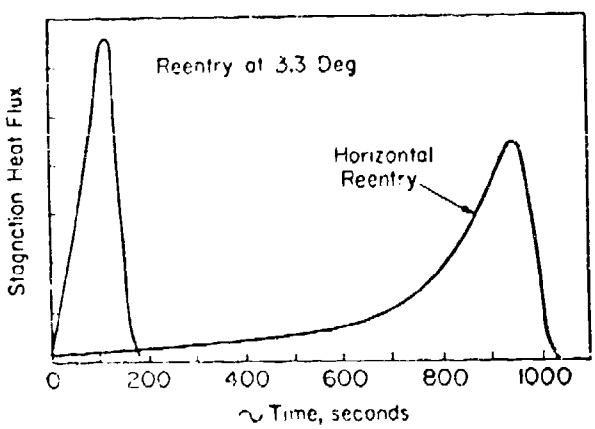


Fig. 3-5. Stagnation heat flux vs reentry time from 60 miles./11 (From Recovery from a Satellitic Orbit, paper presented at semiannual meeting of American Rocket Society, June 1958, courtesy of R. Hoglund, Dr. J. Thale and American Rocket Society.

nautically to reduce the stagnation temperature, (4) the speed of reentry is controlled, or (5) the angle of reentry is controlled. Figure 3-5 shows that the period of aerodynamic heating is reduced considerably when reentry paths below the horizontal are used. It is also apparent that the total heat flux to the stagnation point is reduced, although the peak heating rate is increased. The high temperatures also bring about other problems. At temperatures equivalent to Mach 10, oxygen begins to dissociate and chemical reactions occur, resulting especially in the formation of nitric oxide. The nose coating must be able to resist chemical action to protect the vehicle. A typical ballistic-

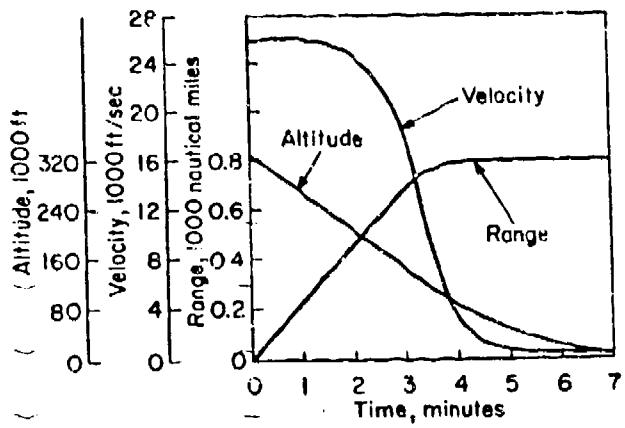


Fig. 3-6. Ballistic missile reentry trajectory./12/

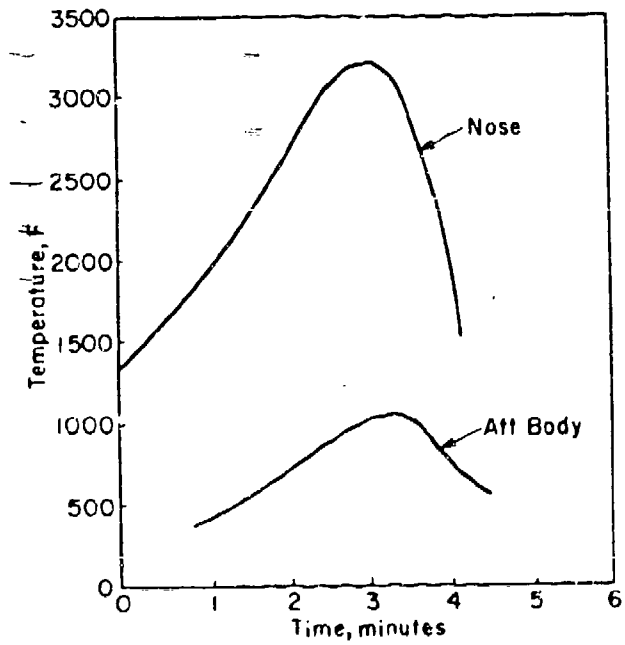


Fig. 3-7. Ballistic missile surface temperature during reentry./12/

missile reentry trajectory is shown in Fig. 3-6. Figure 3-7 shows the missile heating that results from this trajectory.

The heating effects of reentry into the atmospheres of other bodies in the Solar System are speculative. This is because reentry characteristics depend on the gravitational acceleration, g, and variations of density with altitude, which at the present time are only estimates. In general, the greater the value of g and changes of density with altitude, the greater will be the heating during reentry.

SHOCK AND VIBRATION

Although shock and vibration are often treated as separate and distinct phenomena, the distinction between the two is not clear cut. The difference between transient shock motion and periodic vibration is fairly obvious, but the existence of any basic differences between shock and random vibration, which is not periodic, is much less obvious. However, shock may be considered as intermittent excitation and vibration as sustained excitation.

Shock/13/

Shock connotes impact, collision, or blow, usually caused by physical contact. It denotes a rapid change of load, or a rapid change of acceleration with a resultant change of load. A shock motion cannot be defined by assigning numerical values to established parameters; it can only be defined by describing the history of a significant parameter such as acceleration, velocity or displacement.

Shock occurs when a structure is subjected to a suddenly applied force, resulting in transient vibration of the structure at its natural frequencies. The magnitude of the vibration may become great enough to cause fracturing of brittle material or yielding of ductile material. A secondary effect of shock is that large accelerations, characteristic of the abrupt changes associated with shock, may be transmitted to equipment and components supported by the structure.

Vibration /13

Vibration is an oscillation wherein the quantity is a parameter that defines the motion of a mechanical system. Vibration has also been described as the variation, usually with time, of the magnitude of a quantity with respect to a specified reference, when the magnitude is alternately greater and smaller than the reference. Vibration may be periodic, in which case it consists of motions at one or more frequencies, with the motion at each frequency being harmonic, or it may be random, in which case the amplitudes and various frequencies vary randomly with respect to time. An additional type of vibration, termed white-noise vibration, has no defined frequencies of motion. The excitation forces that cause vibration may be mechanical in nature, such as caused by a reciprocating motion or, they may be acoustic in nature, such as caused by rocket engine noise.

Acceleration

Acceleration is the change of velocity, or the rate of change with regard to either speed or direction, or both. Whether displacement, velocity or acceleration is used in defining shock, the implication of a relatively sudden change in acceleration is always present. Acceleration by itself does not constitute shock. For example, a structure subjected to steady-state acceleration is not considered to be undergoing shock.

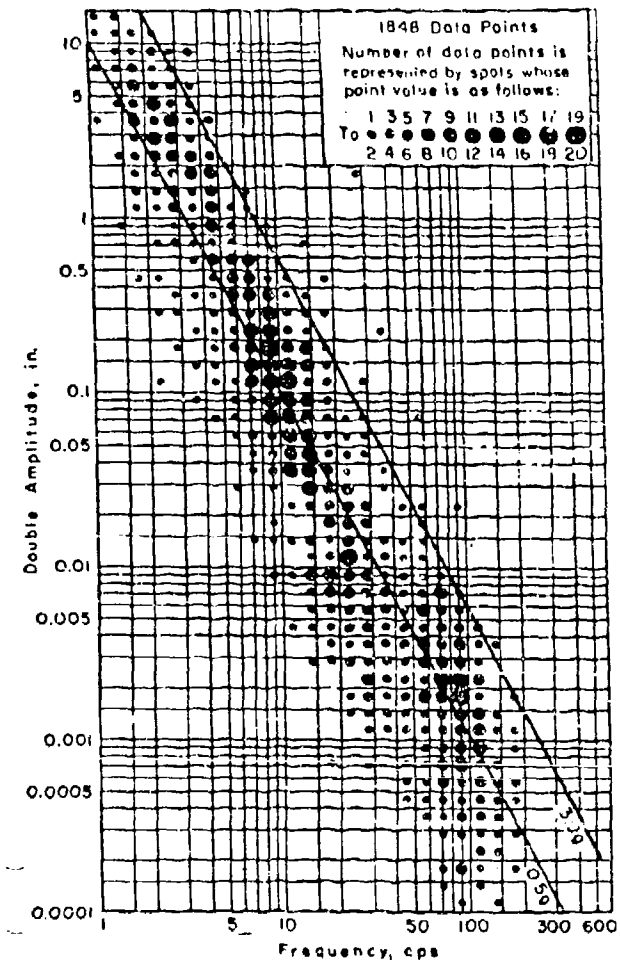


Fig. 3-8. Truck transportation vibration data./14/

Acoustics

Intense acoustic pressure loads are generated by the noise from turbojects, ramjets, rocket engines and aerodynamic boundary layers. The high levels of sound impinge on the aircraft skin, and the sound energy is converted to mechanical energy that can eventually reach the equipment in the form of vibration. The sound, generally attenuated when it reaches the equipment compartment, can also impinge directly on the equipment.

Transportation

All or part of every weapon system is transported at some time during its life. The shocks and vibrations to be expected during transportation vary, depending upon the type of carrier, and are discussed in the following paragraphs.

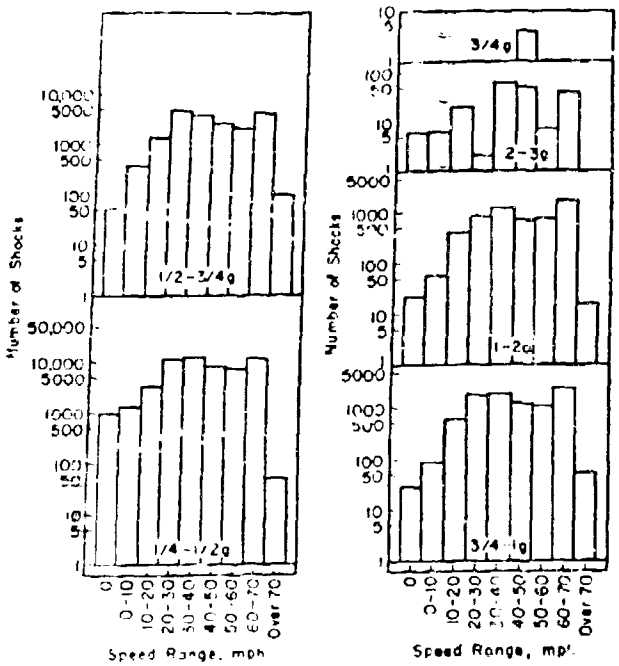


Fig. 3-9. Total or average number of vertical, longitudinal and lateral shocks per 1000 miles of travel measured on freight car floor./14/

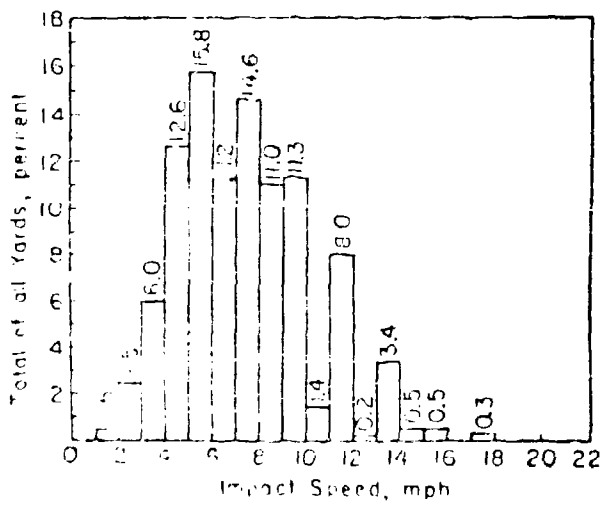


Fig. 3-10. Impact speed during freight car switching operation. 14,15/ (From ASME paper 52-SA-41, courtesy of J.M. Rhoem and American Society of Mechanical Engineers)

Truck transport. Vibration frequencies in motor trucks are dependent upon the natural frequency of the unsprung mass on the tires, the natural frequency of the spring system, and the natural frequencies of the body structure. The vibration amplitudes are dependent upon

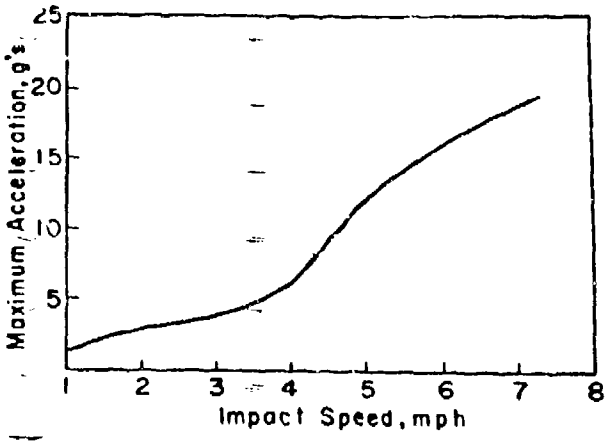


Fig. 3-11. Maximum horizontal accelerations of freight car body vs switching impact speed./14/

road conditions and the speed of travel. Intermittent road shocks of high magnitude can occur, will resultant extreme body displacements. These large displacements may result in a severe shock environment for unlashed cargo as it bounces about the truck floor. Vibrations due to the truck engine and transmission system are relatively insignificant in the cargo area./13/ Figure 3-8 shows measured vibration data for truck transport.

Rail transport./14/ Vibrations in moving freight cars arise from track and wheel irregularities, and occur principally in the lateral and vertical directions. Shock data obtained from an instrumented, moving railroad car loaded in excess of 27,900 pounds are shown in Fig. 3-9. The frequencies concurrent with each shock were not determined; however, for the shocks analyzed, the pulse duration varied from about 10 to 50 milliseconds, and the predominant shock-excited vibrations occurred in the 30- to 90-cps range. Very few steady vibrations as large as 0.25 g, zero-to-peak, were observed.

Shock and transient vibrations during coupling and during starting and stopping are generally considered to be the most damaging phases of rail shipment. Figure 3-10 shows the velocity of impact during switching operations taken from a representative number of railroad yard operations. It should be noted that the mean speed of impact is 7 mph, which is well above the approximate 5 mph limit for which the switching gear provides cushioning protection. Longitudinal accelerations of a freight car body that can be expected for impact speeds of 1 to 7 mph are shown in Fig. 3-11.

Air transport./13/ In air transport as in all other modes of transportation, the shocks encountered in handling, loading and unloading must be considered. Figure 3-12 shows the

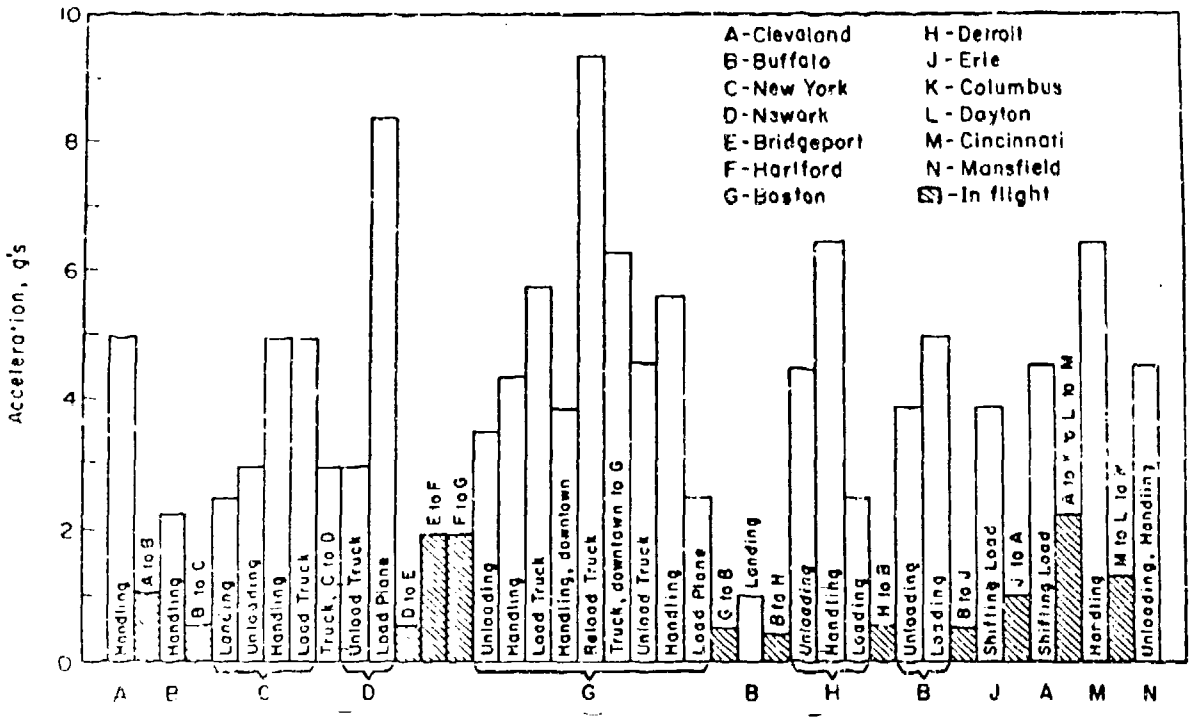


Fig. 3-12. Shocks recorded during airline test shipment./13/

maximum shocks recorded during a test shipment by a major airline. Two impact recorders were placed in a wooden box (having 73 pounds total weight) and both longitudinal and vertical shocks were recorded. It is evident that the most severe shocks recorded arose from handling.

Ship Transport./14/ The principal excitation forces for ships' vibrations result from the ship's structure interfering with the flow of water from the propellers, and from imbalance or misalignment of the propeller shaft system. The maximum frequency for which vibrations are considered important is about 1200 cycles per minute for a typical modern ship. Exceptions may occur for smaller ships and modern submarines, both of which may have greater upper limits. Vibration amplitude versus frequency data derived from representative ships are shown in Fig. 3-13. All points in the illustration represent motions of the ship's structure and not of equipment mounted on the ships.

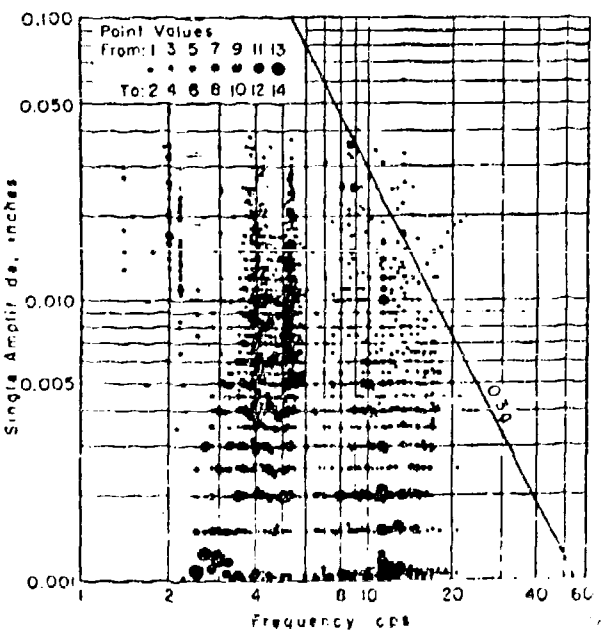


Fig. 3-13. Vertical and athwartship hull and deck vibrations for ships./14/

Turbojet Aircraft

The shocks and vibrations encountered by turbojet aircraft in flight arise from many sources, some of which are:

1. High-intensity noise.
2. Pulsations of engine thrust.
3. Turbine "chugging."
4. Imbalance of spinning components.
5. Aerodynamic forces arising from gusts, wind shear, turbulence, etc.

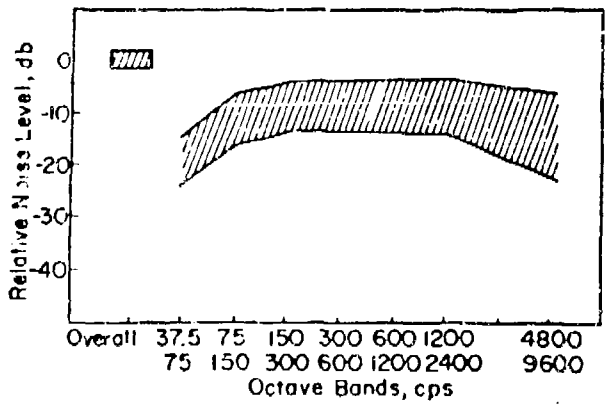


Fig. 3-15a. External spectra for near field jet noise relative to overall noise./16/

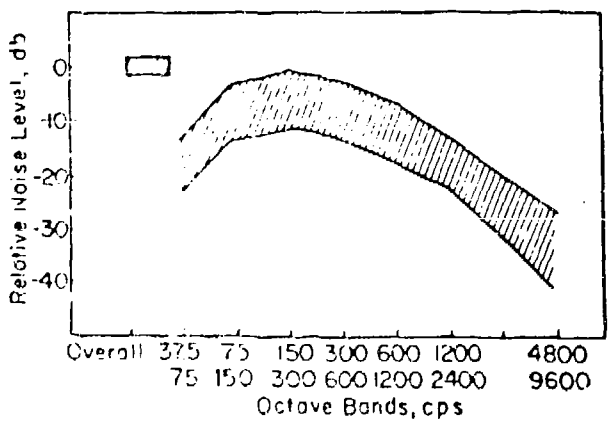


Fig. 3-15. Internal spectra for jet noise in untreated compartments relative to overall noise./16/

In addition, during taxiing and landing aircraft experience shock loads and transient vibrations. However, these vibrations are at different frequencies from those experienced during flight. 13/

Jet Noise. 16/ An important consideration in acoustic environments is whether the sound spectrum is discrete or continuous. A discrete spectrum has characteristics such that the time history of sound fluctuations is periodic and therefore can be analyzed by methods of Fourier series. Noise produced by a spinning propeller is the most frequently met example of a discrete spectrum.

If the time history of sound pressures is aperiodic, the frequency analysis is sometimes possible by use of the Fourier integral. The function of frequency resulting from this analysis may be continuous over a wide band of frequencies. If it is, the sound spectrum is said to be continuous. Noise produced by a jet or rocket

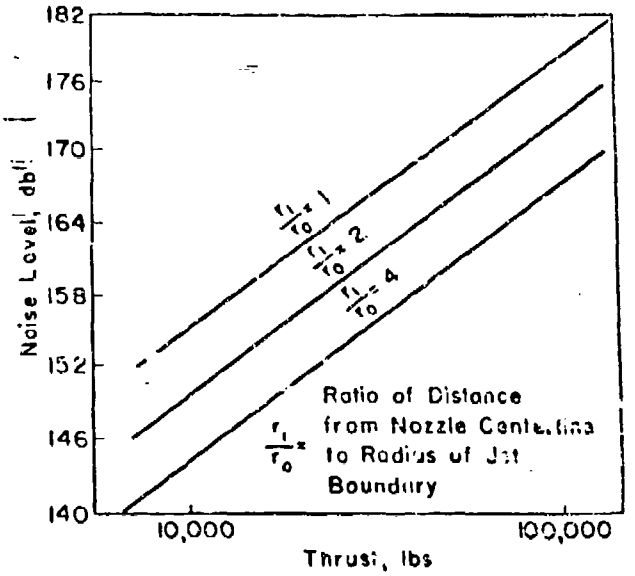


Fig. 3-16. Trend of external overall levels of jet and rocket noise./17/

engine is frequently of the continuous spectrum type. Continuous and discrete noise spectra may exist simultaneously, as well as individually.

A continuous spectrum type of noise for both jet and rocket engines is shown in Fig. 3-14. The method of presenting the spectrum differs considerably from that used for the discrete spectrum type. Noise in specific octave frequency bands is plotted relative to the overall noise level that would be obtained if the noise was passed through a 37.5- to 9600-cps filter. The range of octave levels in the illustration was obtained from measurements of jet and rocket engine noise. The changes in the spectrum due to passage of the sound through an ordinary fuselage wall is shown in Fig. 3-15. It is assumed that the fuselage wall has not been treated with soundproofing or other insulation.

Figure 3-16 shows the trend of the overall noise level with increasing thrust as well as with increasing distance from the jet stream. The range is from about 140 to 180 db. The same trend of overall noise level after the sound has passed through a typical fuselage wall is shown in Fig. 3-17. This illustration gives typical sound levels encountered near equipment or structural components on the interior of the flying vehicle.

The noise characteristics of selected jet aircraft are shown in Figs. 3-18 through 3-21. Similar data for many other jet aircraft are contained in reference/17/.

Jet Aircraft Vibration. Although all jet aircraft are subject to vibration, the amplitude and frequency of the vibrations depend upon the type of aircraft and the particular location on the aircraft. Charts 3-1 through 3-4, located at the

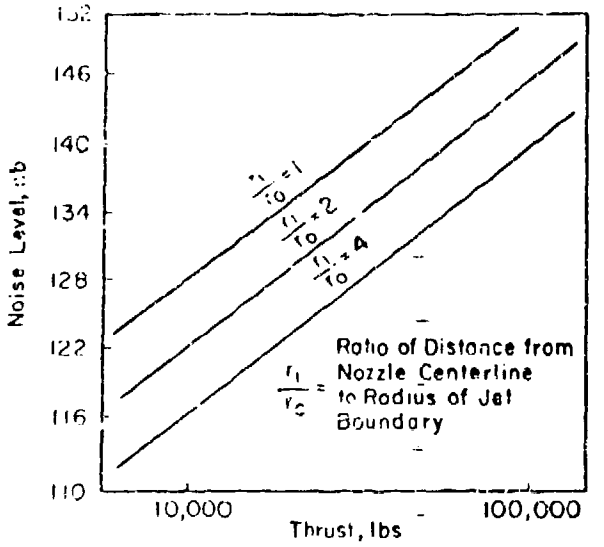
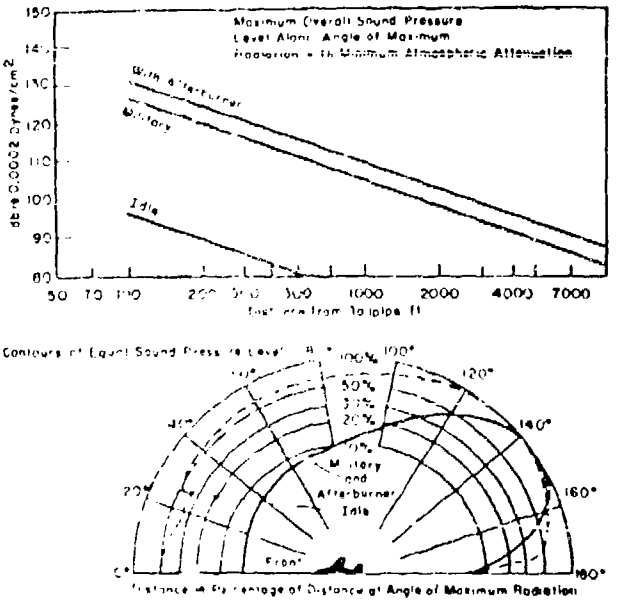


Fig. 3-17. Trend of internal overall jet and rocket noise levels for untreated compartments./16/

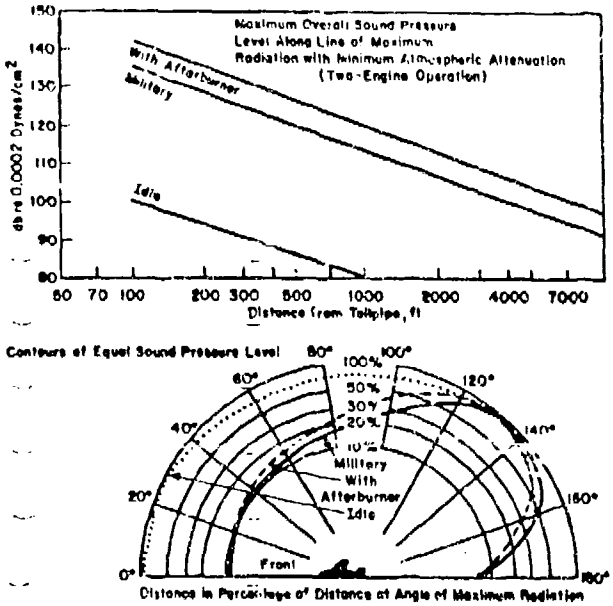


Overall Levels at Specific Maintenance Positions

Position	Overall Noise Level During Operation					
	Idle			Military *		
	Min	Max	Avg	Min	Max	Avg
Wing tip	97	102	100	114	118	117
Main wheel well	105	110	107	117	122	120
Nose wheel well					121	
[illegible]	91	100	95	106	111	110
[illegible]	113	122	118	117	124	121
[illegible]	105	110	107	122	125	124
[illegible]	91	122	103	116	130	123

* Add 7db to military levels for afterburner operation

Fig. 3-18. Noise Characteristics of F-94A and F-94B aircraft./17/



Overall Levels at Specific Maintenance Positions

Position	Overall Noise Level During Operation					
	Idle			Military *		
	Min	Max	Avg	Min	Max	Avg
Wing tip	104	106	105	123	127	125
Main wheel well	104	113	109	121	126	124
Nose wheel well	107	115	110	114	122	119
Engine access	112	118	115	124	126	125
General area	97	118	108	119	149	129

* Add 7db to military levels for afterburner operation

Fig. 3-19. Noise characteristics of F-101 aircraft./17/

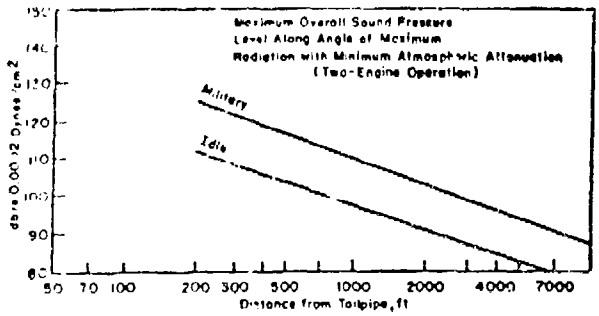
end of this chapter, show the vibration environment at various locations on turboprop transports, jet bombers, century jet fighters, and helicopters, respectively. The charts indicate the number of occurrences of frequency-amplitude combinations. Upon request, vibration data for many more locations as well as for additional types of aircraft are available from:

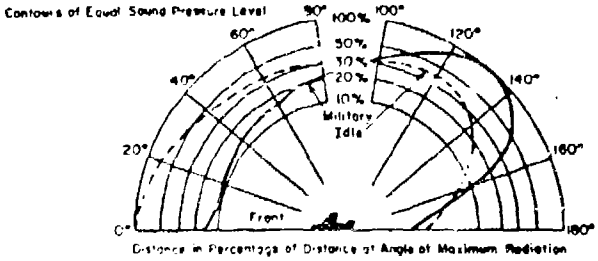
Environmental Division
Engineering Test Directorate
Deputy for Test and Support
Aeronautical Systems Division
Air Research and Development Command
U.S. Air Force
Wright-Patterson Air Force Base, Ohio

Vibration data covering jet engines J-48, J-47, J-71, J-75, and J-79; turbo-jet engines T-34, T-40, T-49 and T-56; and jet target drones Q-2 and Q-4 are also available.

Missiles/18/

Throughout their operational life, missiles are subjected to shock and vibration loads due





Overall Noise Level During Single-Engine Operation

Position	Overall Noise Level During Single-Engine Operation					
	Idle			Military		
	Min	Max	Avg	Min	Max	Avg
Wing, top				135	139	136
Along bottom of [illegible]				125	141	131
Thrust adjust panel	116	120	118	133	138	136
Cockpit			95	107	113	111
General area				107	150	131

Fig. 3-20. Noise characteristics of B-66 aircraft./17/

to noise, thrust and aerodynamic disturbances, and extreme changes in accelerations, effective gravitational forces, density and temperature. /13/ Figures 3-22 through 3-24 are selected examples of shock and vibration data obtained from restrained firings and free-flight tests of the following missiles:

Bomarc	Rascal
Corporal	Regulus
Falcon	Snark
Matador	Talos
Nike	Terrier

For security reasons, the data presented in Figs. 3-22 through 3-24 are not associated with specific missiles. More complete missile shock and vibration data are contained in reference 14.

Orbital and Space Vehicles

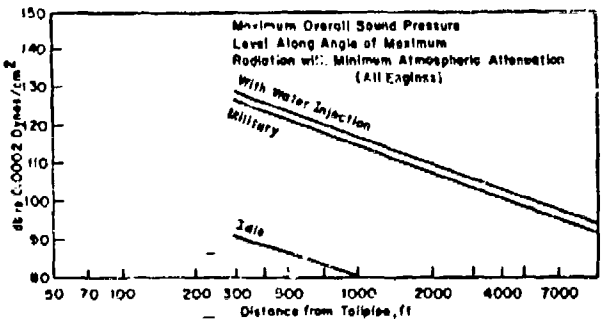
The shock and vibration environments of orbital and space vehicles have not been confirmed due to the limited number of operational experiences. The following, however, are considered reasonable limits for these environments:

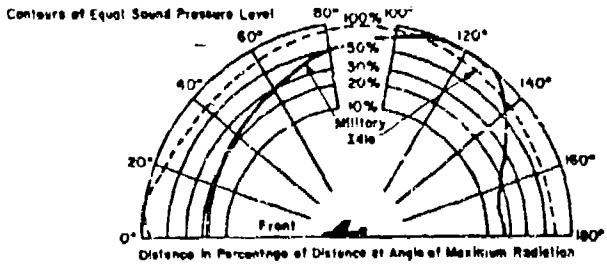
Vibration

Boost phase	0.2-inch double amplitude from 5 to 55 cps
Sustained flight	from 55 to 2000 cps ±3 g

Shock

Engine ignition, cutoff and stage separation	0 to 200 g for one millisecond
Soft landings	15 g for 11 milliseconds
Acceleration or deceleration	0 to 7 g during boost phases, and 0 to 100 during reentry to Earth's atmosphere
Acoustics	0 to 190 db from 37 to 10,000 cps





Overall Levels at Specific Maintenance Positions

Position	Overall Noise Level During Operation					
	Idle			Military*		
	Min	Max	Avg	Min	Max	Avg
General area, single engine * *				115	150	135
General area, all engines	105	124	118	115	156	
Wingtip, all engines						147
Engine trim, single engine	110	118	114	125	141	131

* Add 2db to military levels when water injection is activated
* * Levels vary widely throughout general area

Fig. 3-21. Noise characteristics of B-52 aircraft./17/

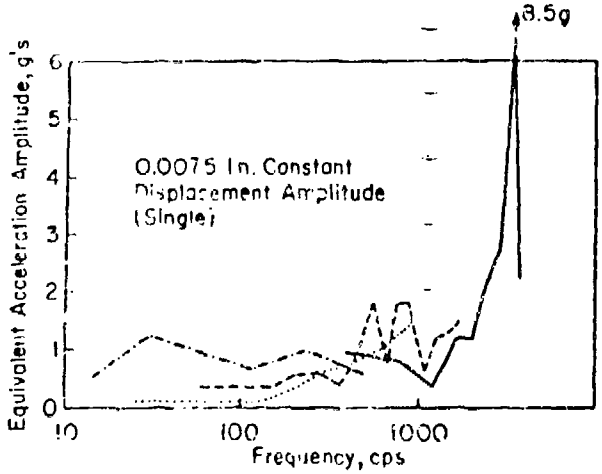


Fig. 3-22. Vibration characteristics of four operational missiles during sustained flight after boost./18/

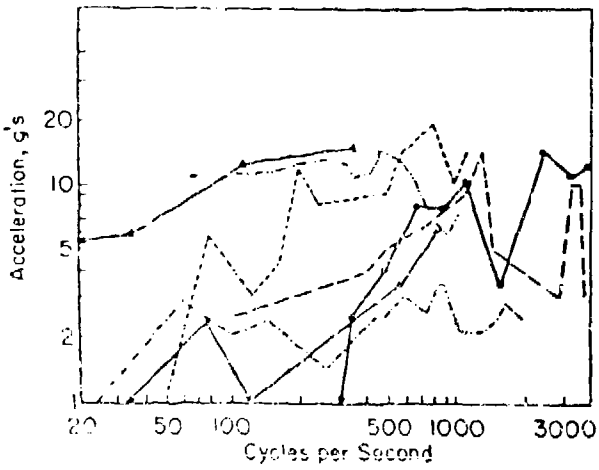


Fig. 3-23. Vibration characteristics of seven operational missiles during boost phase./18/

Effects of Shock and Vibration

The general effects of shock and vibration, together with acceleration and acoustics, are structural disturbances (Figs. 3-25 and 3-26). The response of a structure to shocks and vibrations is dependent not only upon the magnitude of the disturbance but also upon the dynamic characteristics of the structure itself. An imposed vibration of the same frequency as the natural frequency of a structure, even though small in amplitude, may be very destructive to the structure, while a different frequency, even though of greater amplitude, may cause no trouble.

Disturbances can cause progressive deterioration, since improperly designed structures and components subjected to recurrent shocks and vibrations can eventually fail because of fatigue. Material or parts failures result from mechanical stresses imposed within the material. Failure can occur either through fatigue, excessive single stress, or excessive deflection. Although fatigue failure usually im-

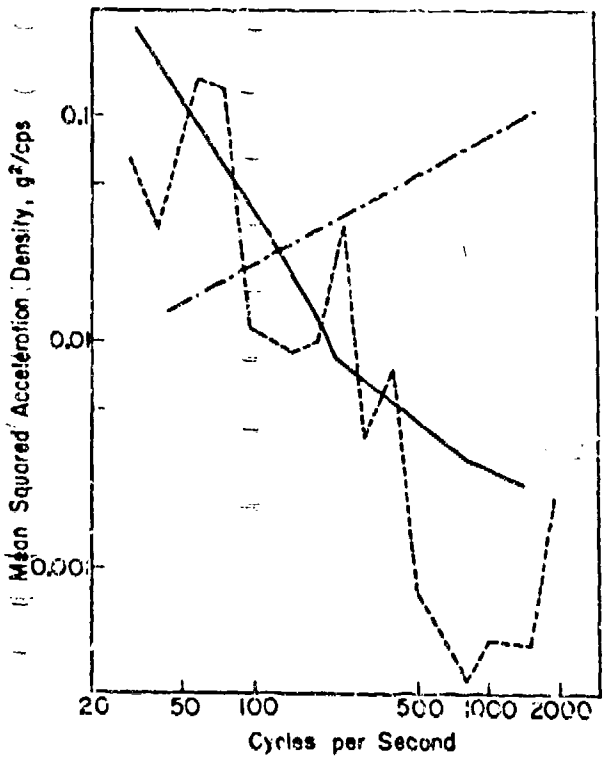


Fig. 3-24. Mean-squared acceleration density plots for three operational missiles./18/

Fig. 3-25. Vibration and flutter damage to elevator of F-86H jet fighter.

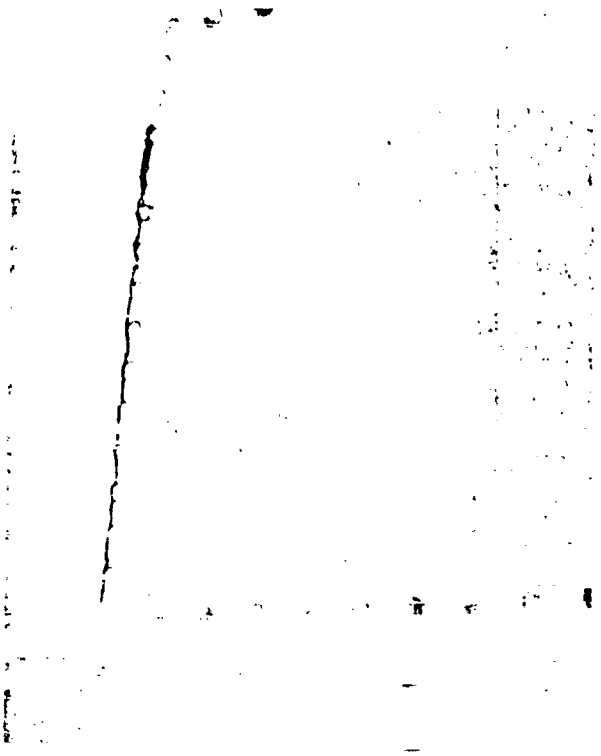


Fig. 3-26. Crack in skin of aircraft fuselage caused by vibration.

plies a large number of stress cycles, the time required for these stresses to accumulate is short when a component is vibrating at hundreds of cycles per second. Excessive single stress may cause brackets or other supporting structures to yield or fracture. Excessive deflections of parts may result in their hitting one another with high impacts, leading to failure.

Types of Shock and Vibration Damage

The weapon system designer can gain considerable insight into the shock and vibration problem from summaries of shock and vibration damage to typical structures and components. Following is some data taken from one series of tests. /19/

Cabinet and Frame Structures. Among some 200 equipment cabinet and frame structures subjected to shock and vibration there were 30 permanent deformations, 17 fractures in areas of stress concentration, 2 fractures at no apparent stress concentration, 23 fractures in or near welds, and 26 miscellaneous, undefined failures.

Chassis. Nearly 300 chassis subjected to shock and vibration resulted in 18 permanent deformations, 8 fractures in or near welds, 9 fractures at no apparent stress concentrations, 46 fractures at points of stress concentration and 12 miscellaneous failures.

Cathode-ray Tubes. In general, shock and vibration damages cathode-ray tubes if they are improperly mounted and inadequately supported. Tubes with screens larger than five inches are especially susceptible. Of 51 cathode-ray tubes subjected to shock and vibration, 1 tube had the deflection plates become deformed, another had a filament failure, 5 suffered envelope fractures, and 1 had the glass-socket-seal break.

Meters and Indicators. The moving-coil type of meter represented the majority of units in this category. Other indicators were Bourdon tubes and drive-type synchros. Of the latter group most of the failures were either erratic performance or zero shift difficulties.

Nearly 200 units were subjected to shock and vibration. Two suffered permanent deformation of the case, 1 had elements loosened, 12 gave erratic readings, 1 had the glass face fractured, 2 developed internal open circuits, 2 had loose or damaged pivots, 3 had the pointers deformed, and 10 others failed from miscellaneous causes.

Relays. Relays present a problem for dynamic conditions because of the difficulty in balancing all of the mechanical moments. Shock generally causes failure in the form of the armature failing to hold during the shock.

Three hundred relays were subjected to shock and vibration. Armature difficulties accounted for 29 defects, 4 relays had contacts fuse or burn because of arcing, 1 had the coil loosened on the pole piece, 2 had the springs disengage from the armature, and there were 4 miscellaneous defects.

Wiring. Wiring failure as a result of shock and vibration is a serious problem. A defect not only results in malfunctioning of the equipment, but it is difficult to locate for repair. In a number of equipments subjected to shock and vibration the failures were as follows: 10 cold solder joints opened, 14 lead-supported components had the leads fail, insufficient clearance caused 3 cases of arcing, and insufficient slack caused 9 lead failures. In addition, 3 plastic cable clamps fractured, 14 soldered joints or connections failed, 16 solid conductor wires broke, and there were 92 miscellaneous failures.

Transformers./20/ Transformers are probably the heaviest and densest components found on an electronic chassis. Because of the weight and size of transformers, shock and vibration is more likely to produce mechanical failures rather than electrical failures. While not all mechanical failures immediately prevent the transformer from functioning properly, they eventually result in destruction of the transformer and damage to surrounding components.

Thirty transformers were subjected to shock and vibration. 17 had the mounting studs break at the weld, 4 had the bottom frame fail, and 2

suffered broken internal leads due to motion of the core in the case.

Summary/21/

The major failures caused by shock, vibration, acceleration and acoustics are fatigue failures of mounting bases; loosening of fasteners; oscillation of instrument indicators; erratic operation of vacuum tubes; bouncing of motor and generator brushes; sticking of relays, switches and valves; misalignment of optical equipment; and fracturing of propellant, penumatic, and hydraulic lines.

MOISTURE /22/

Moisture is a somewhat all inclusive term used for humidity as well as various forms of condensation and precipitation. More specifically, moisture is liquid, generally water, diffused or condensed in relatively small quantities. Water in the form of vapor is always present in varying amounts in the atmosphere surrounding the Earth. The vapor content in the atmosphere is referred to as humidity. When the temperature of the air is reduced to, or below, the dew point, condensation occurs. In general, dew formation takes place when the surface temperature is above 32 F (0 C). If the temperature is below 32 F, condensation takes place in the form of frost. In some cases, supercooled air droplets will form which later freeze to form ice.

Heat loss from radiation may cause sufficient cooling for the formation of dew. Such cooling normally occurs at night, but it may occur at any time. It is not necessary to reduce the temperature of the entire air mass to the dew point to produce condensation. Condensation can frequently be induced in aircraft compartments by movement of the vehicle from one altitude to another. The colder upper altitudes lower the air temperature within the aircraft and, if the air is relatively moist, it can be cooled sufficiently to cause moisture to condense upon the structure and equipment within the compartment.

Effects of Moisture

Moisture has a deleterious effect on most things, and in addition, fosters microbiological growth and galvanic action in dissimilar metals. Microbiological growth and galvanic action may be termed byproducts of moisture.

Microorganisms. 4 *

Most microbiological forms have an optimum temperature in the range of 59 to 95 F (15 to 35 C), although there are some forms that will grow at nearly 32 F and others that will grow at very high temperatures. The average optimum for fungi is in the vicinity of 86 F (30 C) when relative humidity is 95 to 100 percent.

Relative humidity is important in determining the growth of fungi. Below 70 percent relative humidity there is little opportunity for fungal growth. Many forms will grow fairly well at 80 to 95 percent relative humidity, whereas at relative humidities above 95 percent, fungi flourish abundantly. Optimum temperature for maximum fungal growth in a nearly saturated atmosphere is near 100 F (38 C).

The moisture content of the material attacked is important in determining the extent of the attack. In general, wood containing less than 20 percent moisture is not attacked by fungi. However, a difference of a few percent in moisture may determine whether a given species may grow or not. For example, one particular wood-staining fungus does not grow in pine wood with a moisture content of 23 percent but develops in wood containing 24.5 percent.

Beyond high relative humidity and suitable temperature, the only additional requirement for fungi to thrive is abundant food. This is supplied in large amounts by a great variety of organic materials produced by vegetation. Many items of equipment, as well as clothing, shoes, books, foods, and other items, are composed of organic materials. Textiles, cordage, leather, wood, paper, paints and varnishes, adhesives, plastics, resins, rubber and waxes are for the most part composed of organic materials and are thus susceptible to attack by micro-organisms. Furthermore, damage is not limited to organics alone, but extends to inorganic materials such as metals, cements and plasters, clay products, glass, stone and various others.

Galvanic Action/23/

Every metal has a certain inherent electrical potential. When one metal is placed in contact with a metal of a different potential in the presence of moisture and an electrolyte, galvanic action occurs whereby an electrochemical current flows from one metal to the other. The metal from which the current flows is the anode, and the one to which the current flows is the cathode. The current flow causes chemical byproducts, but principally results in the dissolution of one of the metals. The severity of corrosion by a dissimilar metal contact in the presence of a corroding medium can be predicted qualitatively from the potential difference of the metals making up the cell. The greater this difference, the more severe the corrosion. The galvanic series is given in Table 3-7. Those metals farthest apart in the table have the greatest potential differences and tend to be the most severely corroded due to galvanic action.

*(From Deterioration of Materials -- Causes and Preventive Techniques, By Glenn A. Greathouse and Carl J. Wessel, courtesy of Reinhold Publishing Corporation, Book Division.

Table 3-7. Galvanic Series in Sea Water /23/

1. Magnesium	19. Muntz metal
2. Magnesium alloys	20. Mangenese bronze
3. Zinc	21. Naval brass
4. Galvanized steel	22. Nickel (active)
5. Aluminum (52SH, 61S, 3S, 2S, 53ST in this order)	23. Inconel (active)
	24. Yellow brass
6. Aluminum clad, 24ST, 17ST	25. Admiralty brass
	26. Aluminum bronze
7. Cadmium	27. Red brass
8. Aluminum (75ST, A17ST, 17ST, 24ST, in this order)	28. Copper
	29. Silicon bronze
9. Mild steel	30. Ambrac
10. Wrought iron	31. 70-30 copper nickel
11. Cast iron	
12. Ni-Resist	32. Comp. G-bronze
13. 13% chromium stainless steel, type 410 (active)	33. Comp. M-bronze
	34. Nickel (passive)
14. 50-50 lead-tin solder	35. Inconel (passive)
15. 18-8 stainless steel, type 304 (active)	36. Monel
	37. 18-8 stainless steel, type 396 (passive)
16. 18-8-3 stainless steel, type 316 (active)	
17. Lead	38. 18-8-3 stainless steel, type 316 (passive)
18. Tin	

Effects of Moisture on Materials/4/*

Nearly all materials are adversely affected by moisture. In the usual case, the more moisture present and the easier the access to it, the more serious is the detrimental effect on materials. Ordinarily, the more severe the moisture conditions, the more rapid is the degradative effect. A peculiar feature of moisture is the fact that in a negative sense it can contribute to the breakdown of some materials by its absence. For most materials there is some optimum moisture content for the maintenance of useful properties. For example, paper that is too dry is brittle, and leather devoid of moisture is apt to be stiff and unworkable.

*(From Deterioration of Materials -- Causes and Preventive Techniques, By Glenn A. Greathouse and Carl J. Wessel, courtesy of Reinhold Publishing Corporation, Book Division).

Stone and Concrete. Much of the natural weathering and disintegration of rocks is caused by moisture. Moisture entering the pores and freezing there effects a sort of explosive action which, over a period of years, can reduce rock to gravel. Similar physical breakdown can occur in freshly quarried building stone or in certain types of stonework where the cleavage planes are so oriented that incipient seams can fill with moisture.

Paper and Textiles. Because moisture as an agent of deterioration can function in so many different ways, it is difficult, and sometimes impossible, to pinpoint any particular kind of deterioration as caused by any particular properties of moisture. When ordinary paper becomes wet it loses its structural strength and falls to shreds because the moisture dissolves, or at least softens, the gelatinous binder intended to hold the fibers together. Although the wetting of a cotton textile does not usually result in disintegration of the material, simple evaporation of the water produces the so-called brown-line effect at the wet-dry boundary.

Metals and Alloys. Moisture is essential to the corrosion of iron, steel and other structural metals (Fig. 3-27). The rate of corrosion is influenced by the physical way in which the moisture is applied, as for instance, alternate wetting and drying, as a spray, by immersion, as condensation, and so on. Alternate wetting and drying is especially apt to cause rapid corrosion, and even more severe is a thin layer of dew condensed from the atmosphere. There is a marked increase in the corrosion rate of steel when the relative humidity is over 80 percent. Also, the higher the relative humidity the more rapid is the corrosion of zinc.

Paint Films. The effect of moisture on paints and lacquers is the formation of blisters, which eventually break and peel off. When the substrate happens to be wood, moisture may reach the paint-substrate interface from underneath.

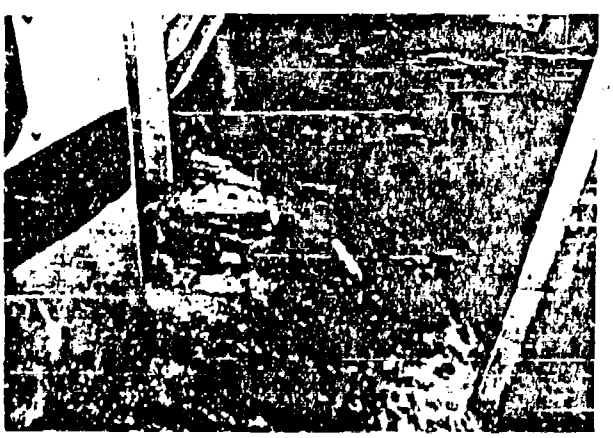


Fig. 3-27. Severe corrosion of floor of C-124 aircraft.

The moisture may be present in the wood before the paint is applied, it may come from faulty construction or it may enter directly from the reverse side. The effect of the moisture is to destroy adhesion, and a blister, once it has begun to form, is readily enlarged. The progressive breakdown of the paint film is a mechanical one.

Glass. Glass exhibits a solubility in water. Certain constituents are more soluble than others, and certain glasses are more susceptible to moisture damage than others. In the presence of high concentrations of moisture, the more soluble constituents of glass migrate to the surface. If the amount of liquid water on the surface is insufficient to dissolve the resulting hydroxides and carbonates, a slushy layer of microscopic crystals is formed. The rate of fogging by this process depends on the composition of the glass.

Wood. Wood owes much of its physical properties to its moisture content, and a change in the moisture level results in a modification of one or more of the properties. Wood is subject to rather large dimensional changes with changes in the moisture content. When moisture is taken in or given up, a moisture gradient is established, and not all fibers of a piece of wood swell or shrink at the same rate during wetting or drying. The internal stresses set up by the loss or reentry of moisture often results in warping. In addition, moisture in wood is responsible for rotting and staining.

Effects of Moisture on Components

In addition to affecting the material from which components are made, moisture degrades the operating characteristics. For example, high relative humidity reduces insulation resistance and promotes fungus growth, which may etch meter faces or produce mechanical interference in motors, tuning capacitors, and so on. The effects of moisture on several typical components are given in the paragraphs that follow.

Resistors. /24/ Moisture on the body of a resistor forms a leakage path that is equivalent to a variable resistance in parallel with the resistor. Composition resistors are especially affected by moisture. The phenolic case is not a good moisture barrier and the absorbed moisture causes instability.

Capacitors. Moisture in the dielectric of fixed capacitors decreases the dielectric strength, insulation resistance, and life, and increases the power factor. In addition, several commonly used capacitor materials (paper, wax, and other impregnants) are fungus nutrients. High relative humidity also causes corrosion of the containers of metal-clad capacitors. In one test, fifteen metal-clad capacitors were subjected to a relative humidity of from 95 to 100 percent at 95 F (35 C) for 84 days. At the end of this time all capacitor enclosures were 80 to 100 percent corroded./25/

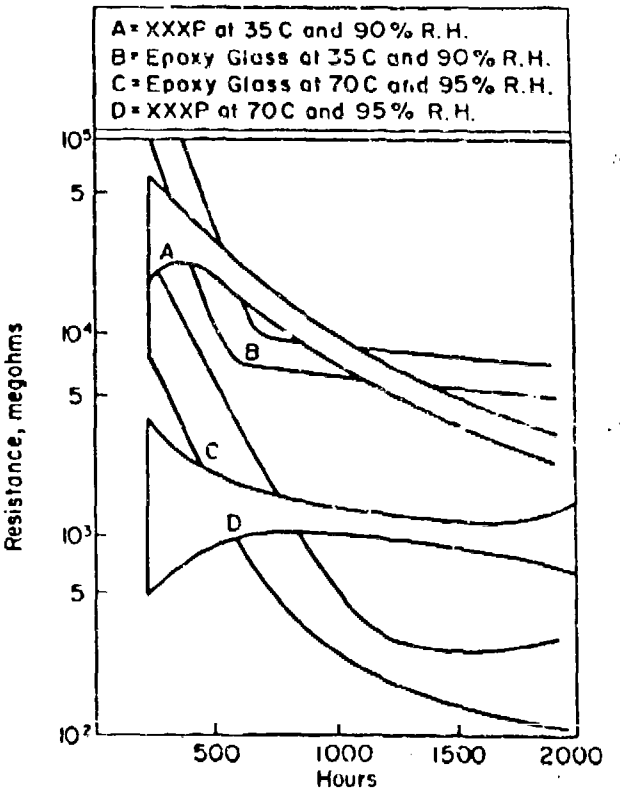


Fig. 3-28. Effects of humidity and temperature on unetched clad laminates./26/

Printed Circuits./26/ The effect of moisture on printed circuits resembles that of its effect on the base laminates alone, except that when an adhesive is present, an adhesive layer is left exposed after etching. The effect of humidity and temperature on clad laminates not subjected to etching is shown in Fig. 3-28. The poorer insulation endurance of epoxy at 70 C may be due to copper corrosion products resulting from moisture.

Transformers./27/ Moisture in transformer windings promotes corrosion, supports fungus growth, and reduces dielectric strength of insulation resistance. Electrolysis and electrolytic corrosion of the metal also may take place in the presence of a suitable electrolyte.

Motor and Generators. Moisture in and across windings of motors and generators reduces the insulation resistance and dielectric strength. It can also result in arcover between high voltage points. Galvanic action corrodes the bearings, causing rough running and early failure. Fungal growth destroys insulation, resulting in short circuits. However, should the atmosphere become too dry, there will be excessive dusting of the commutator from the brushes./4/

Effect of Moisture on Equipment

Moisture degrades the overall performance of most equipment (Fig. 3-29). The sensitivity and frequency stability of radio receivers are reduced. High humidity can cause the tuning capacitors in the output stage of a transmitter to flash-over, especially during periods of modulation. Condensate on the spreaders of open wire feeders will detune the final amplifier of a transmitter. This reduces the output power and may cause r-f feedback in audio stages. Moisture can corrode fasteners, making access to the equipment interior for adjustment and maintenance purposes more difficult.

In hydraulic, pneumatic and fuel systems, condensed moisture accumulates in low spots and freezes at low temperatures. This blocks lines and valves and makes the system inoperative./22/

Moisture also promotes fungal growth on optical and photographic equipment. This causes fogging of lenses, destroying the usefulness of the equipment. Fungus also attacks leather cases used for storing or transporting such equipment./4/

Effect of Moisture on Flight Vehicles

Besides affecting vehicles mechanically, moisture can also have operational effects. For example, if sufficient moisture fills the pitot tube, and airspeed indicator will give an incorrect reading. Also, moisture in fuel, even if it does not freeze, may cause rough engine operation or complete engine stoppage. Moisture in jet engine fuel has caused icing of filters and subsequent engine failure either by bypassing contaminated fuel that plugged nozzles or by "starving" the engine.

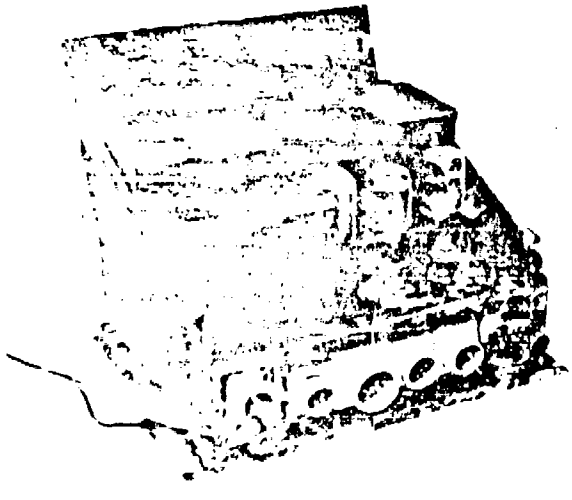


Fig. 3-29. Severe corrosion of piece of electronic equipment.

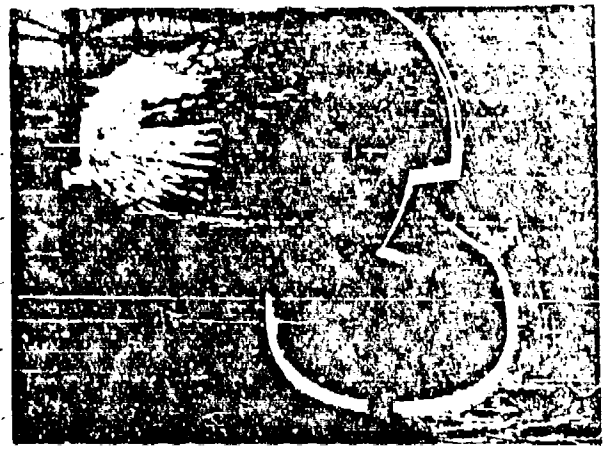


Fig. 3-30. Hail damage to aircraft nose radome.

Erosion of external aircraft surfaces by rain and other forms of precipitation is a problem. External plastic parts, such as radomes, windshields and antenna insulators, are susceptible to rain and sleet erosion at high subsonic speeds. As speeds increase above Mach 1, even metal surfaces begin to suffer severe damage when precipitation is encountered for more than a few seconds.

It has been estimated /28/ that if a ratio of one hail encounter to ten thunderstorm penetrations is taken as an average, there is a one percent probability that an aircraft penetrating a thunderstorm will encounter hailstones 2 inches or greater in diameter. Likewise, one thunderstorm penetration in 40 will involve hailstones 1 inch or greater. The leading edges of the wing and tail are most susceptible to hail damage. Damage to the fuselage is generally confined to the nose and cockpit areas Fig. 3-30). Windshields are sometimes broken or cracked by hail, and engine cowlings are damaged to about the same extent as leading edges. Turrets, radar coverings, antenna loop housings and lights are frequently struck.

Fog causes serious operational difficulties by interferring with take-off or landing. Low temperatures on the ground during fog cause ice frost. This glazes the aircraft, creating hazardous conditions for personnel. Ice-frost also adds weight to the aircraft and changes its aerodynamic characteristics. In addition, ice-frost obscures vision through windshields and makes access to fuel tanks and doors difficult.

ICING/22/

Ice, as the term is generally used, refers to solid water exclusive of snow, hail, ice-fog or frost. It occurs naturally on the surface of the Earth as well as in the atmosphere during aircraft flight. Basically, there are three forms of icing: Rime ice, clear ice, and frost. Variations and mixtures of these occur and use

such names as glaze, glime, soft rime and hard rime.

Rime ice is an opaque ice formed by the instantaneous freezing of small supercooled droplets. Since these droplets adhere in approximately spherical shape, they trap air in the ice, giving it an opaque appearance and making it brittle. Clear ice is formed by slower freezing of larger supercooled droplets. These have a tendency to spread and assume the shape of the surface on which they deposit prior to complete freezing. Clear ice contains little air. Frost is a deposit of ice crystals formed on exposed upper surfaces. Frost can also form on aircraft in flight upon descent from subfreezing air into a warm, moist layer.

In general, the condition required for icing is the presence of liquid droplets at subfreezing temperatures, that is, supercooled clouds. A supercooled cloud is one whose suspension of water droplets remain unfrozen even though the temperature may be far below freezing. This is an inherently unstable suspension. When a supercooled droplet hits the surface of an aircraft or missile, the impact destroys the stability of the droplet and raises its spontaneous crystallization point so that freezing is initiated.

Charts showing the probability of potential aircraft icing conditions existing in the Northern Hemisphere at various altitudes during the different seasons are included in reference/29/.

Icing Conditions

Icing conditions denote a state of the atmosphere defined by a set of values comprising pressure, altitude, drop diameter, liquid water content and temperature. The factors are as follows:

1. Although icing has been encountered up to 40,000 feet, the limiting altitude for all but the highest icing is about 25,000 feet.

2. Droplet size normally does not exceed 30 to 35 microns but may reach a maximum of 90 to 100 microns in diameter.

3. The water content varies from 0 to 4 grams per cubic meter.

4. The temperature range for icing conditions various from -40 to 32 F (-40 to 0 C).

High water contents are associated with strong convective clouds, and the general indications are that such clouds start to precipitate when they attain temperatures between -12 and -15 C (approximately 3.2 and 11.4 F). It is unlikely that maximum water content will be combined with temperatures below -16 C.

Effects of Icing

Icing can either decrease the performance capabilities of an aircraft, or it can cause complete failure, resulting in the aircraft being destroyed and the mission unfulfilled. Icing remains a hazard whenever adequate means of removal are not provided.

Aircraft are affected in several significant ways by the buildup of ice. The aerodynamic properties of wing and tail surfaces are changed by the ice decreasing the lift and increasing the drag. An aircraft burdened with ice requires a longer runway for takeoff or landing. In addition, ice adds to the total weight of the aircraft, decreasing its operational radius. Ice also prevents or hinders functional operation of miscellaneous units, accessories or equipment, by blocking the air intake duct, distorting the radiation pattern of the antenna, etc. Structural damage to turbine engines may result when ice breaks off inlet surfaces and is ingested by the engine. Ice accumulates on leading edges, propellers, compressor inlets, wings, induction systems, pitot tubes and all aerodynamic surfaces of aircraft. It is also induced by operating conditions in fuel and oil lines, fuel filters, vent lines and engine breather lines.

Air induction systems in general, and turbine engines in particular, are most critically affected by an encounter with icing conditions of high liquid-water content, even though the duration of the encounter is very short. On the other hand, propellers, windshields, wings and tail surfaces can usually tolerate brief and intermittent encounters with icing conditions of greater severity. Severe icing may cause a reciprocating engine to stall.

Ice-fog, which is a suspension of very small ice crystals in the air, presents an operational hazard to flight vehicles. Ice-fog usually occurs under conditions of clear, cold, windless weather in the high latitudes.

SAND AND DUST

The sand and dust environment is a major factor in desert areas; however, it is not restricted to those areas alone. Dust also includes airborne impurities, which can become a problem in almost any location. The amount or concentration of sand and dust at a given point is one of the most important factors in such an environment. At the present time, concentration is usually measured either as weight per unit volume of air, or as number of particles per unit volume. To relate the two methods it is necessary to know the number of particles per unit weight. This is a very complex factor which must take into account the particle size distribution, composition, shape and density of the particular sand and dust being analyzed. For this reason much of the data obtained from air pollution studies and sand and dust storms cannot be readily applied to the subject of deterioration, since engineering performance has usually been related directly to the weight of sand and dust encountered over a certain period. /30/

A normal atmosphere always contains a certain amount of impurities in the form of natural sand or dust originating from the soil and other sources. Among such sources are: /30/

1. Condensation of vapors and gases. The formation of rain or the condensate from metallic vapors.

2. Mechanical dispersion of liquids. The salt particles in seaboard atmosphere or particles originating from spray evaporation.

3. Chemical reactions. The smoke from industrially used chemicals.

4. Crushing. The aerosols generated by the disintegration of concrete or asphalt, milling, pulverization of coal, quarrying or allied operations.

5. Combustion or explosion. The fumes, smokes, and ashes from the burning of solid or liquid fuels, volcanic activity, or meteoric dust.

Atmospheric Pollution

The normal amounts of atmospheric pollution found in various locations are given in Table 3-8. It is apparent from this table that industrial areas have a higher degree of pollution than do other areas. It has been reported that approximately 200 million cubic feet of dust exist permanently in the atmosphere; as many as 80,000 aerosol (soot, metal, dusts, fungus) particles were found in one cubic centimeter of the air in New York City.

In moderate dust storms the concentrations at the 1000 foot level is about 0.0005 gram per cubic foot, whereas in a severe storm it may be five to ten times as heavy. Table 3-9 gives the variation of concentration of a dust storm with increasing altitude. The fact that significant concentrations of dust are found at upper altitudes should be an indication that some degree of protection must be given to aircraft and airborne equipment. The upper limit for this dust appears to be about 10,000 feet.

Particle Size/30/

The size of a dust particle usually refers to the effective or mean diameter and is given in microns. Dusts are generally limited to particles ranging from about 0.1 to 50 microns; wind blown sands are particles between about 50 to 200 microns; and sand tailings from flotation (airborne by wind or some mechanical means) range upward from 300 microns in diameter.

Natural Dust Condition/30/

The effect of wind in creating a natural dust condition is one of the more important variables. Because moving air absorbs more moisture than still air, wind acts as desiccant by drying out the top soil, and then as an agent or erosion by removing the dry dust. The dustier seasons of the year are the seasons of tight atmospheric pressure gradients, sharp troughs and frequent frontal passages.

Table 3-8. Normal Atmospheric Pollution in Various Areas

Region	Average dust concentration (grams per 1000 cubic feet)	
	From Clower/31/	From Kayse/32/
Rural and suburban	0.2 to 0.4	0.0013 to 0.0032
Metropolitan	0.4 to 0.8	0.0032 to 0.0130
Industrial	0.8 to 1.5	0.0130 to 0.0485

Table 3-9. Variation of Concentration of Dust Storm With Increasing Altitude /30/

Height (ft)	Weather condition	Air temperature (C)	Mean concentration (milligram/ft^3)
500	Clear to slight	33.0	0.0060
1000	haze. Visibility	30.5	0.0065
2000	about 80 miles.	30.0	0.0049
4000		29.0	0.0039
6000		19.0	0.0015
500	Slight haze.	34.0	0.0067
1000	Visibility about	33.0	0.0074
2000	20 miles.	32.0	0.0057
4000		27.0	0.0039
6000		21.5	0.0054
500	Moderately dense	27.0	0.057
1000	dust storm. Vis-	25.0	0.493
2000	ibility about 100	24.0	0.197
3000	feet. Wind 20 to	23.0	0.051
4000	25 knots.	22.0	0.018

The intensity of the wind is also a factor in determining the dust condition, since the force exerted by the wind is proportional to the square of the velocity, and the energy, or work-doing ability, is proportional to the cube of the velocity. Table 3-10 shows the surface wind velocity necessary to transport various sized dust particles.

Wind velocity increases logarithmically with height above the ground. These data are closely associated with the transportability of dust. Unless a distinct dust storm occurs, wind-blown sand rarely rises more than three feet off the ground; the average height being about 4 inches. It has been estimated that a 33 mile an hour wind at a five foot level is required to set sand particles in motion.

The height to which a dust storm rises is a function of the wind velocity and the stability of

Table 3-10. Surface Wind Velocity Related to Moving Dust Particles /30/

Wind velocity (mph)	Mean particle size (microns)
1.1	40
2.2	80
4.4	160
8.8	320
19.6	650
29.6	970

the entire air mass. Unstable air masses create extreme vertical air movements, resulting in turbulence and convection currents, which can carry the dust as high as ten to fifteen thousand feet.

Effects of Sand and Dust

Almost all dusts, and many kinds of dirt, are to various extents hygroscopic, and so they tend to adsorb moisture. A film of dust or dirt on a material, therefore, tends to maintain a higher moisture level. This tends to increase the degradation and corrosion rate of most materials. /4/ Sand and dust penetrate every crack and crevice of a weapon system. When mixed with lubricants, the mixture becomes an excellent grinding compound. Accumulation of dust, sand and other gritty matter accounts in large part for the drying and caking of greases in exposed bearings. For example, an internal combustion engine operated without an air filter will be rendered unless in about 10 hours or less, depending on the dust concentration.

From a component viewpoint, if the component is in a moistureproof housing, it is also protected from sand and dust. Hermetically sealed components, such as relays, transformers, and vacuum capacitors, are not affected by sand and dust.

Dust accumulates between high-tension electrodes and promotes arcing. It gets into connectors, causing them to stick and make poor contact. The abrasive action of sand and dust rapidly damages bearings and the armatures of motors, dynamotors and generators. Volcanic dust contains constituents that hasten the corrosion of iron surfaces. Dust can even become embedded in some types of die castings and be responsible for a phenomenon known as growing. If parts so affected are intended to be moved, seizure eventually takes place./4, 33/

Dust in propellants or propellant systems clog fuel metering passages, causing erratic operation or even explosions. For example, impurities contacting heavily concentrated hydrogen peroxide have caused explosions. Dust in cooling passages of regeneratively-cooled liquid rockets can cause hot spots, leading to possible motor burnout or explosion./33/

The abrasive action of wind-driven sand wears away paint and other protective coatings. It can make windshields, radomes or star-tracking windows opaque and thereby reduce visibility or sensitivity. Sand and dust particles in hinge bearings of control surfaces on aircraft can cause sufficient friction to make the controls stiff and difficult to operate. Wear is increased and additional maintenance is required.

Dust will plug the drain holes in the wings and tail structure of aircraft and prevent drainage of water; pitot tubes become plugged, and the dead air spaces in wings, fuselage and tail allow dust to accumulate, possibly affecting the aerodynamic stability or performance of the aircraft seriously. Dust will also clog or plug components of spark ignition engines. This is especially true where dust in combination with leaded fuel will rapidly increase spark plug fouling. This is a serious problem in the operation of helicopters because of the relatively high percentage of time they operate in heavy dust concentrations./30/ Cooling systems are affected because the dust adheres to oil-soaked or wetted surfaces and forms insulating layers that reduce heat transfer rates.

PRESSURE

The effects of pressure fall into two categories: Those resulting from ambient pressure, and those caused by wind.

Ambient Air Pressure/34/

Ambient pressure is the surrounding air pressure of a given point at a prescribed altitude and location; it is equal to the weight of a column of air, over a given area, from that point to the outer extreme of the atmosphere.

All aerodynamic and thermodynamic characteristics of a flight vehicle are dependent to some extent on ambient pressure. Drag, lift, thrust from air-breathing propulsion systems, vapor pressure and cooling rates increase directly with increases in ambient pressure. Effective thrust from rocket engines and control surface size, on the other hand, decrease with increased ambient pressures.

Low ambient pressures adversely affect human beings and make pressurization systems mandatory. This, in turn, presents the danger of explosive decompression, which would occur if the cabin or compartment pressure were suddenly lost due to mechanical failure, damage by a meteor, or possibly enemy action.

Many lubricants have a relatively high vapor pressure that renders them useless under conditions of extremely low ambient pressure.

Graphite is especially affected, becoming an abrasive. Without lubrication, oxide coatings, or molecular gas films, coefficients of friction between moving surfaces rise sharply, with galling inevitable and cold welding probable. Extremely low pressures will also drastically affect all kinds of seals; even a good welded joint may prove to be porous.

Electrical Arcover and Corona. The insulating effect of air between high-voltage electrodes, or other high tension points, decreases with decreasing pressure. Therefore, at high altitudes, high voltage equipment may have a voltage arcover between the high tension points. At a pressure corresponding to an elevation of 45,000 feet, the voltage breakdown potential is approximately a third less than at sea level. At 60,000 feet, the breakdown potential is about one fifth of its breakdown value at sea level./4, 35/

Destructive arcs can damage conductive parts, and break down insulators so that they will conduct. Connectors, terminal boards and relay contacts are examples of parts that are subject to arcover problems. Other parts, such as resistors, capacitors and transformers, unless hermetically sealed, can develop internal arcing in a low pressure environment. Arcing is particularly damaging to brushes used in motors and generators.

If voltages are not high enough or the air pressure is not quite low enough to support arcover, minute arcs may take place in the area of the high voltage points. This is known as corona, and can damage components and materials and cause considerable communication interference. The ionized air caused by corona produces ozone and oxides of nitrogen. The ozone oxidizes natural rubber and synthetic materials, and the oxides of nitrogen combine with water to form acids that contaminate and degrade insulators and bushings, and corrode metals./4,35,36/ At a pressure of approximately 10^{-3} millimeters of Hg the air becomes too thin to support a corona discharge.

Heat Removal. Convection is a common means of removing heat from equipment. Since the density of air decreases with increasing altitude, the heat absorbing capacity of air falls off proportionately. Table 3-11 shows the heat-absorbing capacity of a given volume of air at various altitudes as a percentage of its heat-absorbing capacity at sea level. Since the air is less able to absorb and remove heat at higher altitudes, the temperature of heat producing components may rise above their safe operating levels, unless preventive measures are taken. At a pressure of approximately 10^{-4} millimeters of Hg air can no longer be considered a heat conductor.

Wind /34/

Wind is usually caused by differences in atmospheric density, which produce horizontal differences in air pressure. A pressure gradient force develops, setting the air in motion and causing it to flow from high to low pressure. Any sudden, brief movement of air at a velocity in excess of the steady air velocity is a gust.

Table 3-11. Heat Absorbing Capacity of Air at Various Altitudes /34/

Altitude (feet)	Percent heat-absorbing capacity of given volume of air to that at sea level
0	100
20,000	50
40,000	25
60,000	10
80,000	3
100,000	1

Operational Effects. Wind can affect the flight path and range of missiles and aircraft. In horizontal flight, the direction and speed of the winds at specific levels, such as the jet streams, can increase or decrease the range of a vehicle. A change in wind speed or direction with height can force a vehicle off its intended course and possibly out of control. Surface winds as well as atmospheric winds must be considered in selecting missile launching sites. In addition, wind is instrumental in producing other troublesome environments, such as wind-blown sand and wind-blown snow.

Wind Load Stress. Stress caused by wind loading is a basic consideration in flight vehicle design, since sufficient strength must be provided in all structural members to withstand all wind and gust loads likely to be encountered. The force exerted by wind varies as the square of the wind speed, and wind velocity generally increases with altitude. However, at high altitudes the loading caused by wind is greatly diminished due to the decreased atmospheric density. Data on the probability of occurrence of winds of various speeds are given in Chapter 2./36/

Low velocity and short duration gusts producing accelerations of 0.1 to 0.5 g can shake and jerk a flight vehicle, but usually will not displace it from its intended course or cause any structural damage. However, higher velocity and longer duration gusts may accelerate the vehicle and also cause structural damage. On the ground, gusts may produce dangerous structural loads on ground support equipment.

EXPLOSIVE ATMOSPHERE/37/

Combustible gases, usually a mixture of hydrocarbon vapors and air, may seep into equipment and create a potentially explosive atmos-

phere. Electrical arcover, corona or a spark from any moving electrical equipment may ignite these combustible gases and cause an explosion or fire. Some of the factors involved in producing a potentially explosive atmosphere are the fuel-air mixture ratio, the atmospheric pressure the temperature, the humidity and the source of ignition.

Fuel-Air Mixture Ratio

A mixture of fuel and air may be either too rich or too lean to be an explosion hazard. At sea level pressure, a mixture consisting of 1 to 7.5 percent fuel, by weight and volume, constitutes a potentially explosive atmosphere. Mixtures of 3 to 5 percent fuel are extremely hazardous and will readily produce high-speed explosions and flame propagation. Below 3 and above 5 percent, the fuel-air mixture will be more difficult to ignite. If ignited, the explosion will be mild and the speed of flame propagation will be slow.

Atmospheric Pressure

A potentially explosive atmosphere varies only slightly with decreases in pressure. As atmospheric pressure is reduced, the dielectric constant of air decreases, thereby increasing the possibility of electrical discharge. However, with decreased atmospheric pressure, the explosive mixture becomes more difficult to ignite./438/

Temperature

Temperature has little effect on the explosiveness of a gas mixture within the temperature range of 86 F (30 C) to 131 F (55 C). However at low temperatures, which exist at higher altitudes, the explosion hazard is considerably reduced.

Humidity

Increased humidity does not affect the explosive atmosphere itself. However, it does slightly decrease the speed of flame propagation.

Sources of Ignition

Even in the most potentially explosive atmosphere, a visible spark may occur a number of times and not ignite the mixture. The spark must give off enough heat to bring the temperature of the mixture to the flash point. An electric spark delivered over a relatively long period is the most effective ignition source. Above 20,000 feet, corona rather than electric arcover acts as a source of ignition./4,35/

ATMOSPHERIC ELECTRICITY

Atmospheric electricity includes static electricity and lightning. Both can cause serious damage, and may interfere with the operation of flight vehicles (Fig. 3-31). Atmospheric electricity is discussed in Chapter 2. The following paragraphs are primarily concerned with the effects of static electricity and lightning on the operation of flight vehicles./37,39,40/

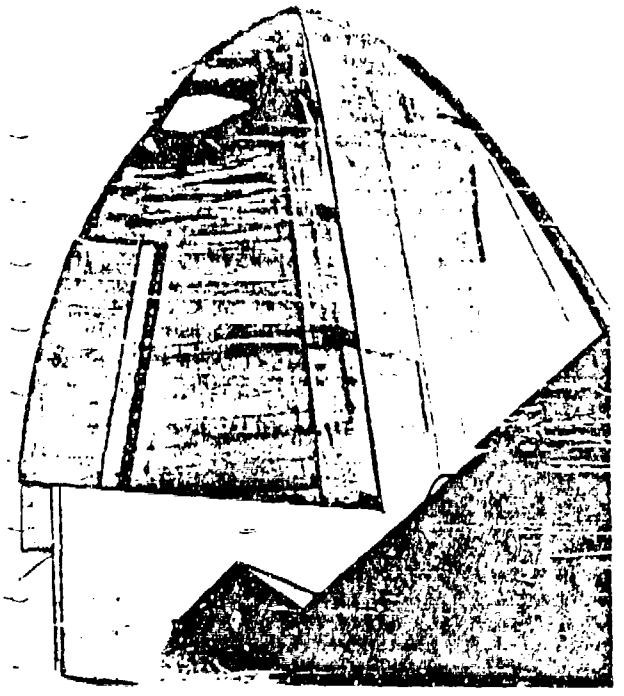


Fig. 3-31. Aircraft damage caused by static discharge or lightning strike.

Static Electricity

The electrification of flight vehicles with high static electrical charges is produced in two different ways: autogenous electrification and exogenous electrification. Autogenous electrification is the most common form and usually of the longest duration. It is caused by the rubbing of particles, such as snow, dust, sand, and smoke, against the outer surface of the vehicle. Exogenous electrification results from high potential gradients existing in the atmosphere independent of the presence of the flight vehicle. It is especially apt to occur during thunderstorm activity./37/

Effects of static electricity include shocks to personnel, ignition of fuel and other combustible materials, and arcing in electrical equipment. Static electricity may also cause pitting and rupture of rubber deicing boots, windshields and other highly insulating materials, such as polystyrene and methylacrylates.

The principal effect of static electricity is interference with radio reception. Radio reception, particularly in the lower frequency ranges below 100 megacycles, may be blocked out completely by static electricity. Another related flight problem is the blanketing of anten-

nas by exhaust gases from the vehicle propulsion system. These charged gases make the antenna nonreceptive.

Lightning

Lightning is a disruptive discharge of electricity and may cause damage to flight vehicles during thunderstorm activity. Control surfaces may develop small pit marks and holes. Nonmetallic parts, such as radomes, windshields, antenna insulators and canopies may be shattered. And the vehicle skin may be burnt and pitted, with most of the damage taking place at sharp edges or the smallest radii of a curvature. Apart from the risk of the crew being temporarily blinded, there is little danger to humans in a properly bonded flight vehicle.

Radio equipment is frequently damaged by lightning. Antennas are most likely to be hit. Unless preventive methods are used, the current from the lightning is conducted along the antenna to the electronic equipment causing serious damage. Command antennas, fixed antennas and dry wick discharge antennas are the types most often damaged./37,39/

MICROMETEORITES

Table 3-12 shows the probability of a meteorite or micrometeorite hitting the surface of a space vehicle and approximately how deep the particle will penetrate if the vehicle skin is made of aluminum. Meteorites having a mass of one microgram and travelling 30 miles per second will penetrate approximately one millimeter of aluminum skin. However, the probability of a meteorite this size hitting a space vehicle is very slight. On the other hand, space vehicle encounters with smaller and less energetic particles, such as micrometeorites, would be more frequent, but the depth of penetration would be considerably smaller./41,42,43,44/

Although micrometeorites do not penetrate the surface skin to any extent, they may nevertheless present a hazard to space vehicles. Micrometeorites will gouge out small pieces of the surface skin, similar in effect to sand blasting. The erosion that results may change the heat transfer properties of the surface. In addition, the energy released by the small particle may travel through the skin and lead to erosion on the inside of the skin.

Another effect of micrometeorites is the electrostatic interaction between the particles and the space vehicle. The positively charged micrometeorite particles increase the erosion rates of the skin and may affect radio communication. /42/

Generally, if a space vehicle is exposed to meteoritic and micrometeoritic bombardment for long periods, a gradual erosion of the vehicle's skin will take place. However, for short durations, the hazard from meteorites and micrometeorites is negligible (Fig. 3-32)./44/

Table 3-12. Probability of Meteorite or Micrometeorite Hitting 1000 ft^2 of Surface, and Its Penetration of Aluminum /42/

Mass (gm)	Kinetic energy (ergs)	Probability of 1 hit per 24 hours*	Depth of penetration of aluminum (cm)
1.25	1.0×10^{13}	1.2×10^{-8}	10.9
0.50	4.0×10^{12}	3.1×10^{-8}	8.0
1.98×10^{-1}	1.6×10^{12}	7.7×10^{-8}	5.9
7.9×10^{-2}	6.3×10^{11}	2.0×10^{-7}	4.3
3.1×10^{-2}	2.5×10^{11}	4.9×10^{-7}	3.x
1.2×10^{-2}	1.0×10^{11}	1.2×10^{-6}	2 3
5.0×10^{-3}	4.0×10^{10}	3.1×10^{-6}	1.7
2.0×10^{-3}	1.6×10^{10}	7.7×10^{-6}	1.3
7.9×10^{-4}	6.3×10^{9}	2.0×10^{-5}	0.93
3.1×10^{-4}	2.5×10^{9}	4.9×10^{-5}	0.69
1.2×10^{-4}	1.0×10^{9}	1.2×10^{-4}	0.51
5.0×10^{-5}	4.0×10^{8}	3.1×10^{-4}	0.37
2.0×10^{-5}	1.6×10^{8}	7.7×10^{-4}	0.27
7.9×10^{-6}	6.3×10^{7}	2.0×10^{-3}	0.20
3.1×10^{-6}	2.5×10^{7}	4.9×10^{-3}	0.15
1.2×10^{-6}	1.0×10^{7}	1.2×10^{-2}	0.11

*For vehicle operating outside of Earth's atmosphere (From "Meteoretic Phenomena and Meteorites", by Fred L. Whipple, in Physics and Medicine of the Upper Atmosphere, edited by Clayton S. White and Otis O. Benson, copyright 1952 by the Lovelace Foundation, published by University of New Mexico Press, Albuquerque).

RADIATION

Exposure to large amounts of radiation induces changes in most materials. From the standpoint of proper operation in military systems, these changes are generally harmful. It should be pointed out, however, that some radiation induced changes are beneficial. For example, the yield strength of a metal and the temperature resistance of polyethylene may be improved by irradiation.

Cosmic Radiation

To date, little in the way of induced effects can be attributed to cosmic radiation encountered in space operations. However, two effects may be postulated:

1. Radiation damage of a permanent nature to less resistant components, such as transistors.

2. Short term ionization, which may cause spurious pulses to be induced into computer or anti-coincidence circuits.

The permanent damage that can occur in components such as transistors should not be too serious. Estimates indicate that semiconductor components will operate at least 5 to 8 years in a cosmic radiation environment without more than a 20 percent reduction in their electrical characteristics.

The occurrence of transient ionization effects in the form of random pulses in transistor circuits was indicated by Drayner./46/ However, these pulses did not follow known cosmic ray particle distributions. Due to this lack of correlation, effects cannot be predicted on the basis of available data. It might be concluded that ionization effects caused by cosmic rays will be no more trouble than interference from other sources. Photomultiplier tubes, however, may be an exception. Cosmic radiation striking the cathode will produce a great number of electrons. The electrons will cause instantaneous saturation of the tube, resulting in a noise pulse.

Cosmic radiation damage to structural materials will be negligible.

Solar Radiation

Solar radiation causes heating, which results in the breakdown of complex molecules that make up materials such as paints, lacquers, rubbers and plastics. The extent to which heating takes place depends on the heat transfer characteristics, thermal capacity and absorptive properties of the object or material.

Solar radiation is also responsible for many of the processes in the Earth's atmosphere. Ultraviolet radiation causes ionization of atmospheric nitrogen, as well as ionization and dissociation of oxygen. X-rays emitted by the sun are absorbed by the Earth's upper atmosphere, producing the ionized layers.

Nuclear Radiation

The expanding use of atomic energy in military weapons systems makes it necessary for the equipment designer to know the effects of nuclear radiation on various materials, components and systems.

The nuclear radiation emanating from a reactor consists of fast neutrons, slow or thermal neutrons, gamma photons or gamma rays, and beta particles. The alpha particles, beta particles and fission fragments are generally contained within the reactor core, or, if encountered outside the reactor, their energy has been attenuated. Therefore, the following paragraphs are concerned only with the effects of high energy neutrons and gamma rays.

Unit and Conversion Factors

A problem that arises in using and evaluating information from various studies on the effects of nuclear radiation is the fact that the investigators express their results in different units. Although the true physical unit for radiation intensity is incident radiant energy per unit area per second, exposures are often reported in terms of the rate of energy absorption or ion production in a standard reference material. Thus, the roentgen and the rep, defined as the radiation intensity required to produce a specified ionization in air and a specified energy absorption in tissue, respectively, have been employed as measures of radiation exposure for other materials and applications. Various units are also used to express the energy absorbed by a material, with ergs per gram, rads and electron volts per gram being the most common.

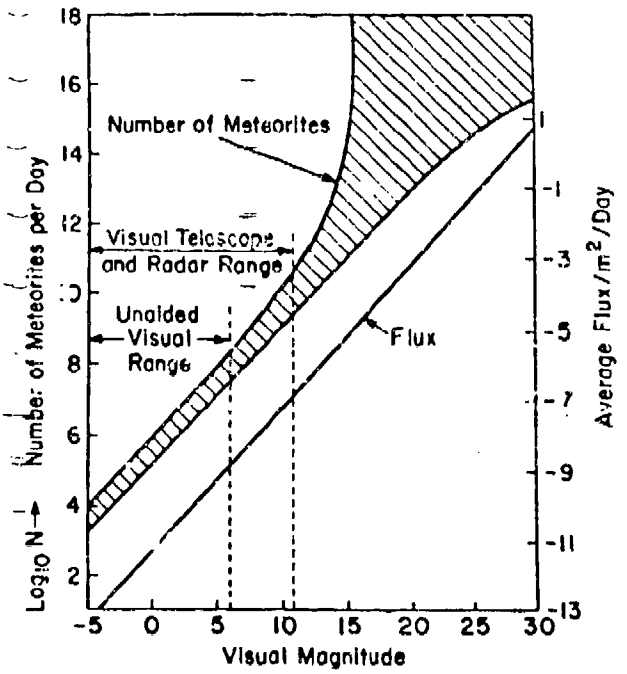


Fig. 3-32. Meteorite intensity./45/

Some degree of uniformity has been achieved, with most investigators now expressing neutrons in terms of flux (ϕ), which is the neutron (n) multiplied by the average velocity (v), or $\phi = nv$. The associated time exposure is integrated, and the total integrated neutron flux is written nvt (n = neutrons per cubic centimeter; v = centimeters per second; and t = seconds).

Another step toward uniformity in expressing nuclear radiation data involves the terms for reporting gamma exposures. Previously, they were extensively described in roentgens, or photons per centimeter squared per second. More recently, in attempting to report measurements by methods that do not involve unnecessary assumptions, investigators have been reporting gamma exposures in terms of carbon dose, which has units of ergs/gm (C).

A list of conversion factors for comparing nuclear radiation data from various sources is given in Table 3-13.

Materials

Elastomeric and Plastic Materials./47,48/ Elastomers and plastics are primarily organic materials. They consist of carbon and hydrogen atoms bound together by covalent bonds that are easily disrupted by nuclear irradiation. However, all the properties of a polymer (elastomeric and plastic materials) are not affected to the same degree by radiation. For example, some elastomers may fail more rapidly by loss of tensile strength under irradiation, while others may fail by loss of compressive strength or development of a compression set. It is therefore important to know the radiation dosages required to damage specific properties of polymers. Tables 3-14 and 3-15 show the effect of radiation on some of the more commonly used elastomers and plastics. These tables list radiation dosages at which threshold damage occurs and 25 percent damage has accrued. Threshold damage occurs when at least one physical property begins to change, while 25 percent accrued damage occurs when at least one physical property, such as tensile strength, has changed by 25 percent. Figures 3-33 and 3-34 also show the effect of radiation on selected plastics and plastic laminates.

Table 3-13. Conversion Factors for Nuclear Radiation Data

To convert	To	Multiply by
rads	ergs/gm	100
ev/gm	ergs/gm	1.6×10^{-12}
roentgen	ergs/gm(C)	87.7
rep	ergs/gm(C)	84.6
rad (tissue)	ergs/gm(C)	90.9
rad (water)	ergs/gm(C)	90.0
*neutrons/cm^2	ergs/gm(C)	4.5×10^{-8}
*protons/cm^2	ergs/gm(C)	4.5×10^{-8}
*photons/cm^2	rep	5×10^{-10}
*rep/hr	n/cm^2/sec	7.1×10^{4}
*rad/hr	n/cm/sec	8.3×10^{4}
*rep/hr	n/cm/sec	8.3×10^{3}
(C^{14})	rad/hr	4.2×10^{-6}
1 roentgen/hr = 5.5×10^{5} gammas/cm^2/sec		
1 rad/hr = 5.77×10^{5} gammas/cm^2/sec		

*Assumed average energy of 1 mev.

Table 3-14. Relative Radiation Stability of Elastomers /47/

Material	Radiation dosage required for threshold damage (ergs/gm)	Radiation dosage required for 25% damage (ergs/gm)
Natural rubber	2×10^{8}	2.5×10^{9}
Styrene-butadiene rubber (GR-S)	2×10^{8}	1×10^{9}
Nitrile rubber	2×10^{8}	7×10^{8}
Neoprene	2×10^{8}	5.5×10^{8}
Butyl rubber	2×10^{8}	4×10^{8}
Silicone rubber	1.3×10^{8}	4.2×10^{8}
Acrylic rubber	1×10^{8}	3.3×10^{8}
Polysulfide rubber	5×10^{7}	1.5×10^{8}

In general, plastic materials are more resistant to radiation damage than are elastomers. Plastics may be exposed to 10^{6} to 10^{10} ergs/gm irradiation before a physical change appears, while elastomers can only absorb dosages of up to 10^{8} ergs/gm before being damaged. Most elastomers tend to increase in hardness when irradiated. Butyl and Thiokol rubbers, however, will soften and become liquid with increased radiation dosages. Natural rubber is the most radiation resistant of all the elastomers. It retains its elongation, strength, resilience, flexibility and abrasion-loss better than any other elastomer.

Of all the plastics, the rigid plastics are the more radiation-resistant. Some of the rigid materials, such as polystyrene and mineral filled phenolics, may be exposed to dosages of almost 10^{12} ergs/gm and only when will 25 percent damage occur. On the other hand, some plastics, such as Teflon and unfilled polyesters, will become degraded at dosages of 10^{6} or 10^{8} ergs/gm to the extent that they will be unserviceable.

Polyethylene. Polyethylene is one of the more radiation resistant plastics. It is unaffected by dosages of up to 1.9×10^{9} ergs/gm. However, at higher radiation dosages, polyethylene becomes a flexible, rubberlike material and, with continued radiation, it becomes a crosslinked material that is somewhat brittle. At a dosage of 9.3×10^{9} ergs/gm, the overall mechanical properties of polyethylene are changed by 25 percent. Tensile strength increases at first, but at approximately 1.1×10^{10}

Table 3-15. Relative Radiation Stability of Plastics /47/

Material	Radiation dosage required for threshold damage (ergs/gm)	Radiation dosage required for 25% damage (ergs/gm)
Polystyrene	8×10^{10}	4×10^{11}
Phenol formaldehyde (asbestos filler)	3.9×10^{10}	3.9×10^{11}
Polyester (mineral filler)	3.7×10^{9}	3.9×10^{11}
Polyvinyl chloride	1.9×10^{9}	1.1×10^{10}
Polyethylene	1.9×10^{9}	9.3×10^{9}
Urea formaldehyde	8.3×10^{8}	5.1×10^{9}
Monochlorotrifluoro-ethylene	1.3×10^{8}	2×10^{9}
Cellulose acetate	2.7×10^{8}	1.9×10^{9}
Phenol formaldehyde (unfilled)	2.7×10^{8}	1.1×10^{9}
Methyl methacrylate	8.2×10^{7}	1.1×10^{9}
Polyester (unfilled)	3.4×10^{7}	8.7×10^{7}
Polytetrafluoroethylene (Teflon)	1.7×10^{6}	3.7×10^{6}

ergs/gm, it begins to decrease and is 25 percent lower than the initial value at approximately 10^{1} ergs/gm. Polyethylene is fairly stable in its elastic modulus values. Polyethylenes containing carbon black have a higher density and are slightly more resistant to nuclear radiation than standard polyethylene./47/

Fluorinated Polymers. Fluorinated materials show poor stability to nuclear radiation. Fluorinated polymers such as Viton-A and Teflon are seriously degraded by relatively low radiation exposure dosage of 1×10^{9} and 5×10^{7} ergs/gm, respectively. The poor stability

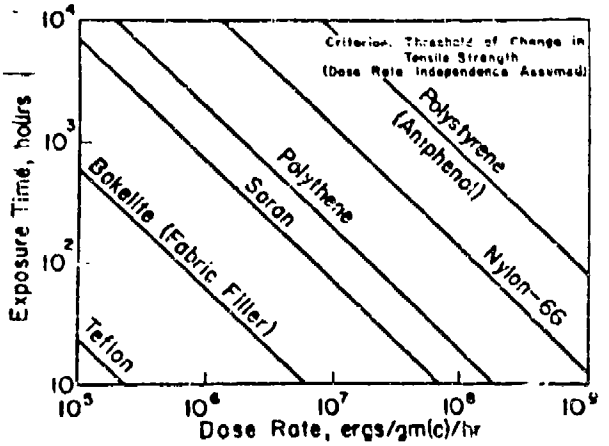


Fig. 3-33. Radiation stability of selected plastics.

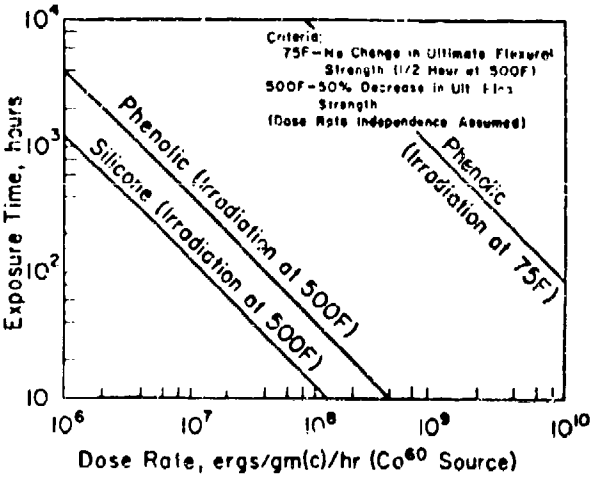


Fig. 3-34. Effect of radiation on glass fabric reinforced plastic laminates.

to irradiation results because these polymers are not cross linked. When the polymers are subjected to nuclear bombardment, the fluorine atom is knocked off and in turn reacts to break a carbon-to-carbon link. This causes a lowering of the tensile strength and hardness of the material./49,50,51/

Metallo-Organic Compounds. Metallo-organic compounds, such as boron, phosphoros and silicone polymers, are resistant to both high temperatures and nuclear radiation. Elements of low atomic weights are generally more radiation resistant. When an element such as boron, atomic weight 10, is coupled by means of gamma radiation with a polymer such as polyethylene, which is also radiation resistant, the combined materials are less affected by radiation. Metallo-organic compounds are still under

development and very little data are available concerning their radiation effects./52,53/

Organic Heat Transfer Materials. The terphenyls are least affected by radiation, and are the preferred class of organic heat transfer materials at high temperatures. The density, viscosity and carbon-hydrogen ratio of the terphenyls increase, and the melting point decreases with increased nuclear irradiation. The terphenyls will become unsuitable for use as a heat transfer medium when exposed to a nuclear dosage of 4×10^{12} ergs/gm.

Mono-isopropylbiphenyl, biphenyl, diphenyl ether and silicate esters also are little affected by radiation. Mono-isopropylbiphenyl becomes unsuitable as a heat transfer medium only when 2×10^{12} ergs/gm are absorbed, and both biphenyl and silicate esters become unsuitable at 1.4×10^{12} ergs/gm. The density, viscosity and carbon-hydrogen ratio of this group increase, and the melting point decreases with increasing decomposition.

The least suitable for use as heat organic materials are ethylene glycol, chlorinated diphenyls, DC-710 silicone and phosphate esters. They become rapidly degraded at nuclear exposures as low as 10^{10} ergs/gm.

The physical changes due to irradiation vary considerably with molecular weight. Low molecular weight polymers are usually less affected by nuclear exposure./54/

Structural Metals. In general, any property of a metal that depends on plastic flow may be affected by irradiation with fast neutrons in integrated flux levels above 10^{15} nvt. Yield strength may increase up to 450 percent for annealed metals and to a lesser extent for cold-worked metals or metals strengthened by heat treatment. The ductility, measured by percent elongation, of a metal is lowered. Loss of ductility can range from one-fifth to one-third or more. The hardness of a metal may be increased by as much as 100 Bhn after exposure to radiation./55/

Other effects of radiation on metals are an increase in electrical resistivity of generally less than 10 percent, and decrease in density of less than 0.2 percent. Very little change due to radiation is noted in the thermal conductivity and thermoelectric properties of metals./55/ Table 3-16 shows what properties of metals are affected by irradiation, and Tables 3-17 and 3-18 show how some of these properties are affected in various structural metals.

Coating Materials. A problem often encountered in designing equipment or systems to be used in a nuclear radiation environment is the choice of satisfactory coating materials.

Table 3-16. Properties of Metals Affected by Radiation

Property	Effect
Tensile strength	Increase
Ductility	Decrease
Hardness	Decrease
Impact strength	Decrease
Electrical resistivity	Increase
Density	Decreased moderately
Thermal conductivity	Decreased moderately
Dimensional stability	Affected moderately
Elastic constants	Little or no change
Creep strength	Little or no change
Fatigue strength	Little or no change
Damping capacity	Little or no change
Diffusion coefficient	Little or no change
Thermoelectric emf	Little or no change
Corrosion resistance	Little or no change
Internal friction	Little or no change
Microstructural and phase transformations are possible in some systems.	

Various coatings and their susceptibility to radiation damage are as follows:

Satisfactory to 10^{11} ergs/gm (C)

Phenolic coatings (MIL-R-3043)
Silicone-alkyd enamels (unbaked)
Alkyd-enamels (MIL-E-5557, 40% phthalic anhydride)
Furane coatings (alkaloy-550)

Satisfactory to 10^{10} ergs/gm (C)

Nitrocellulose lacquers (Black)
Alkyd enamels (32% phthalic anhydride)
Kel-F elastomer coatings
Silicone-alkyd enamels (baked)
Silicone enamel (baked)
Epoxy enamel (baked)

Satisfactory to 10^{9} ergs/gm (C)

MIL-C-8514 wash primer

Glass. At a dose of 10^{6} ergs/gm of gamma radiation, most glasses develop a brownish color. At a dose of 10^{8} ergs/gm, many optical glasses become so darkly colored that transmission of light through the glass is severely reduced. At dosages over 10^{12} ergs/gm, the discoloration of the glass reaches a saturation point. If the radiation dosage is increased, displacement and transformation of atomic nuclei in the glass may cause fracture or physical disintegration. Silica glass, Pyrex glass and plate glass generally increase in density after

Table 3-17. Effects of Radiation on Tensile Properties of Various Metals /55/

Material	Integrated neutron flux (10^{19} nvt)	Yield strength (1000 psi)		Tensile strength (1000 psi)		Elongation (percent)	
		Before radiation	Change	Before radiation	Change	Before radiation	Change
Tantalum	5(F)	-	-	68	+19	21	-4
Tungsten	5(F)	-	-	153	-36	0	0
Tantung G	5(F)	-	-	73	-4	5	-1
QMV beryllium	240(F)	24.5	-	35.7	+15.7	1.4	-1.2
356 aluminum	240(F)	24.1	+18.3	32.4	+11.9	2.7	-2.3
1100 aluminum	240(F)	18.4	+4.8	20.3	+6.7	22.3	+3.2
Copper	20-70(S)	9.5	+42.5	35.3	+16.7	56.7	-29.4
Nickel	20-70(S)	10.3	+46.3	52.6	+13.9	52.7	-23.1
Titanium (Ti-75A)	20-70(S)	61.5	+43.0	82.2	+23.3	27.3	-13.8
Zirconium	20-70(S)	12.7	+17.2	36.1	+3.1	36.4	-11.7
Iron	20-70(S)	13.4	+26.4	35.0	+8.0	56.7	-22.3
Molybdenum	20-70(S)	98.1	+53.6	99.8	+51.9	43.7	-43.7
Monel	4(S)	-	-	86.0	+5	32	-3.0

(F) Fast Neutrons. (S) Slow neutrons.

Table 3-18. Effects of Radiation on Hardness and Density of Various Metals /55/

Material	Integrated neutron flux (10^{19} nvt)	Hardness (Bhn)		Density (gm/cm^3)	
		Before radiation	Change	Before radiation	Change
Tantalum	5(F)	147	+53	-	-0.10
Tungsten	5(F)	-	0	-	-0.15
Tantung G	5(F)	-	0	-	-0.20 to 0.25
QMV beryllium	240(F)	127	+52	1.847	0
356 aluminum	240(F)	67	+29	2.665	-0.02
1100 aluminum	240(F)	38	+34	2.713	-0.004
Copper	20-70(F)	43.5	+56.0	-	-
Nickel	20-70(F)	61.1	+54.8	-	-
"A" Nickel	3.5(F)	-	-	8.894	-0.07
Titanium (Ti-75A)	20-70(F)	177	+33	-	-
Zirconium	20-70(F)	68.5	+21.4	-	-
Iron	20-70(F)	52.7	+41.8	-	-
Molybdenum	20-70(F)	204	+23	-	-
Monel	4(F)	150	+59	-	-
Monel	3.5(F)	-	-	8.836	-0.05

(F) Fast neutrons

irradiation. However, irradiation causes no measurable change in the thermal conductivity of glass./56/

Magnetic Materials. Structure-sensitive properties of magnetic materials, such as permeability, remanence and coercive force, are affected by nuclear irradiation. These effects are most serious in the high nickel-iron alloys, such as Permalloy, which have the highest permeabilities and lowest coercive forces. When exposed to a dosage of 10^{17} neutrons/cm^2, the permeability of Permalloy is lowered by 93 percent and the low coercive force is increased 815 percent. Permalloy also shows a change in the hysteresis loop, indicating a deterioration of the material. The properties of 50 and 48 nickel-iron alloys are less drastically effected by irradiation. The most radiation-resistant magnetic alloys are the silicon irons, aluminum irons and 2V Permendur alloys. Properties of magnetic materials that are not structure-sensitive, such as magnetic saturation, are generally not seriously affected by exposure to nuclear radiation./57,58/

Electrical Insulating Materials. The most important effects of nuclear radiation on organic polymers used as insulating materials are ionization and excitation of molecules. The molecules under bombardment induce a series of complex chemical changes that alter polymers. The most important chemical reactions are chain cleavage and crosslinkage. The breaking of chemical bonds and the accompanying side reactions make polymers susceptible to attack from the atmosphere. Ozone and nitrogen may combine chemically with a polymer and destroy its usefulness as an insulator. In particular, the absorption of water, either on the surface of an insulator or in cracks within, may cause electrical leakage./59/

Table 3-19. Resistivity of Organic Insulators After Reaching Equilibrium of 41,750 ergs/gm-hr* /60/

Material	Original resistivity ohm-cm	After equilibrium ohm-cm
Polyethylene terephthalate	1×10^{23}	1.43×10^{20}
Amber, treated	2×10^{21}	1.00×10^{17}
Amber, natural	1×10^{21}	1.00×10^{19}
Polystyrene	1×10^{22}	1.43×10^{20}
Unplasticized perspex	1×10^{22}	2.5×10^{18}
Plasticized perspex	1×10^{20}	3.33×10^{17}
Polythene perspex	1×10^{20}	1.25×10^{16}
Polytetrafluoroethylene	5×10^{19}	1.25×10^{16}
Polyethylene	2×10^{20}	3.33×10^{15}

*Determined on the basis that the absorption in carbon of 1 roentgen is equivalent to 87.1 ergs/gm. Time required to reach equilibrium is different for various materials.

Table 3-20. Breakdown Exposure Doses of Organic Insulators /59/

Insulator	Breakdown exposure dosage (neutrons/cm^2)
Polystyrene	1×10^{20}
Polyethylene	1×10^{19}
Silastic 80	1×10^{19}
Sil-X	9×10^{18}
Teflon	5×10^{18}
Silicone rubber	4×10^{18}
Neoprene	3×10^{18}
Formvar	2×10^{18}
Polyvinyl chloride	1.9×10^{18}
Rubber	1.3×10^{18}
Kel F	1×10^{18}
Suprenant A-10	1×10^{17}
Suprenant B-2	5×10^{16}

The various chemical reactions are accompanied by changes in the physical properties of polymers. For example, polymers may become softened and have greater solubility as a result of chain cleavage, and tensile strength and melting points may decrease. Crosslinking causes hardening, an increase in strength and melting point, an increase in density and a decrease in solubility. The electrical resistivity of all polymeric materials generally decreases after exposure to nuclear radiation. However, the decrease in resistivity is small in comparison with the original resistivity. Table 3-19 shows the original resistivity of various polymers and their resistivity after reaching equilibrium.

In general, the electrical failure of organic insulators is usually due to physical and mechanical deterioration. Cracking and flaking of brittle polymers or excessive weakening and bubble formation in softened polymers finally lead to breakdown. Table 3-20 lists the accumulated exposure doses at which insulators may be expected to fail. In evaluating the data in Table 3-20, it should be noted that an insulator exposed to nuclear radiation may serve satisfactorily at one voltage and frequency but fail under different operating conditions./59,60/

Inorganic materials are, in general, much more resistant to radiation damage than are or-

ganic substances. Atomic displacements account for nearly all the permanent damage in inorganic insulators, causing changes in the lattice parameters, density, strength and electrical properties. The density of crystalline insulators decreases, while the density of amorphous insulators, such as fused quartz and glass, increases. There is also a strong photoconductive effect accompanying the nuclear irradiation of most inorganic ceramics. The threshold flux for detectable radiation damage of inorganic materials is as follows:

Metals	10^{19} n/cm^2	(fast neutrons)
Ceramic (except glass)	10^{17} n/cm^2	(fast neutrons)
Glass	10^2 ergs/gm(C)	(gamma rays) /59/

Dielectric Materials. Little change in the physical or electrical properties of dielectric materials has been observed below a dosage of 10^{15} neutrons/cm^2. Above this dosage, some physical properties may begin to deteriorate. However, the electrical properties of many dielectric materials, such as polyethylene, polystyrene, Teflon, fused quartz, nylon and phenolformaldehyde, are relatively unaffected for dosages of up to 5×10^{18} neutrons/cm^2./12,17/

In general, nuclear radiation affects the physical properties rather than the electrical properties of dielectric materials. Embrittlement in solid dielectric materials, transformation of a liquid dielectric to a gel, loss of flexibility, and changes in thermal conductivity cause mechanical deterioration of the dielectric material. For example, polyethylene and nylon, when exposed to a dosage of 10^{16} neutrons/cm^2, have decreased impact strength and become so brittle that parts of the material chip off. However, very little degradation of their electrical properties takes place. The effects of nuclear radiation on the physical properties of inorganic dielectric materials, such as quartz, mica, alumina, zircon and glass-bonded mica, are less severe. However, electrical resistivity and dielectric strength may decrease./52/

Semiconductor Materials. Radiation causes two effects in semiconductors: transient changes in electrical properties and permanent changes in atomic structures. Transient effects arise from the ionization caused by energetic photons or charged particles, such as electrons, traversing the material. This ionization injects excess minority carriers into the material and can give rise to "electronic noise" in semiconductor devices. Transient changes are also produced in surface recombination velocities.

Permanent changes in atomic structures may occur due to introduction of defects in the crystal lattice in the form of interstitial atoms and vacancies, or by transmutation, which results from capture of thermal neutrons by the atoms of the material. Both of these processes introduce new levels into the forbidden energy gap, causing permanent changes in conductivity and minority carrier life time.

Mechanism of Semiconductor Damage. Experiments have indicated that radiation exposure affects conductivity and Hall coefficient much more than can be attributed to impurities introduced by transmutations. It was therefore concluded that the displacement mechanism is the source of most damage in semiconductor materials. However, for completeness, transmutation effects are also described.

New energy levels are caused by the introduction of impurities into the crystal lattice as a result of radioactive decay. These impurities mostly influence the conductivity of the material. The transmutation atom may emit energetic beta particles of gamma photons, causing secondary radiation that may be capable of causing displacements.

When incident energetic particles, such as neutrons or electrons, collide with lattice atoms, they may impart sufficient energy to cause a recoil to a displaced interstitial site. This results in an interstitial-vacancy pair. If the primary recoil receives sufficient energy, subsequent collisions may occur, producing secondary and tertiary displaced atoms. Thus, many lattice defects result from the collision of a single energetic particle with a lattice atom. This reaction may result from any of the following processes.

1. Elastic collision with the nucleus.

2. Coulomb interaction with the nucleus (Rutherford scattering).

3. Elastic collision with the atom.

The first process occurs when an uncharged particle such as a neutron is involved. The second results from a charged particle having sufficient energy to penetrate the charge barrier of the electron cloud of the lattice atom. And the third process takes place when the energy is not large enough to penetrate the charge barrier. Charged particles may also lose energy by electrostatic interaction which causes electronic excitation and ionization of the lattice atoms.

Gamma photons interact with orbital electrons, producing photo electrons and compton electrons, which in turn may have sufficient energy to cause atomic displacements. However, gamma photons do not cause atomic displacements directly. Electrons generally do not have sufficient energy to produce a cascade of displacements, since to do so they must have energies in the relativistic range. In summary, semiconductor materials are damaged by high energy particles and radiation through any or all of the following processes:

1. Ionization.

2. Transmutation.

3. Elastic displacement.

4. Displacement of atoms.

The thermodynamic approach to the radiation damage problem is also possible. A particle traversing a material produces an enormous amount of heat at a particular point, and a region of material around the tract of the particle will be heated to a high temperature. This rapid heating and quenching of a small volume of material, termed a thermal spike, may leave a portion of the lattice in a disordered state. The end result is equivalent to a localized production of vacancies and possibly interstitials.

Cosmic rays, previously described, produce lattice defects and noise, and because of the small number of collisions expected, noise will probably be the primary effect.

Radiation Effects. Neutron irradiation of N-type germanium results initially in a decrease in conductivity, and finally conversion to P-type material. The conductivity of P-type germanium increases with neutron irradiation, provided the radiation level is not too high initially. Resistivity changes in P-type germanium occur at a slower rate than in N-type. The conductivity of both N-type and P-type silicon decreases with irradiation.

The life time of minority carriers in semiconductor material is sensitive to radiation, decreasing with increasing bombardment. In addition, unstable minority carrier traps are produced, leading to plate conductivity.

Compound Semiconductor Materials. Some new semiconductor materials, particularly compounds, offer great promise for use in future semiconductor devices. However, as far as radiation damage is concerned, no great improvements are expected, since basically, one semiconductor material is nearly as vulnerable as another. This is true with respect to mechanical displacement caused by incident particles, with the exception that materials of lower atomic weight are in general more vulnerable than materials of high atomic weight. Also, transmutations will produce the usual donor or acceptor elements, but mechanical displacement will still be the most severe problem.

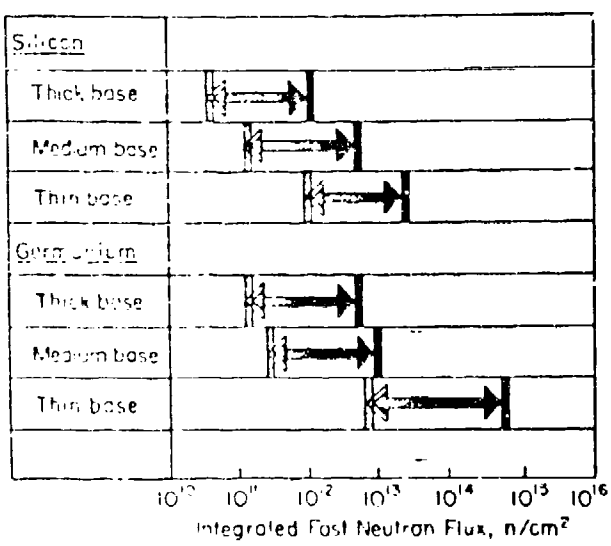


Fig. 3-35. Radiation damage to silicon and germanium transistors.

Components

Transistors. Transistor parameters continually change with irradiation. Forward current gain is reduced because minority carrier lifetime is reduced, and reverse collector-to-base leakage is increased as a result of changes in bulk characteristics and surface effects at the collector-base junction. These cause changes in circuit parameters, such as a decrease in the forward-current transfer ratio, and increased reverse leakage current.

Transistors eventually become unusable in a radiation environment. They experience complete failure when the N-type material converts to P-type, thus destroying the junctions. In low-frequency germanium transistors, the changes in minority carrier lifetime degrade the transistor's usefullness long before N to P conversion occurs. The sensitivity of various types of transistors to damage by neutron irradiation is shown in Fig. 3-35.

Semiconductor Diodes. Both silicon and germanium diodes show susceptibility to nuclear radiation by a large permanent increase in the forward voltage drop and increased leakage current of a transient nature. Increased forward resistance creates excessive power dissipation and reduced voltage output. Germanium semiconductors may also fail under nuclear radiation as a result of a deterioration in their reverse characteristics. It has been found that gamma radiation affects backward resistance while neutron damage primarily affects the forward characteristics of a diode. The extent of damage to germanium and silicon diodes is determined by the ultimate nuclear dosage. Microwave semiconductor diodes are considerably more radiation tolerant than the general purpose types.

Transformers. Physical damage rather than damage to the electrical characteristics are the main effects of irradiation on transformers. Transformers have been exposed to high energy neutrons of 3.6×10^{17} neutrons/cm^2 with very little damage. Coil resistance as well as voltage and current characteristics remained satisfactory at high exposure dosages. However, at such high radiation exposures, rupturing of the transformer cases may take place due to expansion of the potting compound and shorting of the transformer terminals.

Electron Tubes. Tubes, in general, are quite resistant to nuclear radiation. Vacuum and gas-filled electron tubes are less affected than phototubes. Phototubes irradiated by a flux of 10^{12} neutrons/cm^2 for a three-hour period showed a dark current equivalent to the normal output from a light source. When the radiation was stopped, the dark current decreased to zero, but the sensitivity of the phototube also decreased. One of the largest causes of tube failures due to nuclear irradiation is envelope and seal fractures, caused by the use of borosilicate glass./57,67,63/

Capacitors. Mica, glass and ceramic capacitors suffer little damage when exposed to radiation doses of 10^{18} nvt. However, plastic, electrolytic, and oil filled or oil impregnated capacitors are extremely susceptible to radiation. Many organic materials evolve gases under radiation, and this gas may rupture the capacitor case. Generally, non-organic capacitors function satisfactorily, and capacitance is only slightly decreased under nuclear irradiation. /57,62,63,64/

Resistors. Certain resistors change resistance values during or after irradiation, but most of the wire-wound and carbon types suffer little damage. Resistors, in general, function satisfactorily after doses of 10^{15} nvt, with wire-wound resistors being least affected. Wire-wound resistors show a decrease of about 5 percent in their resistance values, while carbon-type resistors may change in value by approximately 15 percent after exposure to radiation./57,62,63,64/

Insulators. Insulators decrease in insulation resistance during and after exposure to nuclear radiation. However, polyethylene insulators, even after exposure to 10^{19} nvt, show very good insulation resistance. Insulation resistance for most insulators decreases uniformly with exposure time to between 5000 and 500,000 ohms. Insulator breakdown voltage may be reduced by a factor of 5 due to nuclear radiation. However, the voltage breakdown value may return to near its original value after removal of the applied voltage./62,64/

Seals, Gaskets and Sealants./65,66/ Most elastomers, and a number of plastic materials, have been used as seals, gaskets and sealants. There is no elastomer or plastic sealing material available at present that has radiation stability above 2×10^{12} ergs/gm. However, several materials may function properly and could hold a vacuum at lower radiation dosages. The effects of radiation on various elastomers and plastics used for seals, gaskets and sealants have been discussed previously under "Elastomeric and Plastic Materials."

Hoses and Couplings. /67/ Relatively little information is available on the effects of nuclear radiation on hoses and couplings, particularly on the solid organic materials used in hose manufacture. However, standard aircraft hoses

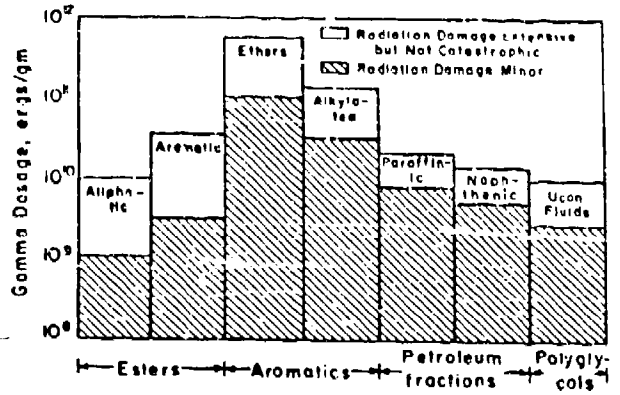


Fig. 3-36. Radiation damage to lubricants./68/

and couplings contain organic polymeric materials, and the effect of nuclear radiation on these materials is known. For example, Buna N, a solvent-resistant synthetic rubber, and Teflon, a temperature-resistant plastic, are materials used in hoses. Buna N is much more radiation resistant than Teflon. It will leak at an exposure dosage of 4×10^8 ergs/gm, compared with 1×10^8 ergs/gm for Teflon.

Lubricants. Lubricants are generally not affected after exposure to nuclear radiation of 2×10^9 ergs/gm. Above this dosage and up to approximately 1×10^{10} ergs/gm, they still have good lubricating properties, but impurities such as sludges are formed. In addition, gases that in some cases may contain halogens, which are corrosive, are evolved.

Aromatic ethers, alkylated aromatic ethers and alkyl aromatics are less affected by radiation. The polyphenyl ethers are not affected up to a dosage of 1.8×10^{11} ergs/gm. However, most organic compounds and all conventional lubricants show extensive physical changes after radiation dosages of 10^{10} to 10^{11} ergs/gm. Figure 3-36 shows the gamma dosages necessary to cause minor and extensive damage to lubricants. Minor damage occurs when impurities are formed, but the compound still has good lubricating properties and with proper filtering its useful life is not markedly affected. Extensive damage to a lubricant denotes that it has become a poor lubricant. /65,68,69/ The radiation stability of gas-turbine lubricants are listed in Table 3-21. Figure 3-37 shows the radiation stability of various organic liquids.

Greases. Greases differ from other types of lubricants in that they rely on the formation of a gel structure by the interaction of the base fluid and high melting thickener. On exposure to radiation, this gel structure breaks down, resulting in a soupy product. On further irradiation the material hardens to a rubber-like substance. This is attributed to the polymerization of the base fluid overriding the gel destruction. It is estimated that conventional greases will have poor operational properties after exposure

Table 3-21. Radiation Stability of Gas-Turbine Lubricants

Approximate useful temperature range (F)	Lubricants	Approximate radiation limit for moderate change (ergs/gm(C)		
		Viscosity	Oxidation resistance	Relative lubricity (4-ball wear test)
	Commercially available			
-65 to 350	Polyalkylene glycols	-	-	Fair
	Esters	5×10^{10}	$<1 \times 10^{9}$	Good
	Silicons, chlorinated	$<5 \times 10^{9}$	$<5 \times 10^{9}$	Fair
	Mineral oils	5×10^{10}	1×10^{9}	Very good
-65 to 400	Trimethylol propane	5×10^{11}	$<1 \times 10^{9}$	Good
	Experimental materials			
-65 to 500	Super refined mineral oils	5×10^{10}	1×10^{10}	Very good
	Silanes	1×10^{10}	$>1 \times 10^{10}$	Fair
	Alkyl aromatics	5×10^{10}	$<1 \times 10^{10}$	Good
0 to 600	Polyphenyl ethers	1×10^{11}	5×10^{10}	Good

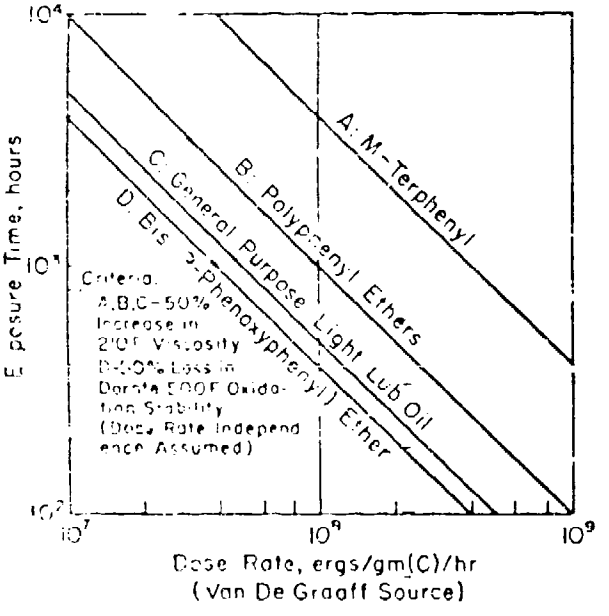


Fig. 3-37. Radiation stability of organic liquids.

to 1×10^{10} ergs/gm. Newer greases, such as the indanthrene-thickened polyphenyl ether based type, are expected to be usable at radiation exposures as high as 1×10^{11} ergs/gm. Possible radiation-resistant aircraft greases are listed in Table 3-22. Estimated dose limitations in the use of various greases are shown in Fig. 3-38.

Hydraulic Fluids. Hydraulic fluids based on disolaxane or silicone ester base fluids are relatively unaffected by gamma dosages approaching 1×10^{10} ergs/gm. It is estimated that they will function satisfactorily as high as 5×10^{10} ergs/gm. Petroleum based fluids show excessive viscosity decrease as low as 5×10^{9} ergs/gm. This is attributed to degradation of the polymeric viscosity improver. Alkyldiphenyl ethers and alkybiphenyl base hydraulic fluids are expected to be usable in the range of 5×10^{10} to 1×10^{11} ergs/gm. Use of the meta-linked unsubstituted polyphenyl ethers in hydraulic systems is expected to provide satisfactory use to as high as 2×10^{11} ergs/gm. They are particularly desirable in that they need no additives and no viscosity-index improvers to enhance their characteristics. Possible radiation-resistant hydraulic fluids are listed in Table 3-23. Estimated dose limitations in the use of various hydraulic fluids are shown in Fig. 3-38.

Hydrocarbon Fuels. In general, aromatic hydrocarbon fuels are usually less damaged by radiation than saturated hydrocarbon fuels. Also pre-irradiated hydrocarbon fuels react differently to radiation than unirradiated hydrocarbons. However, dehydrogenation, polymerization and degradation occur in varying degrees in all hydrocarbon fuels exposed to nuclear radiation. The following physical and chemical changes are produced in hydrocarbon fuels: /70/

1. The hydrogen content decreases with increasing dosage. At a dosage of 1×10^{10} ergs/

Table 3-22. Possible Radiation-Resistant Aircraft Greases

Approximate useful temperature range (F)	Grease composition		Approximate exposure tolerance (ergs/gm(C))
	Fluid	Thickener	
20 to 500	Polyphenyl ether	Indanthrene blue RS	4×10^{11}
-40 to 400	Methylphenyl silicone	Copper phthalocyanine	2×10^{11}
-40 to 350	Octadecyl byphenyl	Sodium terephthalamate	7×10^{10}
-	Methyphenyl silicone	Aryl urea	$>10^{11}$

Table 3-23. Possible Radiation-Resistant Hydraulic Fluids

Approximate useful temperature range (F)	Fluid composition		Approximate exposure tolerance (ergs/gm(C))	Use-limiting characteristics
	Base	Additives		
-65 to 250	Petroleum	-	1×10^{10}	Poor high-temperature properties
-65 to 420	Disoloxane	Alkyl diphenyl	5×10^{10}	-
-65 to 400	Silicate ester (OS-45)	-	2×10^{10}	Does not meet MIL-H-8446
-15 to 500	Alkyl diphenyl ether	Polybutene	1×10^{11}	Poor low-temperature properties
0 to 600	Polyphenyl ether	-	1×10^{11}	Poor low-temperature properties

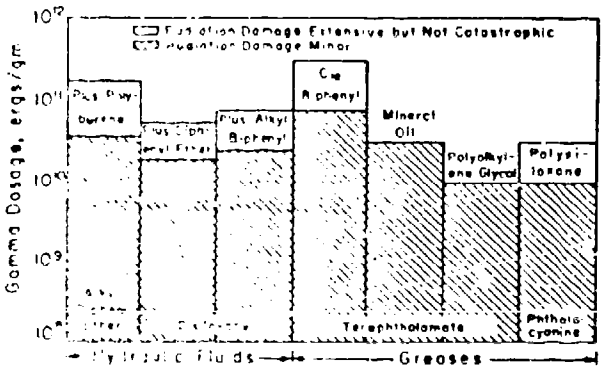


Fig. 3-38. Estimated dose limitations in use of various greases and hydraulic fluids.

gm there is a loss of about 0.05 percent hydrogen.

2. About 8 to 9 percent loss of volume will occur at a dosage of 9 x 1010 ergs/gm.

3. There is no change in the aniline point up to a dosage of 2.6 x 1010 ergs/gm. The aniline point will, however, increase slightly above 9 x 10^{10} ergs/gm.

4. There is no significant change in the heat of combustion up to 9 x 10^9 ergs/gm. A slight decrease will occur above a dosage of 8 x 10^{10} ergs/gm.

5. Viscosity increases with increasing radiation dosages.

6. Density and refractive index increase with increasing radiation dosages.

ZERO GRAVITY

An object experiences a zero-gravity environment, or weightlessness, when:

1. It falls to Earth in a vacuum, in which case the weight of the object is equal to the accelerative force acting on it.

2. It rotates around the Earth with its total radial acceleration equal and opposite to the acceleration caused by gravitational attraction between it and the Earth.

The above definitions apply not only to the Earth, but to the Sun, the planets and the larger natural satellites in the Solar System.

Experimental information concerning zero-gravity and its effects is very limited due to the difficulty of simulating the condition. The present approach to achieving a zero-gravity environment for testing has been to use aircraft flying in an arc in a vertical plane. The duration of weightlessness achieved in this manner, however, is short compared to that experienced by ballistic missiles and satellites. This is shown in Table 3-24.

Table 3-24. Characteristics of Flight Trajectory to Produce Weightlessness of Maximum Duration for Various Vehicles *

Vehicle	Velocity at entry or maximum speed after burnout (mi/hr)	Height of trajectory (mi)	Angle of climb (deg)	Duration of weightlessness (min)
T-33A	370	0.49	55	0.47
F-84C	450	1	53 1/2	0.6
F-100F (modified)	650	4	75 1/2	1
X-15	4000	80	85	5
Redstone	3400	150		6
(Boost glide vehicles)	10,000	200		10
Jupiter	10,300	>600		11
Biosatellites	18,000	>600		Infinite

* The figures given in this table are approximations only.

The most serious aspect of a zero-gravity environment will probably be its effect on humans. This is covered later in the handbook. Some probable effects of zero gravity on equipment are as follows:/71/

1. Springs tensed by a mass will assume new equilibrium positions, and so mechanical devices depending on springs will have changed characteristics.

2. Gas bubbles will not rise in liquids in spite of density differences. Also, gas bubbles generated in batteries will remain in contact with the plates and all contaminate surfaces, resulting in deterioration of electromechanical action

3. Liquid level devices will malfunction. Manometers, for example, will not function due to the absence of weight in the indicating fluid.

4. There will be no convective movement of air due to thermal density gradients. This lack of convective heat transfer will cause serious problems in the heating and cooling of equipment.

5. In general, equipment that will not function properly in an inverted position on Earth may malfunction in a zero-gravity environment.

Other equipment areas in which unique situations may occur due to zero gravity are lubrication, bearing loads and material stresses.

COMMUNICATIONS INTERFERENCE

Strictly speaking, communications interference is an operational effect of other environments. However, because of its unique nature it will be covered separately.

Interference can be defined as any electromagnetic disturbance that has an undesirable effect on electrical or electronic equipment. It can affect equipment ranging from simple relay control circuits to complex radar and navigation systems. Communications interference can be either man-made or natural. Man-made interference results from interaction between signals from different circuits or equipments. Natural interference is caused by things such as atmospheric electricity and magnetic storms. /35/

Man-Made Interference

Man-made interference may be divided into the three following types:

1. Continuous-wave interference, which usually emanates from transmitters and receiver local oscillators.

2. Pulsed continuous-wave interference generated by equipments or circuits that operate in a pulsed mode, such as radars, beacon sets and pulse-type jamming equipments.

3. Broadband interference, which generally originates either in equipments where arcing takes place, such as d-c motors and generators, or in equipments containing relays, vibrators or gas filled tubes. The interfering signals are random, narrow-pulse voltages that contain a broad band of frequencies.

The effects of man-made interference may range from sporadic noise that is only annoying, to complete equipment inoperability./35/

Natural Interference

Atmospheric Effects. - Atmospheric noise may cause serious interference with communications. The highest noise levels are due to scattering of radio frequency waves by the atmosphere. This occurs mostly over land in the tropical regions. Atmospheric electricity, consisting of both static electricity and lightning, can also affect communications. Static precipitation, especially in the lower frequency ranges, may block radio signals and cause corona and electrical arcover. Lighting will block communications and may also damage antenna equipment./72,73/

Ionosphere Effects and Cosmic Noise. The high electron densities within the ionosphere cause reflection of radio signals at lower frequencies as well as radar refraction errors. During periods of great solar activity, such as sunspots and aurorae, the ionosphere rises and interference with communications becomes more pronounced.

The aurorae are sources of optical and radio wavelength interference. They occur mainly in northern and southern latitudes and are directly related to sunspot activity. At medium and high radio frequencies, aurorae cause complete blackout, which may last for several days. At low frequencies, the effect is not as serious. At very-high and ultra-high frequencies, reflections or backscatter may occur. In addition, an aurora causes absorption over a wide frequency range, resulting in attenuation of signals intended to pass through the ionosphere. Electron densities within aurorae may exceed 10^8 per cubic centimeter. The high electron density refracts signals, causing angle and range errors./72,73,74,75/

HYPER ENVIRONMENTS/76/

Hyper environments may be defined as those natural environments existing above an altitude of 75,000 feet, and those induced environments developed by vehicles capable of operating above this altitude. The following is a list of hyper environments:

Natural Hyper Environments

Neutral gases

Dissociated gases

Ionized gases and free electrons

Ozone

Extreme low pressure and density

Thermal extremes

Electromagnetic radiation

Atomic particle radiations

Meteorites and micrometeorites

Magnetic fields

Gravity

Induced Hyper Environments

Acceleration

Acoustic excitation

Mechanical shock and vibration

Extremely high and low temperatures

Thermal shock

Ionization

Explosive decompression

Nuclear radiation

Magnetic fields

Zero gravity

The hyper environments encountered by various types of flight vehicles, as well as the sequence in which they are encountered, are covered in the "Flight Paths" section of Chapter 2. The effects of the hyper environments, to the extent that they are presently known, have been covered previously in this chapter.

EXOTIC ENVIRONMENTS

Exotic environments are those environments that are strange or foreign to the Earth and are based primarily on the findings of astronomers and astrophysicists. The very fact that these exotic environments are strange means that very little is known about them. While the American and Russian satellites and Moon probes have added to the knowledge of what may be found in space, much is still in the realm of speculation. There is little doubt that there are environments in space that are presently beyond our comprehension and imagination.

The full effects of radiation belts and magnetic fields around the Earth and other planets are merely conjecture. Interplanetary gas and meteorite dust clouds are known to exist in space, but exactly what will happen when a vehicle passes through such an environment is not completely known. Other planets undoubtedly have atmospheres which are deadly to man. Such atmospheres may also attack the surface of a space ship, with the possibility of eroding, dissolving or even disintegrating the metals that are now in use on Earth. The composition and characteristics of the Lunar surface, as well as other planetary surfaces, are also matters of speculation at the present time. Man will experience the strange environment of si-

lence after landing on a planet that has little, if any, atmosphere, since the lack of wind and life will result in the absence of sound. The human consciousness may experience a sense of foreboding, desolation and eerieness that will cause disorientation. The same effect will be present in orbiting vehicles that do not have equipment producing some noise. Rooms, called anechoic chambers, are made to simulate the condition of no sound. Within this chamber it is possible to hear the sound of one's own heart beating and the blood circulating through the veins. After a few minutes in such a chamber there is a feeling of oppression and the silence seems to have weight. Some subjects lose their balance, then experience nausea and vertigo, and finally are seized by an irresistible impulse to escape from the chamber.

Exotic environments may be encountered in a direction perpendicular to the plane of the Solar System. The Solar System is disk shaped, and while the planets do not lie in the same plane, the diameter of the Solar System is considerably greater than its thickness. Environments perpendicular to the diameter may be fantastically different than those that exist in the approximate plane of the solar system.

Another unknown environment that has been the subject of considerable theorizing is the effect on an object as its speed approaches that of light. There is conjecture that as living things move closer and closer to the speed of light, they will age less as compared to living things on Earth.

The exotic environments must be probed and cataloged, and their ultimate effects fully understood before space travel, especially manned, can become a safe reality. The environment, engineer will make the greatest contribution toward conquering space when the effects of these and other presently unknown environments are successfully overcome.

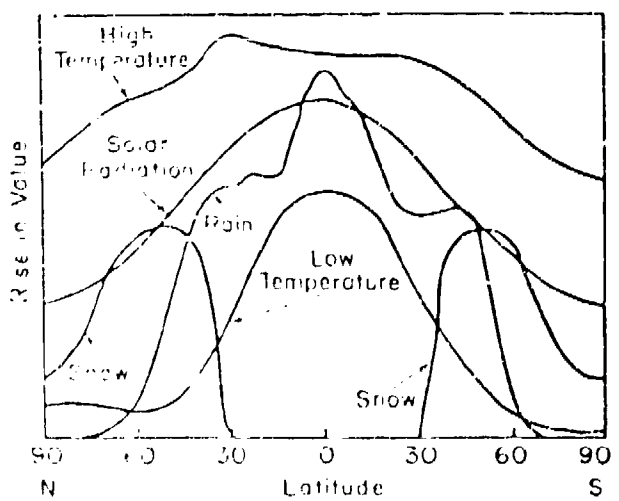


Fig. 3-39. Latitudinal distribution of environmental extremes.

COMBINED ENVIRONMENTS

The prior parts of this chapter consider the environments and their effects as occurring one at a time. This format was chosen, first, to facilitate the presentation of data, and second, because most of the information available to date is on single environments. Very little data exist on effects of the various combinations of environments that may be encountered in actual use. Much more research is needed in this area.

In use, a system will never encounter any single environment by itself. However, even though combinations of environments are encountered, the extremes of environments generally occur singly, and it is the extremes that are most important. An extreme of one environment may intensify the effects of another environment, or in some cases, one environment may tend to neutralize the effects of another.

Although a given extreme of one natural environment is not often encountered with that of another, several extremes of induced environments may be encountered simultaneously, and combinations of natural and induced environments always exist together.

Combined Natural Environments/77/

A list of the natural environments is given in Table 3-1 at the beginning of this chapter. No one of these natural environments will ever occur by itself. Temperature, humidity and pressure are always present in the atmosphere, and each alters and is altered by the others. This varying combination, including the other natural environments, produces what is known as weather. Changes in weather from time to time and place to place result from the variations in quantity, intensity and distribution of the individual natural environments.

Distribution of Extremes. The extremes of the individual environments are covered in Chapter 2. These extremes can be combined on a graph, as shown in Fig. 3-39, to illustrate how they might vary in relation to latitude. Figure 3-39 refers only to the Earth's surface. The distribution of extremes for various altitudes at these different latitudes is shown in Fig. 3-40. It should be noted that Fig. 3-39 and 3-40 are estimated and are not based on actual data. In addition, Fig. 3-39 and 3-40 show only how individual extremes vary, and since the extremes rarely occur together, these two illustrations do not indicate realistic combinations of natural environments. The natural combinations to be expected can only be analyzed through an understanding of the many complex factors that determine the combination.

Combination Factor. The complexity of combined natural environments can be explained by considering how one element is varied. For example, temperature is controlled by incoming solar radiation, which is a function of latitude and time. But the amount of radiation reaching the ground is regulated in part by the cloud cover and the amount of water vapor in the atmosphere, which also help determine how much of the reradiated heat is retained in the atmosphere. Combining to further modify the temperature are the large and small scale movements of the air, both horizontal and vertical, and topographical characteristics, including the nature of the surface, elevation, and the proximity of bodies of water. Also, a change in temperature may set up temperature differences that create pressure gradients, which, through the resulting air movement, alter the temperature again.

A less direct example of interacting natural environments is the evaporation-condensation-precipitation cycles. Evaporation is directly proportional to temperature and air movement. Warm air can hold more water vapor; winds constantly replace the air adjacent to the water with drier air; and turbulent motion transports the water vapor upward. One result of the evaporation process is the cooling of the surface layer of air. This causes heating of the air aloft, since the heat lost at the surface is regained when condensation takes place. Surface and atmospheric temperatures are again modified when precipitation occurs. This hydrological action, which is abetted by air motions stemming from temperature changes, produces further temperature changes.

The most important force in natural environment is solar radiation. It "determines the temperature of land, water and air; fixes, in general, the amount of evaporation and its counterpart, condensation; controls the winds and regulates in greater or less degree every other weather element."/78/

Inherent properties of the air, such as temperature, humidity, and pressure, occur in all combinations and therefore must be considered with every extreme. Temperature is closely linked with solar radiation. In addition to its influence on large and small scale weather patterns, its effects are felt directly as a principal element in combinations. Humidity, or water vapor, is very inconstant. Water vapor varies in amount from place to place and time to time from nearly zero to about five percent by volume of the total atmosphere. This variability is important in its direct immediate effects and in its potential for influencing other elements. The amount of water vapor in a given mass of air is a measure of the atmosphere's capacity for precipitation. Its absorptive effects on terrestrial radiation regulate heat loss and thereby affect temperature. Water vapor represents latent energy stored in the atmosphere for the origin and growth of storms. /1/ Precipitation

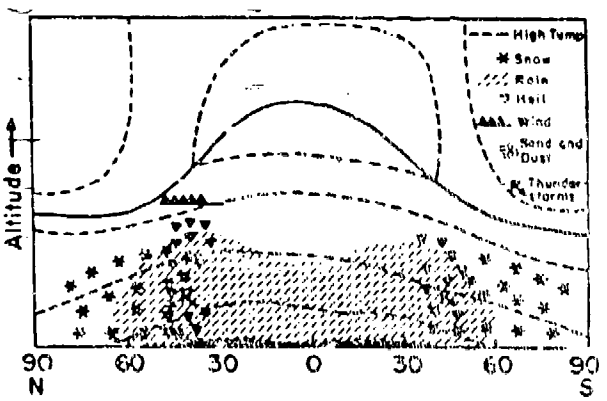


Fig. 3-40. Semi-spatial distribution of environmental extremes.

(liquid, freezing or frozen) is a primary element in many deteriorative combinations because of the immediacy and magnitude of its effect.

How an environment varies and how it is measured are indications of its combining form. Amount, frequency, rate, force and weight are variously used to describe environment intensity. Some environments can be expressed as linear quantities (pressure, temperature, humidity); for others, the rate of occurrence is significant (rain, freezing rain, snow); a few are commonly observed only as a fact of occurrence (lightning, tornado, blowing snow). The complexity of combined interrelationships may be seen by the fact that the value of one element may indicate the presence or the intensity of another. Hail indicates turbulence aloft. Freezing rain reveals the presence of warmer overruning air. Restricted visibility may reflect the rate of rainfall, the intensity of fog, or the severity of blowing sand, dust or snow.

Possible Combinations. Because of their interlocking natures, extremes of some elements are likely to occur simultaneously. Examples include: humidity and rain; pressure gradient and wind; wind and blowing dust, sand or snow; solar radiation and temperature; and wind speed and wind shear. In most combinations, however, the extremes of one element do not occur together with the extremes of another. For this reason it is necessary to consider various combinations that include something less than the extremes of some elements. One approach is to assign an extreme value to one, the highest value of the second, whichever occurs naturally with the first, the highest value of the third concurring with the assigned intensities of the first two, etc., in the descending order of extremes. Assignment of the absolute worldwide extremes may result in as few as one set of values in each case. In practice, therefore, the first assigned value must be arbitrarily reduced (e.g., to 95% probability). The number of possible combinations depends upon the number of elements coexisting ac shown on Table 3-25.

Table 3-25. Possible Combinations /77/

Equation: $x = n(n-1)(n-2)(n-3).....[n-(n-1)] = n!$	
Number of variables (n)	Number of combinations (x)
1	1
2	2
3	6
4	24
5	120
6	720
7	5,040
8	40,320
9	362,880
10	3,628,800

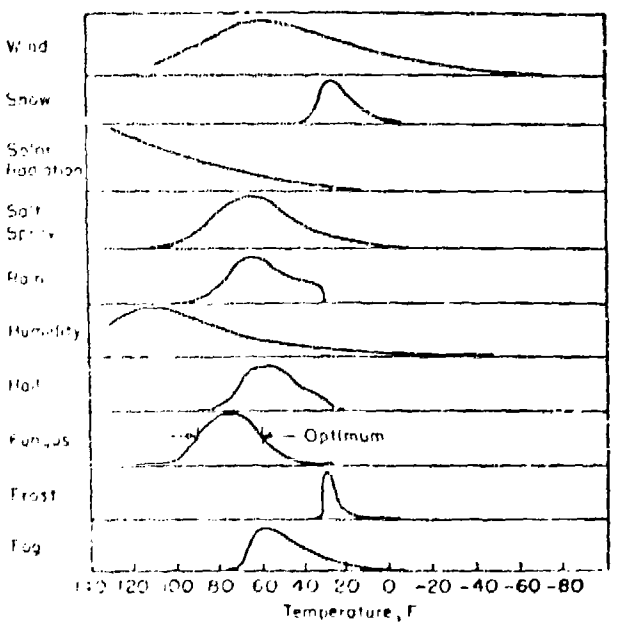


Fig. 3-41. Temperatures at which various other environments occur.

From the table it can be seen that such a procedure produces too large a number of combinations. And actually, these are only a small portion of the possible combinations; omitted are all the arrangements in which no one element approaches the extreme, many of which must constitute extreme total environments.

In nature, although individual elements do recur in like intensity, the total weather is never repeated. This is evidence of the vast number of possible combinations of the elements, which together shape the weather. Therefore, it is necessary to consider the more practical combinations rather than the many possible ones.

Practical Combinations. One element that must be taken into account in all combinations since it is present in all environments is temperature. Weather-wide, everything transpires within a range of temperatures; therefore, it is probably wise to use temperature as a basis for determining useful combination data. A one-to-one comparison of temperature with every other element in turn is a necessary step toward multiple combination analysis. Figure 3-41 illustrates how such an analysis may be presented. Temperature is plotted against the other natural environments. The scales of the other environments can be of intensity, amount or frequency of occurrence. The curves shown in Fig. 3-41 are hypothetical examples, and may not be indicative of actual relationships. More work is needed in this area to determine actual conditions.

From the completed analysis, extension may be made to include a third element. For example, the probability of rain occurring simultaneously with given conditions of temperature and wind speed may be determined statistically. Within the limiting profile of Fig. 3-41, lines of equal probability may then be drawn.

Another point to consider in determining practical combinations is that an extreme environment may be one that is likely to occur in any of several geographical areas, or it may be peculiarly associated with a certain locality. A hot-dry-windy-dusty environment approaching extreme proportions may be found over several relatively large areas. A combination of salt spray and smog, on the other hand, is more characteristically adapted to local peculiarities of terrain and relation to the sea and pollution sources, under ideal conditions of wind direction and speed, solar radiation and lapse rate. The inclusion of environments that are solely the product of local influences may tend to confuse the relationships that normally exist among elements in combination. On the other hand, wind that through oddities of terrain is funneled into a region of very cold air may also create and environment that lies outside the ideal low temperature-wind curve. This type of exceptional extreme should be retained in any extreme environmental study.

To analyze the practical combinations of environments, it is best to examine environmental pairs. Then, any one of a pair can be paired off with another, and this process repeated to determine various strings of possible combinations. When making a practical analysis of a pair of environments, it is necessary to determine: (1) whether the two ever appear simultaneously, (2) whether one tends to intensify or weaken the other, and (3) whether they

are more damaging jointly or sequentially. This type of analysis is shown in Table 3-26 for all dual environments, including natural, induced, and hyper environments.

Combined Induced Environments

A list of the induced environments is given in Table 3-2 at the beginning of this chapter. Like the natural environments, no one of these induced environments will probably occur by itself. Unlike the natural environments, however, the occurrence of the individual induced environments are not too dependent on one another. To date, the interrelationships between the induced environments are not exactly understood, although it is probable that their effects on each other are as great as is the case with the combined natural environments.

The many combinations of induced environments that may exist depend mostly on the type of equipment being considered, its function, and the various possible missions of the weapons system. Since there are many types of equipment and many varied missions, the possible combinations would have to be determined on an individual analysis basis. When such an analysis is made, though, it is more advisable to determine the natural-induced combinations. An analysis of induced environmental pairs is included in Table 3-26.

Natural and Induced Combinations

The problem of examining the combination of both natural and induced environments is a complex one, since two interrelated complex relationships are involved. Too few studies have been made in the area to determine the factors to be considered. One study /79/, which has recently been completed, recommends that only the following environmental pairs be considered, since other possible pairs (1) do not intensify effects, (2) neutralize one another, or, (3) cannot occur in combination.

High temperature and humidity.

High temperature and free moisture.

High temperature and low pressure.

High temperature and salt spray.

High temperature and solar radiation.

High temperature and sand and dust.

High temperature and vibration.

High temperature and shock.

High temperature and acceleration.

Low temperature and humidity.

Low temperature and free moisture.

Low temperature and low pressure.

Low temperature and sand and dust.

Low temperature and vibration.

Low temperature and shock.

Humidity and low pressure.

Humidity and solar radiation.

Humidity and vibration.

Humidity and ozone.

Low pressure and vibration.

Low pressure and explosive atmosphere.

Solar radiation and sand and dust.

Solar radiation and vibration.

Solar radiation and ozone.

Sand and dust and vibration.

Vibration and acceleration.

A complete analysis of combined natural and induced environments is shown in Table 3-26.

Environmental Analysis

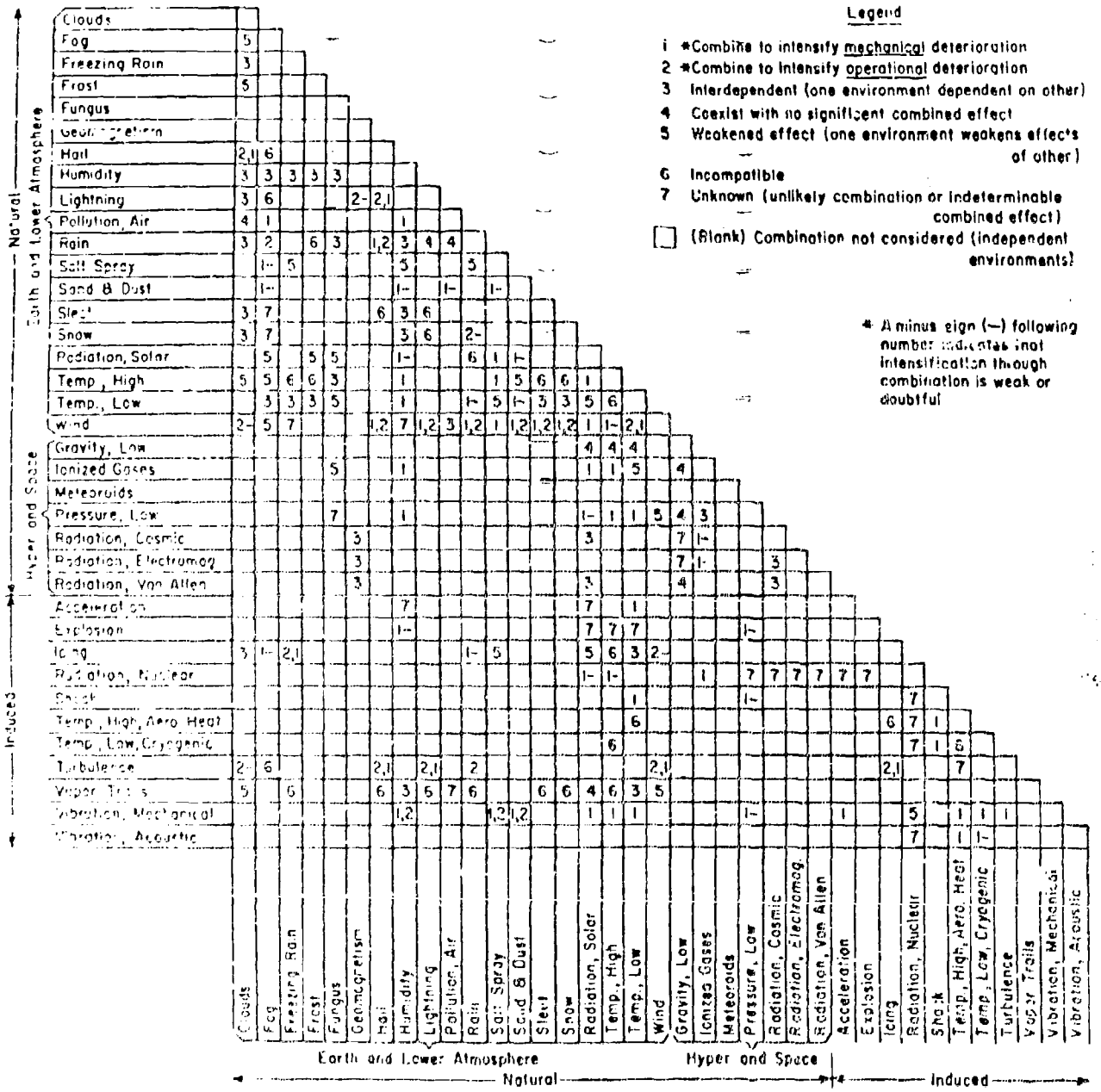
Each weapons system must be analyzed to determine the possible ranges and combinations of environments that may be encountered during operational life. All phases of the mission profile must be considered, such as:

1. Transportation and handling.
2. Storage.
3. Ground handling (pre-launch or pre-take off).
4. Launch or takeoff.
5. Flight.
6. Reentry or descent.

Detailed information on how an environmental analysis is carried out is presented in Chapter 4.

Transportation and Handling. In the initial stages of transportation and handling, equipments are usually kept in temperate climates. The principal environments they encounter are shock, low temperature, moisture, temperature-condensation, solar radiation and possibly sand,

Table 3-26. Qualitative Relationships of Combined Environments



and dust. Ordinarily, because of packaging, most of these environments are negated, and shock due to handling is the only one considered to be serious. However, encounters could include shock in varying combinations with (not all simultaneously) moisture, solar radiation, temperature-condensation, sand and dust, low temperature and high temperature.

As equipment moves on the surface through various areas and climates, typical combinations likely to be encountered are shock and salt spray; high temperature and salt air; high temperature, solar radiation, and shock; low temperature and shock; and moisture and shock.

When equipment is transported by air, the combined environments encountered will generally be the same as these encountered in flight operations.

Storage. Combinations of environmental extremes are rarely encountered during storage. Those environments met include high temperature, low temperature, fungus, humidity, temperature-condensation, and, depending upon the type of storage, rain, blowing snow, salt-spray, solar radiation, sand and dust, and possibly shock.

In a very broad sense, these environmental extremes could be encountered in combinations, such as: low temperature and blowing snow; high temperature and solar radiation; humidity and fungus; and high temperature and sand and dust.

As in transportation, shock due to handling to and from storage could occur in combination with any of the other combined or single environments.

Ground Handling. During ground handling, which includes the pre-launch or pre-takeoff phase of the mission profile, flight vehicles may be exposed to combined environmental extremes such as (1) low temperature, blowing snow, and shock and vibration; (2) high temperature, solar radiation, and shock and vibration; (3) high temperature, sand and dust or rain, and shock and vibration; and (4) temperature-condensation and shock and vibration.

Operation. During actual system operation, which includes the launch or takeoff, flight, and reentry or descent portions of the mission profile, a flight vehicle experiences the most complex and severe combinations of environments. This is due primarily to the fact that during operation many of the induced environments exist, in some degree, continuously. A typical example of environmental combination occurring during the ground handling and operation phases of a mission profile are shown in Fig. 3-42. A detailed discussion of the environments encountered during launch, flight and reentry is given in the "Flight Paths" section of Chapter 2.

Combined Environmental Effects/79/

The following paragraphs discuss the effects of various environmental pairs. The coverage does not repeat the effects of each environment, but discusses only how the combination may intensify, neutralize, or add nothing to the individual effects. Many combinations not considered significant are excluded.

High Temperature and Humidity. High temperature tends to increase the rate of moisture penetration. The general deterioration effects of humidity are increased by high temperatures.

High Temperature and Low Pressure. Each of these environments is dependent on the other. For example, as pressure decreases, outgassing of constituents of materials increases, and as temperature increases, the rate of outgassing increases. Hence, each tends to intensify the effects of the other.

High Temperature and Salt Spray. High temperature tends to increase the rate of corrosion caused by salt spray.

High Temperature and Solar Radiation. This is a natural combination that causes increasing effects on organic materials.

High Temperature and Fungus. A certain degree of high temperature is necessary to permit fungus and microorganisms to grow. But, above 160 F (71 C) fungus and microorganisms cannot develop.

High Temperature and Sand and Dust. The erosion rate of sand and dust may be accelerated by high temperature. However, high temperatures reduce sand and dust penetration.

High Temperature and Shock and Vibration. Since both of these environments affect common material properties, they will intensify each other's effects. The amount that the effects are intensified depends on the magnitude of each environment in the combination. Plastics and polymers are more susceptible to this combination than metals, unless extremely high temperatures are involved.

High Temperature and Acceleration. This combination produces the same effect as high temperature and shock and vibration.

High Temperature and Explosive Atmosphere. Temperature has very little effect on the ignition of an explosive atmosphere. But it does affect the air-vapor ratio which is an important consideration.

High Temperature and Ozone. Starting at about 300 F (150 C), temperature starts to reduce ozone. Above about 520 F (270 C), ozone cannot exist at pressures normally encountered.

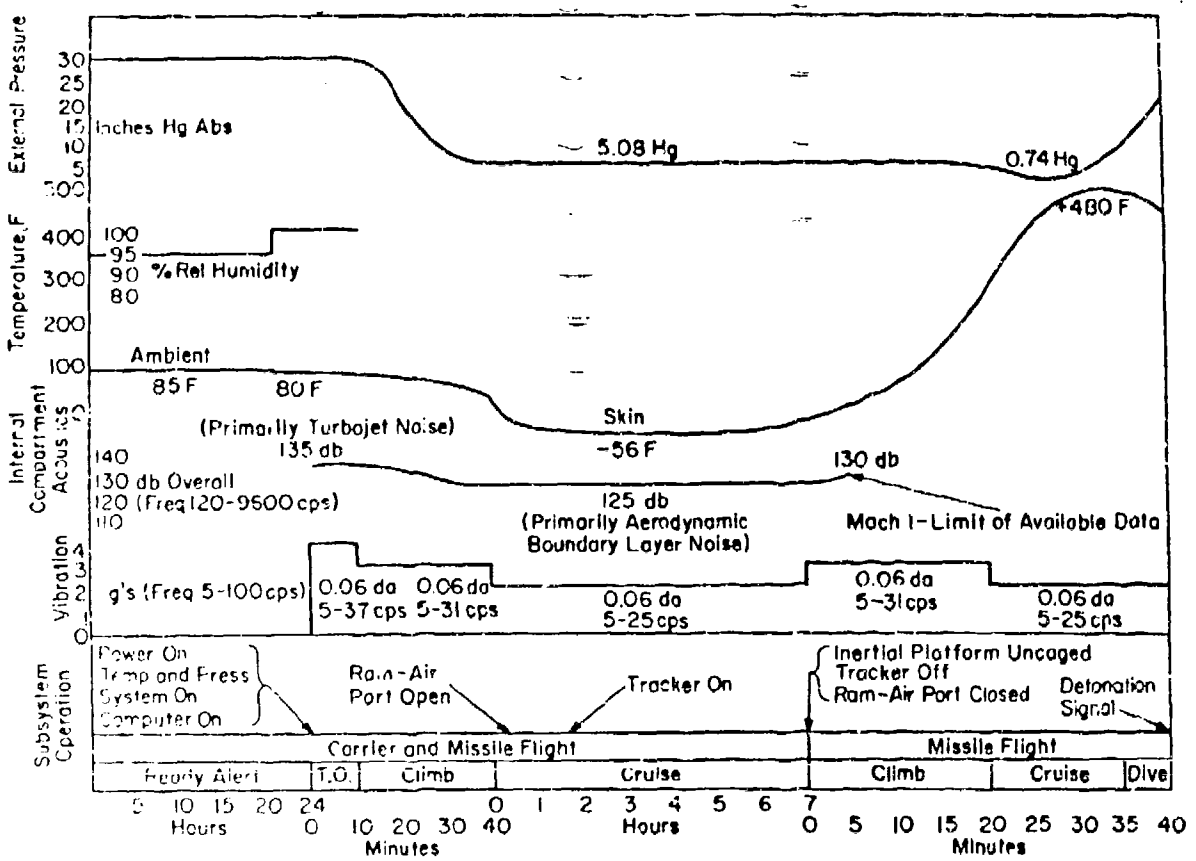


Fig. 3-42. Combined environments encountered during ground handling and operation phases of typical mission profile./80/ (Courtesy of Bell Aircraft Corp.)

Low Temperature and Humidity. Humidity decreases with temperature; but low temperature induces moisture condensation, and, if the temperature is low enough, frost or ice.

Low Temperature and Low Pressure. This combination can accelerate leakage through seals, etc.

Low Temperature and Salt Spray. Low temperature reduces the corrosion rate of salt spray.

Low Temperature and Solar Radiation. Low temperature will tend to reduce the effects of solar radiation, and vice versa.

Low Temperature and Sand and Dust. Low temperature increases dust penetration.

Low Temperature and Fungus. Low temperature reduces fungus growth. At subzero temperatures, fungi will remain in suspended animation.

Low Temperature and Shock and Vibration. Low temperature tends to intensify the effects of shock and vibration. It is, however, a consideration only at very low temperatures.

Low Temperature and Acceleration. This combination produces the same effect as low temperature and shock and vibration.

Low Temperature and Explosive Atmosphere. Temperature has very little effect on the ignition of an explosive atmosphere. It does, however, affect the air-vapor ratio which is an important consideration.

Low Temperature and Ozone. Ozone effects are reduced at lower temperatures, but ozone concentration increases with lower temperatures.

Humidity and Low Pressure. Humidity increases the effects of low pressure, particularly in relation to electronic or electrical equipment. However, the actual effectiveness of this combination is determined largely by the temperature of the environment.

Humidity and Salt Spray. High humidity may dilute the salt concentration, but it has no bearing on the corrosive action of the salt.

Humidity and Fungus. Humidity helps the growth of fungus and microorganisms but adds nothing to their effects.

Humidity and Sand and Dust. Sand and dust have a natural affinity for water, and so this combination increases deterioration.

Humidity and Solar Radiation. Humidity intensifies the deteriorating effects of solar radiation on organic materials.

Humidity and Vibration. This combination tends to increase the rate of breakdown of electrical material.

Humidity and Shock and Acceleration. The periods of shock and acceleration are considered too short for these environments to be affected by humidity.

Humidity and Explosive Atmosphere. Humidity has no effect on the ignition of an explosive atmosphere, but a high humidity will reduce the pressure of an explosion.

Humidity and Ozone. Ozone reacts with moisture to form hydrogen peroxide, which has a greater deteriorating effect on plastics and elastomers than the additive effects of moisture and ozone themselves.

Low Pressure and Salt Spray. This combination is not expected to occur.

Low Pressure and Solar Radiation. This combination adds nothing to the overall effects.

Low Pressure and Fungus. This combination adds nothing to the overall effects.

Low Pressure and Sand and Dust. This combination can only occur in extreme storms during which small dust particles are carried to high altitudes.

Low Pressure and Vibration. This combination intensifies effects in all equipment categories, but mostly with electronic and electrical equipment.

Low Pressure and Shock, or Acceleration. These combinations only become important at the hyper environmental levels, in combination with high temperature.

Low Pressure and Explosive Atmosphere. At low pressures, an electrical discharge is easier to develop, but the explosive atmosphere is harder to ignite.

Salt Spray and Fungus. This is considered an incompatible combination.

Salt Spray and Sand and Dust. This will have the same combined effect as humidity and sand and dust.

Salt Spray and Vibration. This will have the same combined effect as humidity and vibration.

Salt Spray and Shock or Acceleration. These combinations will produce no added effects.

Salt Spray and Explosive Atmosphere. This is considered an incompatible combination.

Salt Spray and Ozone. These environments have the same combined effect as humidity and ozone.

Solar Radiation and Fungus. Because of the resulting heat from solar radiation, this combination probably produces the same combined effect as high temperature and fungus. Further, the ultraviolet in unfiltered radiation is an effective fungicide.

Solar Radiation and Sand and Dust. It is suspected that this combination will produce high temperatures.

Solar Radiation and Vibration. Under vibration conditions, solar radiation deteriorates plastics, elastomers, oils, etc., at a higher rate.

Solar Radation and Shock or Accelerations. These combinations produce no added effects.

Solar Radiation and Explosive Atmosphere. This combination probably produces no added effects.

Solar Radiation and Ozone. This combination increases the rate of oxidation of materials.

Fungus and Ozone. Fungus is destroyed by ozone.

Sand and Dust and Vibration. Vibration might possibly increase the wearing effects of sand and dust.

Shock and Vibration. This combination produces no added effects.

Vibration and Acceleration. This combination produces increased effects when encountered with high temperatures and low pressures in the hyper environment ranges.

Multiple Combinations. The results of one evaluation program /79/ suggest that the following environmental combinations produce essentially the same effects as all of the environment pairs described above:

Transportation and Operation Environments

1. Vibration

   Temperature extremes (cycling and shock

   Humidity

   Altitude

2. Shock

   Temperature extremes

3. Acceleration

   Temperature extremes

4. Explosive atmosphere

(a) Temperature

(b) Altitude

(c) Air-fuel mixture

Ground Handling Environments

1. Humidity extremes (cycling)

Temperature extremes (cycling)

Sunshine and/or rain

2. Sand and dust

High temperature

Solar radiation

Low humidity

ENVIRONMENTAL EFFECTS ON HUMANS

Although the weapon system itself may be properly designed to withstand the various environments, it may still fail to perform its mission if the environments prevent the operators from doing their job. The system, then, must be human-engineered. This section presents a summary of the important environmental effects on humans, such as noise, acceleration, weightlessness, temperature and humidity, radiation and general physical comfort. The material presented is merely intended to introduce the problems that exist. More detailed information is covered in references /81, 82, 83/.

Noise

Sound measurements are usually given in decibels (db). Typical sound levels generated by such sources as jet engines, traffic and factories are given in "The Handbook of Noise Measurement," published by General Radio Co., Cambridge, Mass.

It is difficult to judge the effects of noise on humans, since the effects are generally related to the mental attitude of the individual and his previous exposure to various noises. However noise may have one or all of the following effects on a person:

1. It may only annoy him.
2. It may disturb his sleep.
3. It may interfere with his ability to hear. This is called masking.
4. It may cause progressive damage to his hearing, eventually leading to deafness.

Damage to hearing depends upon the intensity, frequency and duration of the noise. The greatest damage to hearing occurs in the frequency range of 500 to 2000 cps. Sudden damage may result from the noise of a blast or an explosion. Gradual damage may result from continual exposure to noise over a long period. A steady noise, such as from an aircraft engine, will be less likely to damage hearing than an impulsive noise, such as from a pneumatic drill. /37,84/

Acceleration

The effects of acceleration depend on the body position relative to the direction of the accelerating force. The effects of a longitudinal accelerating force applied against a person lying face down or on his back are as follows: /85/

0 g Weightlessness will occur.

1 g Normal gravity.

2 g Hands and feet will feel heavy, making it difficult for a man to walk or climb.

3g Walking and climbing will be impossible. Crawling will be accomplished with difficulty. Soft tissues in the body will begin to sag.

4g Great difficulty will be encountered in moving the body. Crawling will be almost impossible.

5g Only slight movements of arms and head will be possible.

The effects of accelerations greater than 5 g's can range from labored breathing and blackout to structural damage, especially to the spine.

Higher g-levels have less effect on humans in a prone position when the accelerating force is tranverse to the body. For instance, only slight confusion of the subject will occur, and loss of consciousness will not take place until a force of 17 g's is reached. Also, no structural damage to the body will take place until an accelerating force of 30 to 45 g's is reached. In general, a person in a sitting or upright position will also be affected less if the accelerating force is transverse rather than longitudinal relative to the body./85, 86/

Certain post-acceleration affects, such as vertigo and nausea, and occasionally rapid involuntary oscillations of the eyeball, will occur, but these symptoms usually last only a few minutes.

Weightlessness

When a human enters a zero-gravity environment, he tends to lose his sense of orientation. For example, he would not know whether his arm is hanging at his side or stretched out in front of him. If he wanted to pick up a pencil, he would first have to look at his hand to find out where it is. Then, watching his hand closely he would guide it to the pencil. In the dark, his senses could not tell him if he were lying down or standing up.

The worst psychological effect of weightlessness might be felt when the individual is asleep or trying to sleep. There may be a constant sensation of falling or perhaps floating. This might lead to a dread of sleep and a resultant pattern of disturbing fantasies, and even panic. Weightlessness can only be simulated on Earth for short periods, so additional experience is necessary to understand more fully the effects of weightlessness./85,87,88/

Low Temperature

Low temperatures cause loss of body heat, resulting in shivering and tremors. In addition there may be a reduction of blood flow to the limbs, which could result in injuries. When exposure to low temperature follows physical exhaustion, the progressive results are weakness, sleep, paralysis and finally death.

It is not possible to state precisely the low temperature limit for the performance of various human functions because this is influenced by many variables. However, if the body temperature is maintained at the normal level, a bare hand can be kept fairly comfortable for a few minutes at a temperature of -34 C (-29 F). A body temperature below about 21 to 23 C (70 to 73 F) will cause death./3/

High Temperature and Humidity

The general effects of high temperatures, depending upon degree and length of exposure, are apathy, loss of efficiency, weakness, headaches, difficulty in breathing, nausea, increased body temperature, heat stroke and convulsions.

Humidity affects sweat evaporation, and so has a bearing on the effects of high temperatures on humans. For example, a human may endure a temperature of 125 C (257 F) in a dry atmosphere for eight minutes without ill effects. However, if the humidity reaches the point of saturation, a temperature of only 50 C (122 F) can be endured for eight minutes without ill effects. [illegible]

Heat loss can occur by conduction, convection, radiation and evaporation of water from the lungs and skin. Conduction plays a very small part in cooling the body, as it only occurs when the body is in contact with a cold object. The heat loss from the body surface to air by convection is proportional to the difference between their temperatures. In moving air, the convection effect increases roughly as the square root of the air speed. By radiation, the body exchanges heat with its surroundings, such as walls, at a rate proportional to the difference between the fourth powers of their absolute temperatures. However, the radiant surface of the human body is only 70 to 85 percent of the total surface, or about 14 to 17 square feet. Evaporation contributes to body heat loss to a rapidly increasing extent the closer the temperature of the environment comes to that of the skin, and the smaller, therefore, becomes the amount of heat that can be lost by convection and radiation.

In air at or above 95 F (35 C), practically all heat loss of the body is due to evaporation. The rate of evaporation is proportional to the difference in vapor pressure at the skin and of the surrounding air, as well as to the speed of movement of the air. To lower the body temperature of an average man by 1 degree C requires the evaporation of about 120 grams of sweat./90/

Radiation

Space vehicles and their crews will be exposed to many types of radiations. Some of the more important types are X-rays, steady ultraviolet radiation and cosmic radiation. Most forms of radiation, including solar radiation in the visible, ultraviolet and soft x-ray region, do not constitute a hazard, since they can be stopped or weakened by thin layers of structural material. However, cosmic radiation has great penetrating power and can cause radiation sickness and other physiological effects./44,91/.

The ill effects caused by various amounts of cosmic radiation are still undecided. A human may be exposed to small amounts of cosmic radiation and not suffer any genetic ill effects. For example, exposure to 0.3 roentgen (r) per week or an average dosage of 5 r per year is considered acceptable for industrial exposure. However, if a person is exposed to cosmic radiation in excess of these amounts, various radiation symptoms will appear, depending on the dosage. For example, a dosage of 100 r to 200 r causes hemorrhages, a low white blood cell count and livid spots on the skin. Full recovery may be expected within two months. A dosage of 200 r to 400 r is severe and requires hospitalization of the individual, but a full recovery is probable if treatment is started immediately after exposure. A dosage of 500 r causes diarrhea and fever, and death is almost certain to take place within two weeks. A dosage of 2000 r causes convulsions, tremors, lethargy and a general lack of coordination. Death is certain to take place within two days after exposure. In general, a person exposed to between 400 and 600 r has a poor change of recovery. (85,92)

Physical Comfort

The preceeding paragraphs have indicated some of the environmental factors involving human comfort. There are also factors such as composition and pressure of the atmosphere, food requirements, problems due to confinement and isolation, uncomfortable clothing and numerous others. Physical comfort varies for different individuals, and each person will react differently. In general, comfort is a quality that an individual is unaware of, until a feeling of discomfort is introduced. For example, if the cabin temperature is 20 C (68 F) a pilot may be quite oblivious to the sound of his breathing; but if the temperature is increased, his former comfort is interrupted because of compensating body changes, and breathing may suddenly become a serious burden. A complete understanding of the comfort that must be maintained in a manned space vehicle has yet to be determined. /85/

SUMMARY OF ENVIRONMENTAL EFFECTS

A summary of the major environmental effects is given in Table 3-27. Most of the effects covered pertain to materials. However, many of the resulting effects on components and equipments can be deduced from the "Typical Failures Induced" column of the table.

Table 3-27. Summary of Environmental Effects /93/

Environment	Principal effects	Typical failures induced
High temperature	Thermal aging: Oxidation Structural change Chemical reaction	Insulation failure; Alteration of electrical properties
	Softening, melting and sublimation	Structural failure
	Viscosity reduction and evaporation	Loss of lubrication properties
	Physical expansion	Structural failure; Increased mechanical stress; Increased wear on moving parts
Low temperature	Increased viscosity and solidification	Loss of lubrication properties;
	Ice formation	Alteration of electrical properties
	Embrittlement	Loss of mechanical strength; Cracking, fracture;
	Physical contraction	Structural failure; Increased wear on moving parts
High relative humidity	Moisture absorption	Swelling, rupture of container; Physical breakdown; Loss of electrical strength
	Chemical reaction: Corrosion Electrolysis	Loss of mechanical strength; Interference with function; Loss of electrical properties; Increased conductivity of insulators
Low relative humidity	Desiccation: Embrittlement Granulation	Loss of mechanical strength; Structural collapse; Alteration of electrical properties, "dusting"

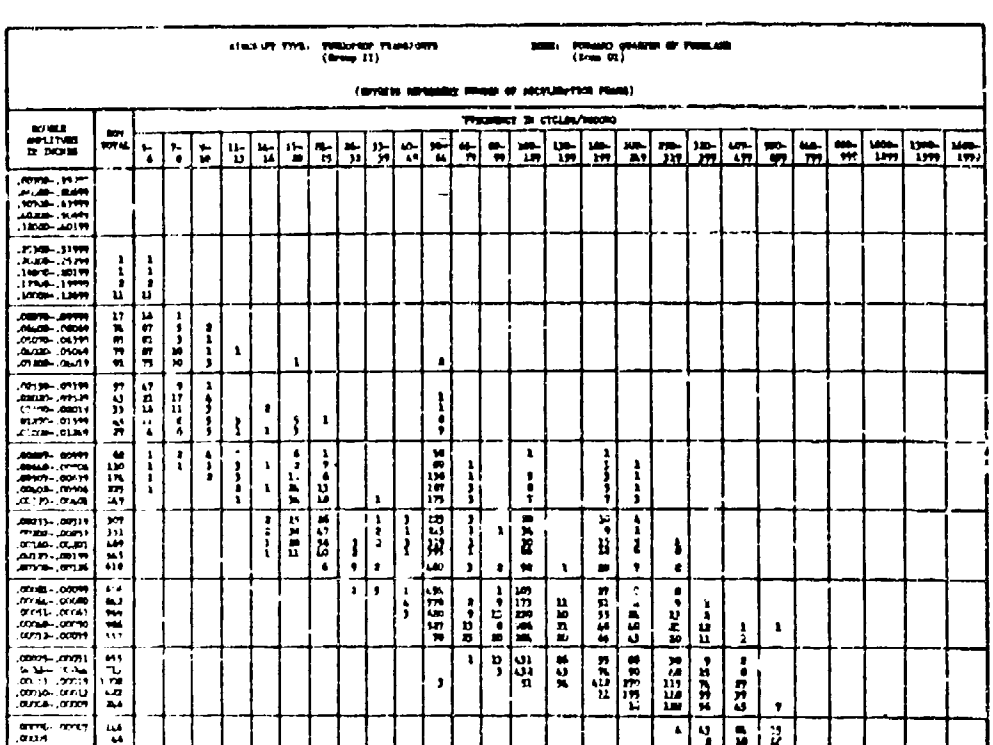
Table 3-27. Summary of Environmental Effects /93/ (continued)

Environment	Principal effects	Typical failures induced
High pressure	Compression	Structural collapse; Penetration of sealing; Interference with function
Low pressure	Expansion	Fracture of container; Explosive expansion
	Outgassing	Alteration of electrical properties; Loss of mechanical strength
	Reduced dielectric strength of air	Insulation breakdown and arcover; Corona and ozone formation
Solar radiation	Actinic and physicochemical reactions: Embrittlement	Surface deterioration; Alteration of electrical properties; Discoloration of Materials; Ozone formation
Sand and dust	Abrasion Clogging	Increased wear; Interference with function; Alteration of electrical properties
Salt spray	Chemical reactions: Corrosion	Increased wear; Loss of mechanical strength; Alteration of electrical properties; Interference with function
	Electrolysis	Surface deterioration; Structural weakening; Increased conductivity
Wind	Force application	Structural collapse; Interference with function; Loss of mechanical strength
	Deposition of materials	Mechanical interference and clogging; Abrasion accelerated;
	Heat loss (low velocity)	Accelerates low-temperature effects
	Heat gain (high velocity)	Accelerates high-temperature effects
Rain	Physical stress Water absorption and immersion	Structural collapse; Increase in weight; Aids heat removal; Electrical failure; Structural weakening
	Erosion	Removes protective coatings; Structural weakening; Surface deterioration
	Corrosion	Enhances chemical reactions

Table 3-27. Summary of Environmental Effects /93/ (continued)

Environment	Principal effects	Typical failures induced
Temperature shock	Mechanical stress	Structural collapse or weakening; Seal damage
High speed particles (nuclear irradiation)	Heating	Thermal aging; Oxidation
	Transmutation and ionization	Alteration of chemical, physical and electrical properties, Production of gases and secondary particles
Zero gravity	Mechanical stress	Interruption of gravity-dependent functions
	Absence of convection cooling	Aggravation of high-temperature effects
Ozone	Chemical reactions	Rapid oxidation;
	Crazing, cracking	Alteration of electrical properties;
	Embrittlement	Loss of mechanical strength;
	Granulation	Interference with function
	Reduced dielectric strength of air	Insulation breakdown and arcover
Explosive decompression	Severe mechanical stress	Rupture and cracking; Structural collapse
Dissociated gases	Chemical reactions; Contamination	Alteration of physical and electrical properties
	Reduced dielectric strength	Insulation breakdown and arcover
Acceleration	Mechanical stress	Structural collapse
Vibration	Mechanical stress	Loss of mechanical strength; Interference with function; Increased wear
	Fatigue	Structural collapse
Magnetic fields	Induced magnetization	Interference with function; Alteration of electrical properties; Induced heating

Chart 1. Vibration Environment At Various Locations on Turboprop Transports



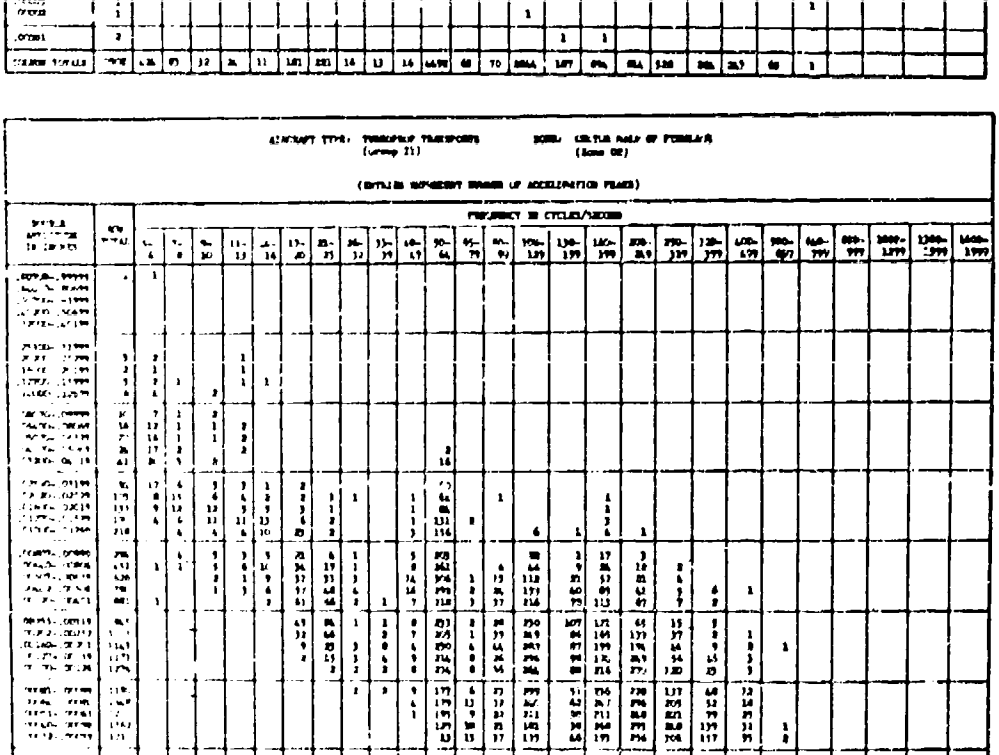
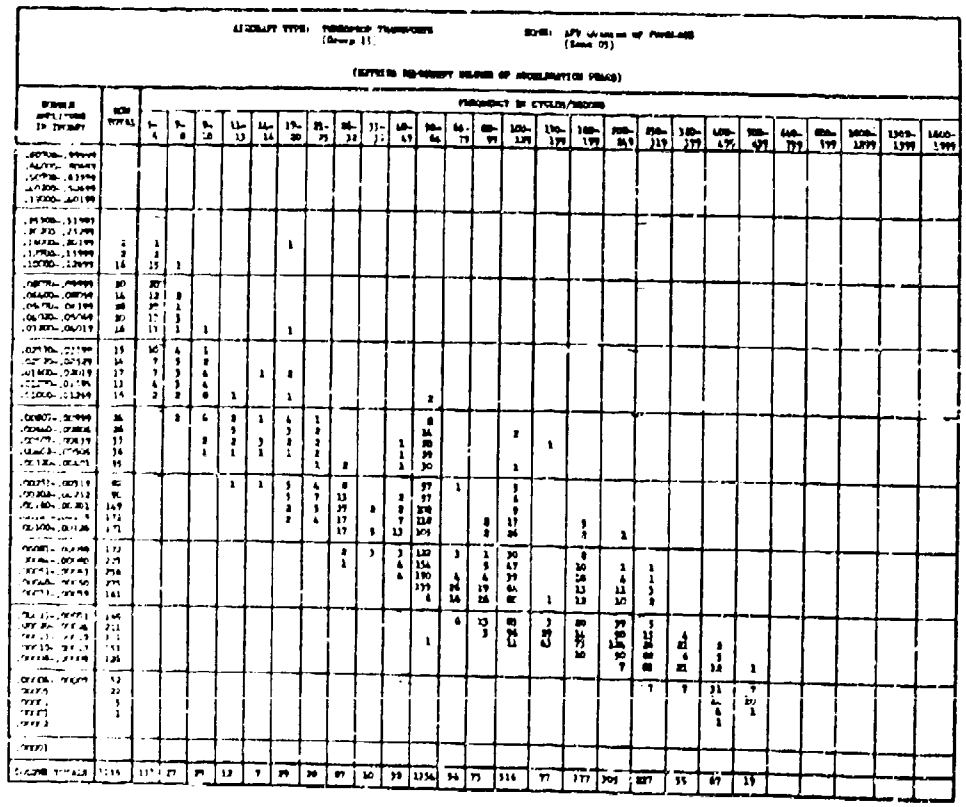


Chart 1. Vibration Environment At Various Locations on Turboprop Transports (continued)



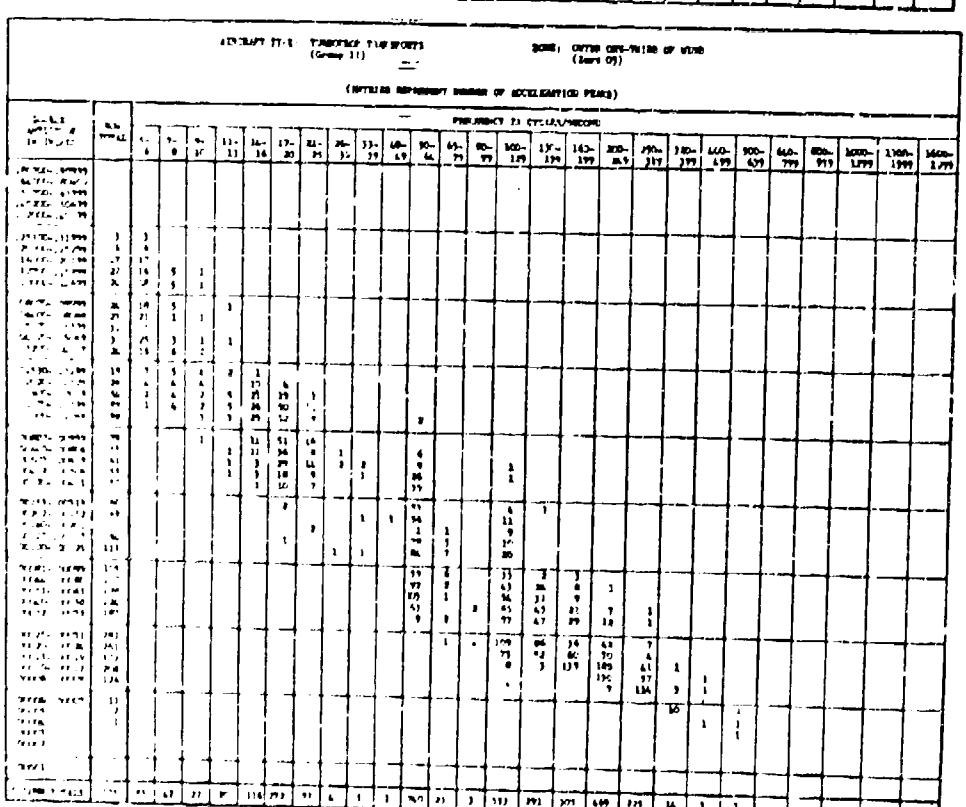
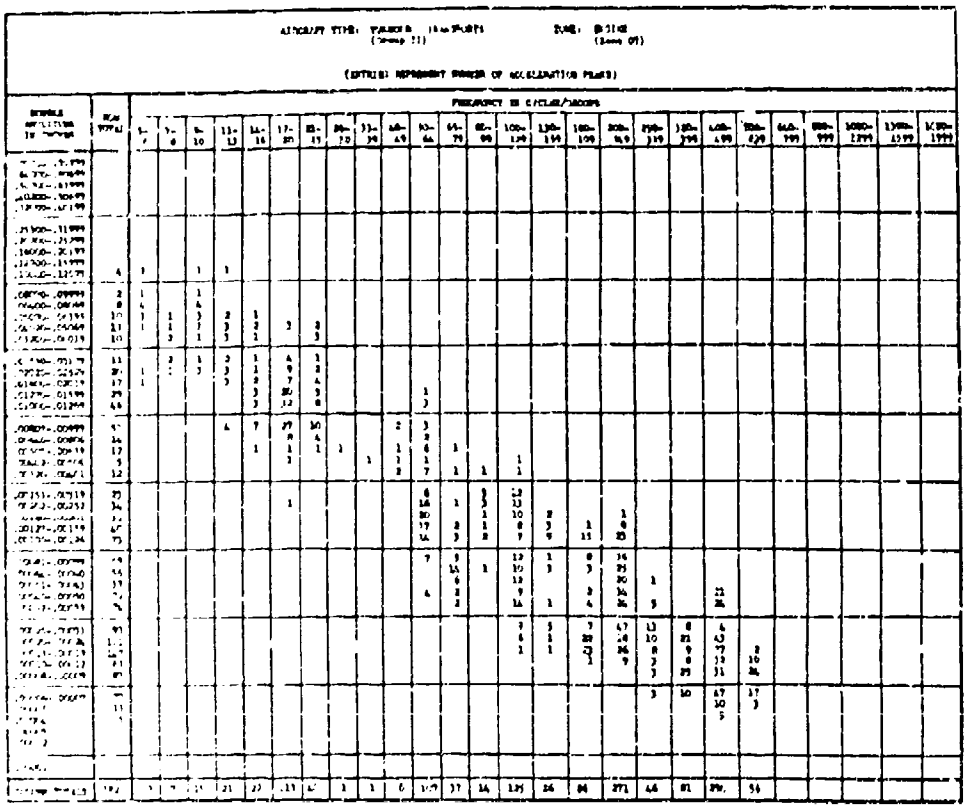


Chart 1. Vibration Environment At Various Locations on Turboprop Transports (continued)



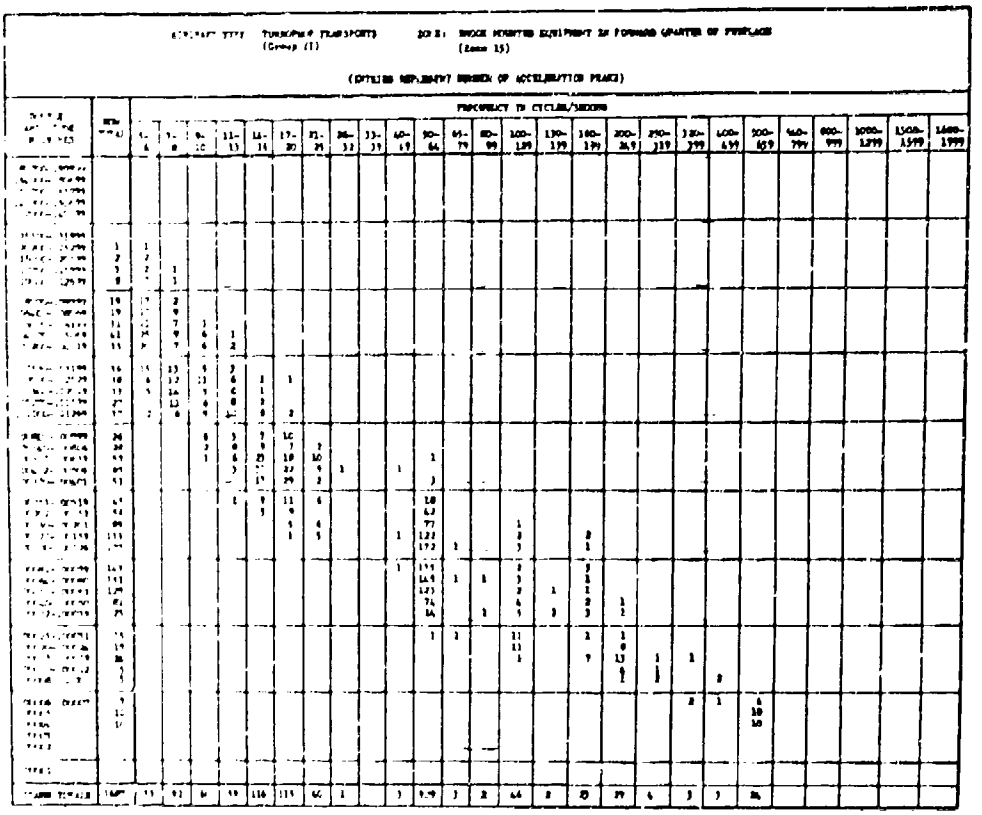


Chart 1. Vibration Environment At Various Locations on Turboprop Transports (continued)

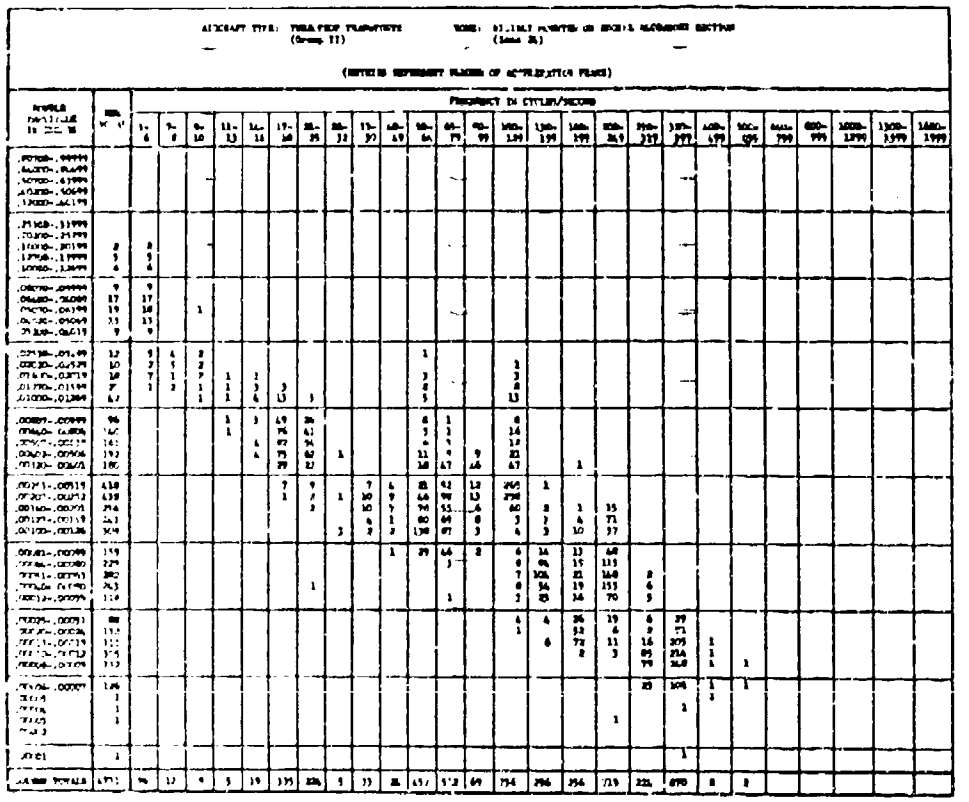
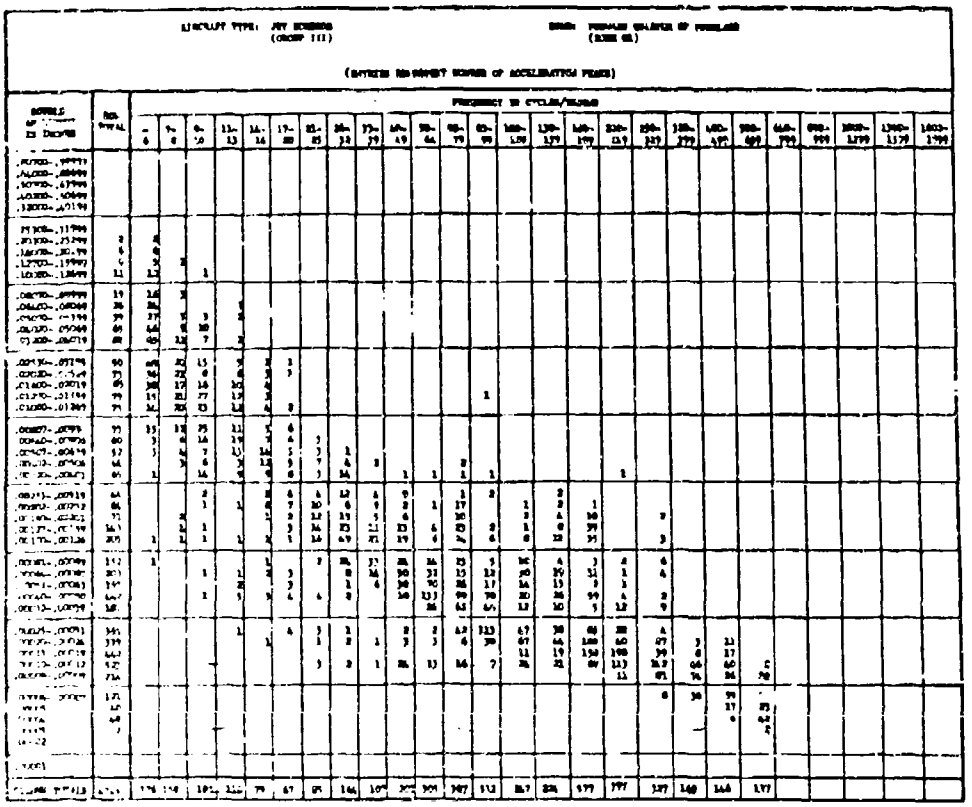


Chart 2. Vibration Environment At Various Locations on Jet Bombers



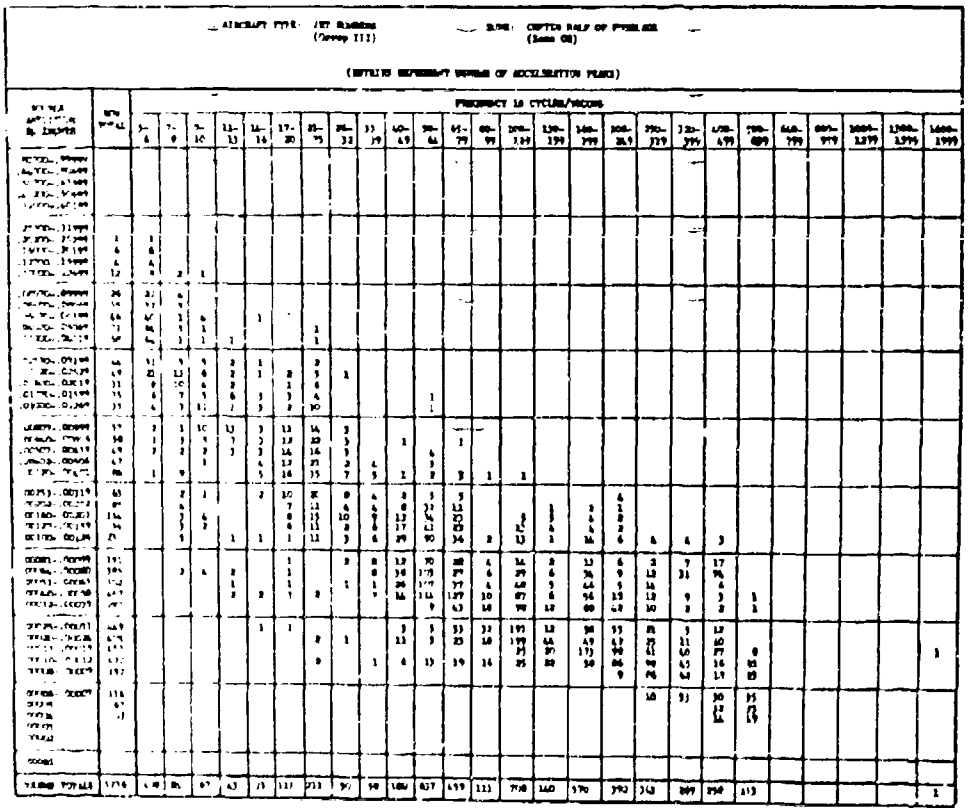
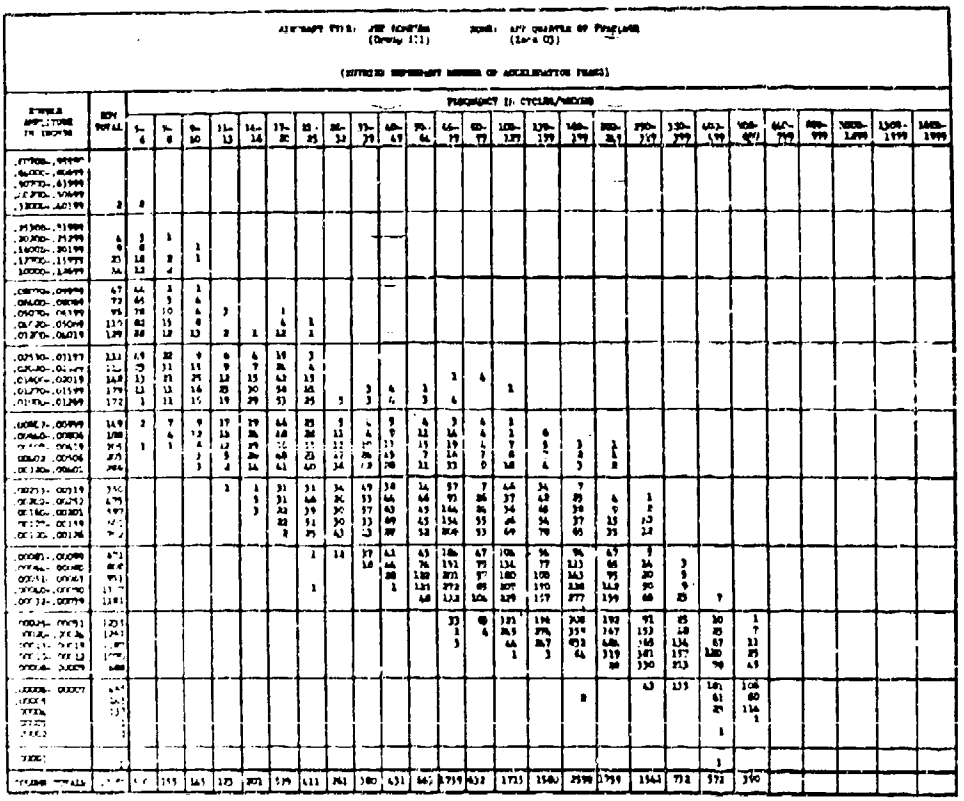


Chart 2. Vibration Environment At Various Locations on Jet Bombers (continued)



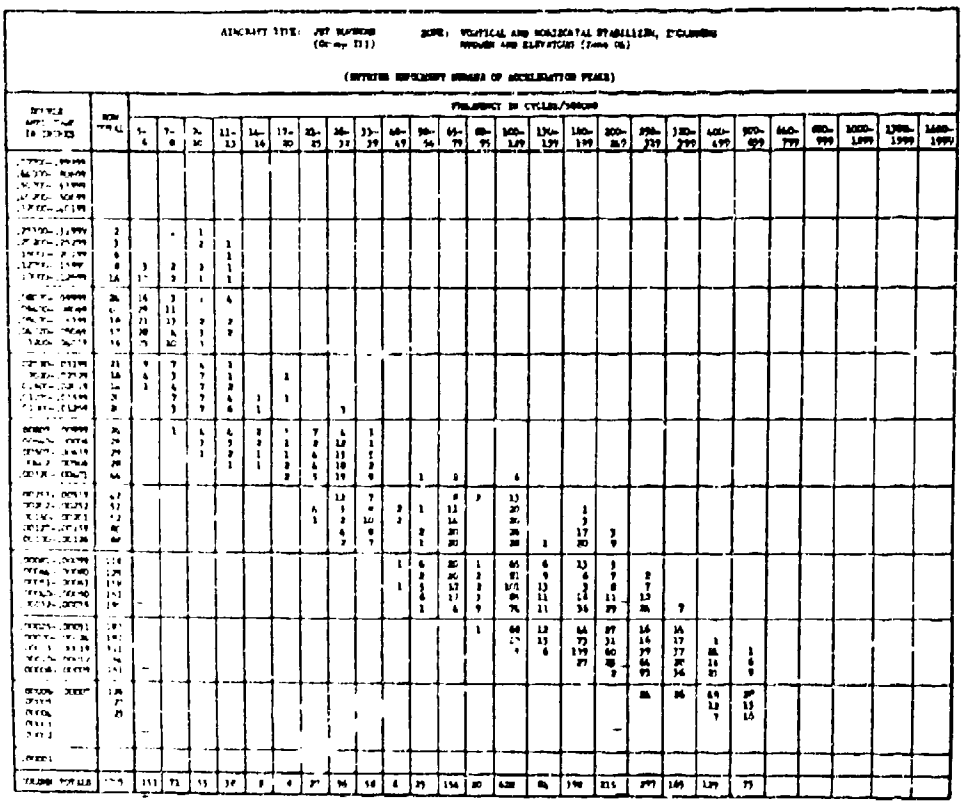
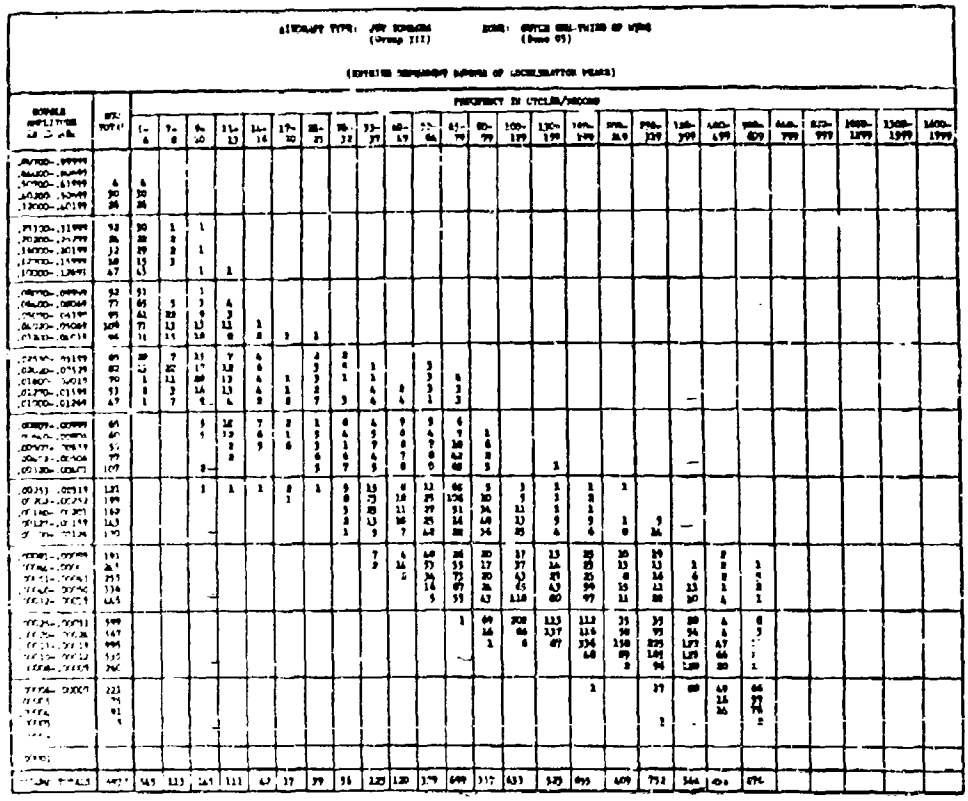


Chart 2. Vibration Environment At Various Locations on Jet Bombers (continued)



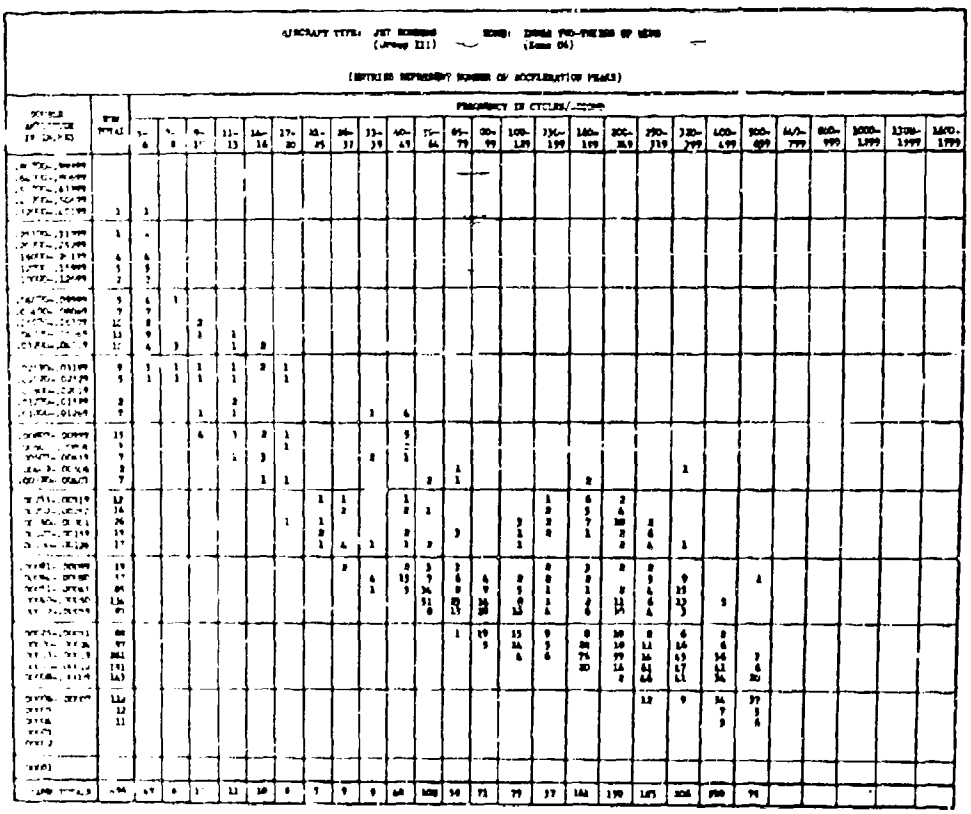
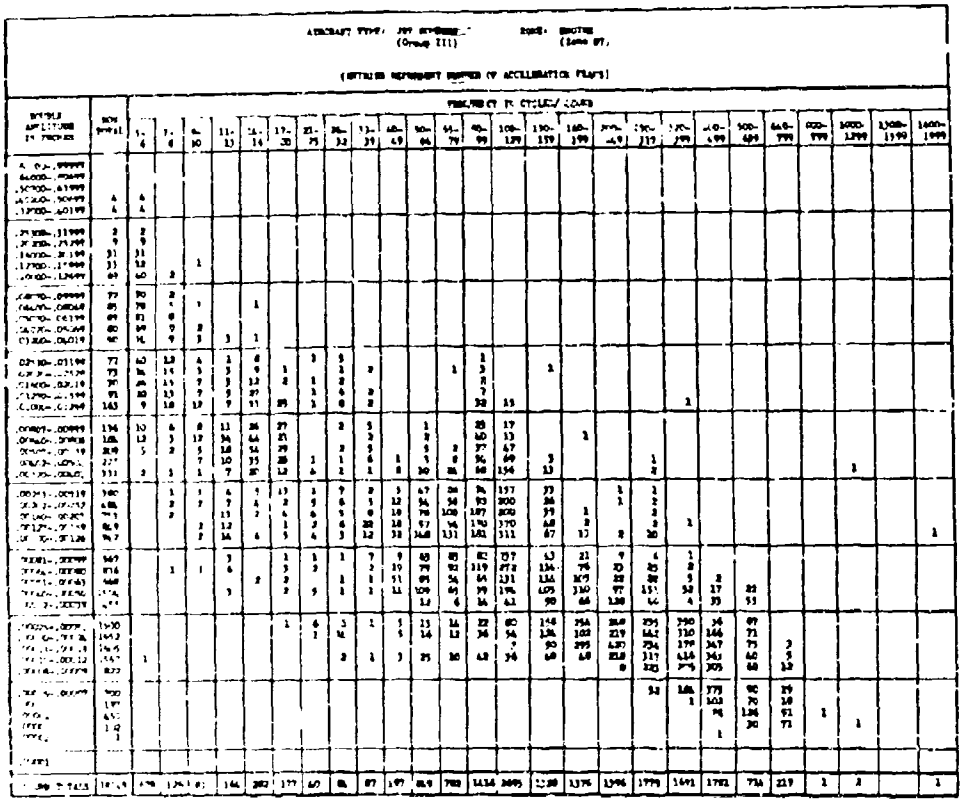


Chart 2. Vibration Environment At Various Locations on Jet Bombers (continued)



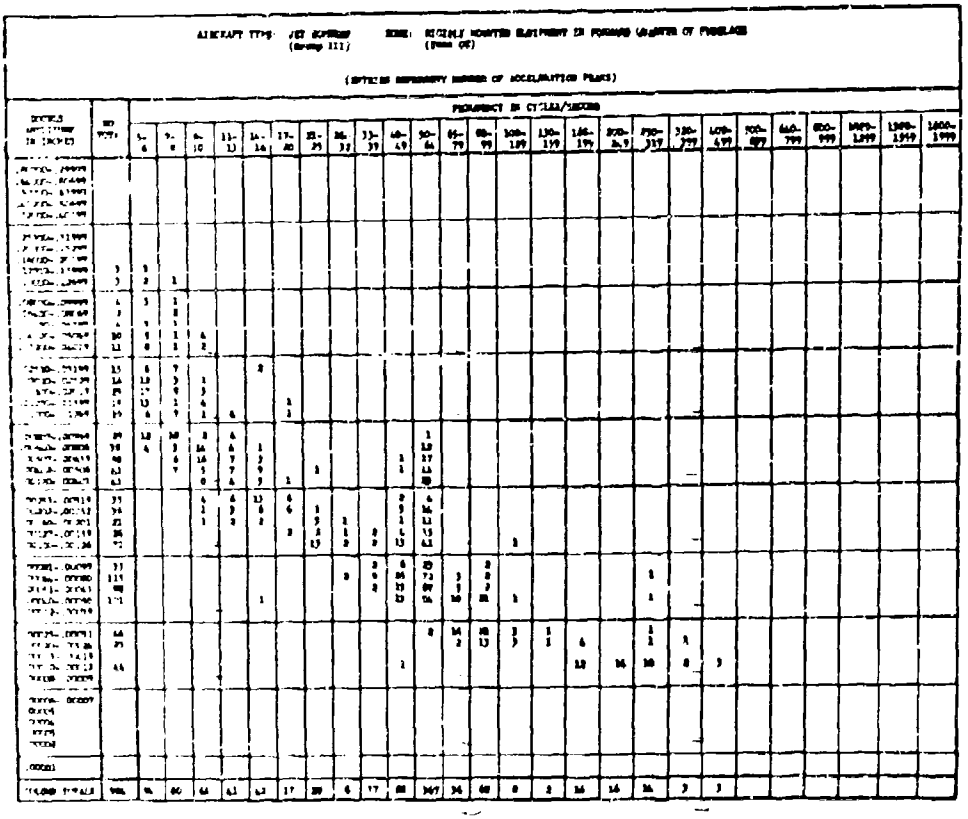
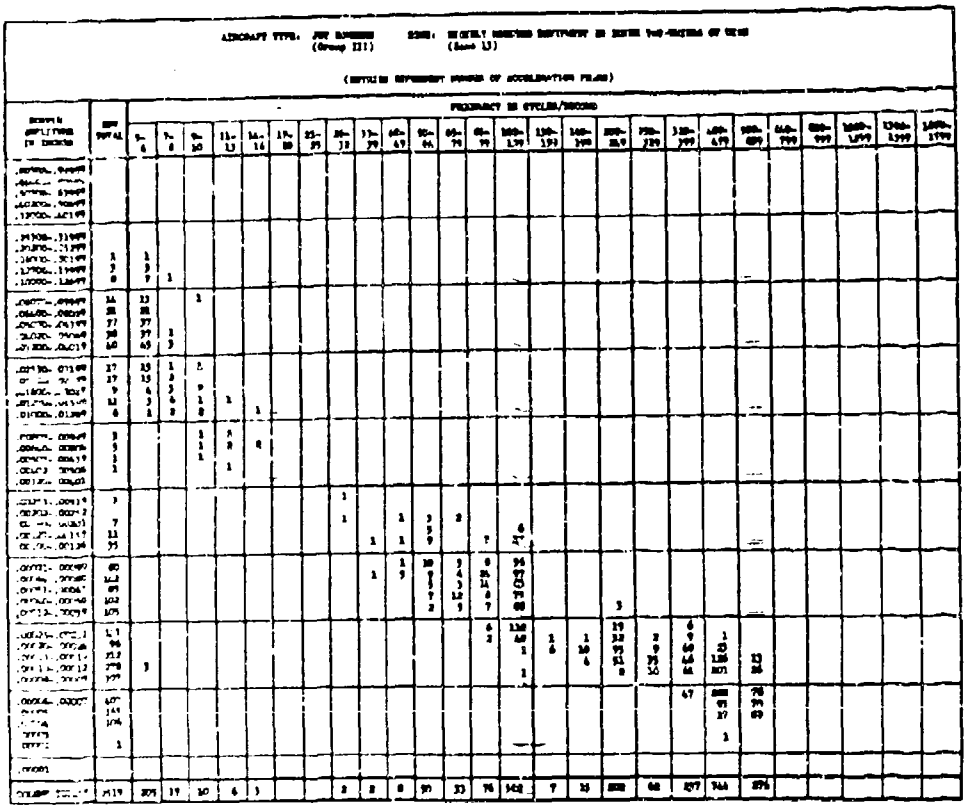


Chart 2. Vibration Environment At Various Locations on Jet Bombers (continued)



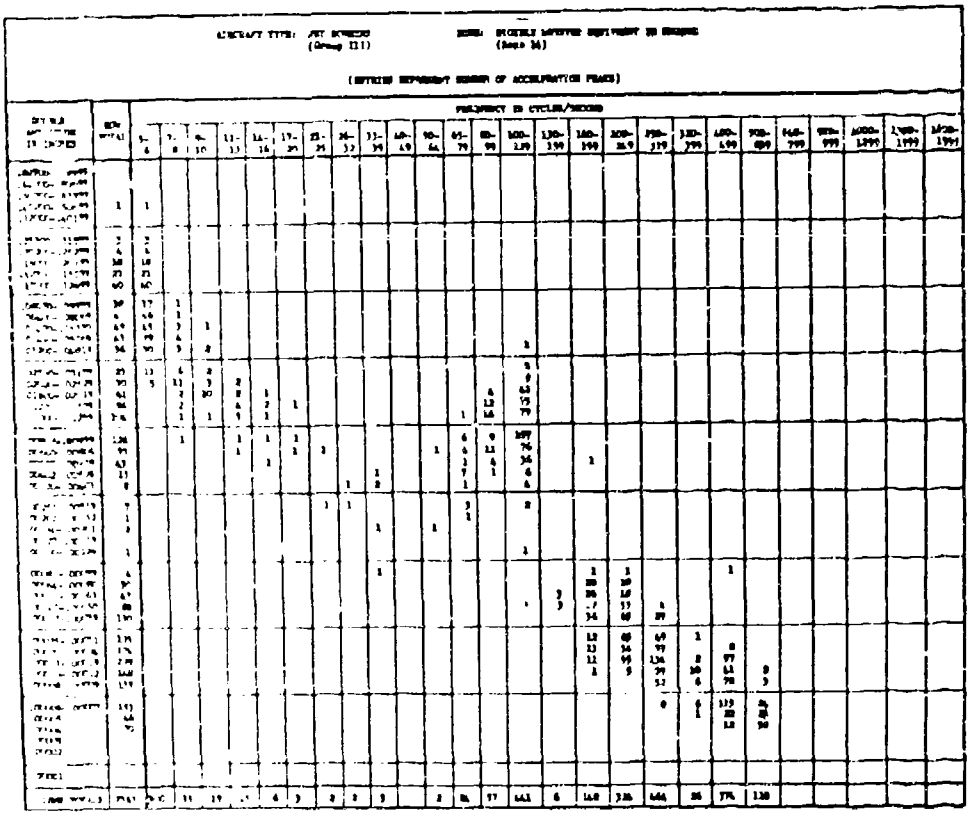
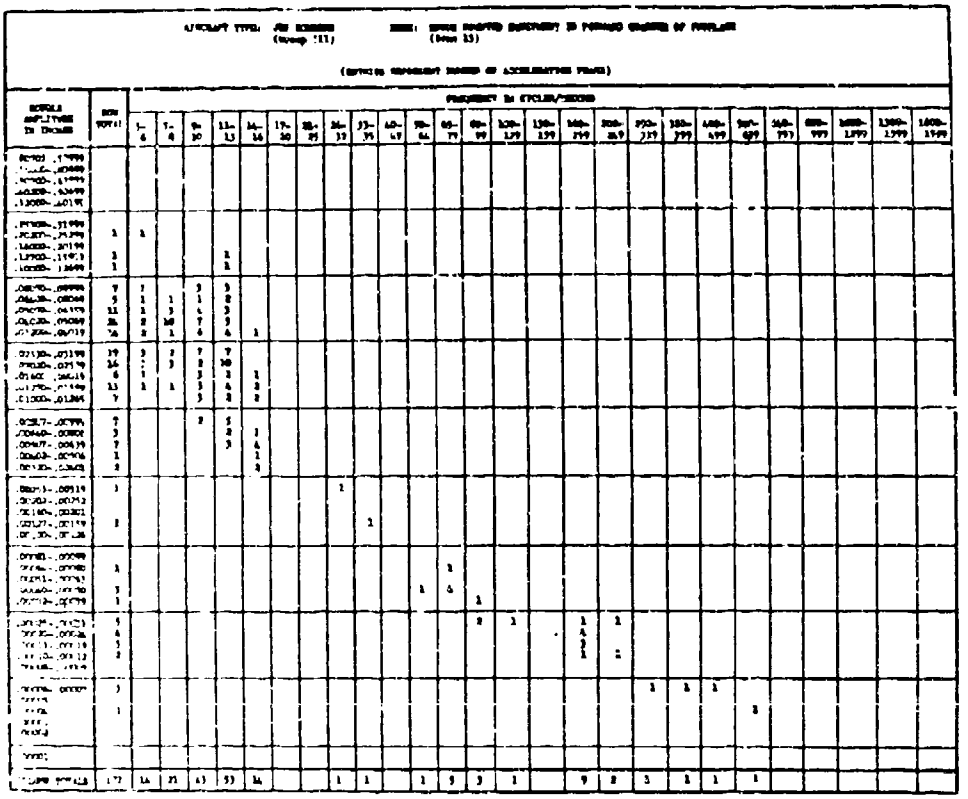


Chart 2. Vibration Environment At Various Locations on Jet Bombers (continued)



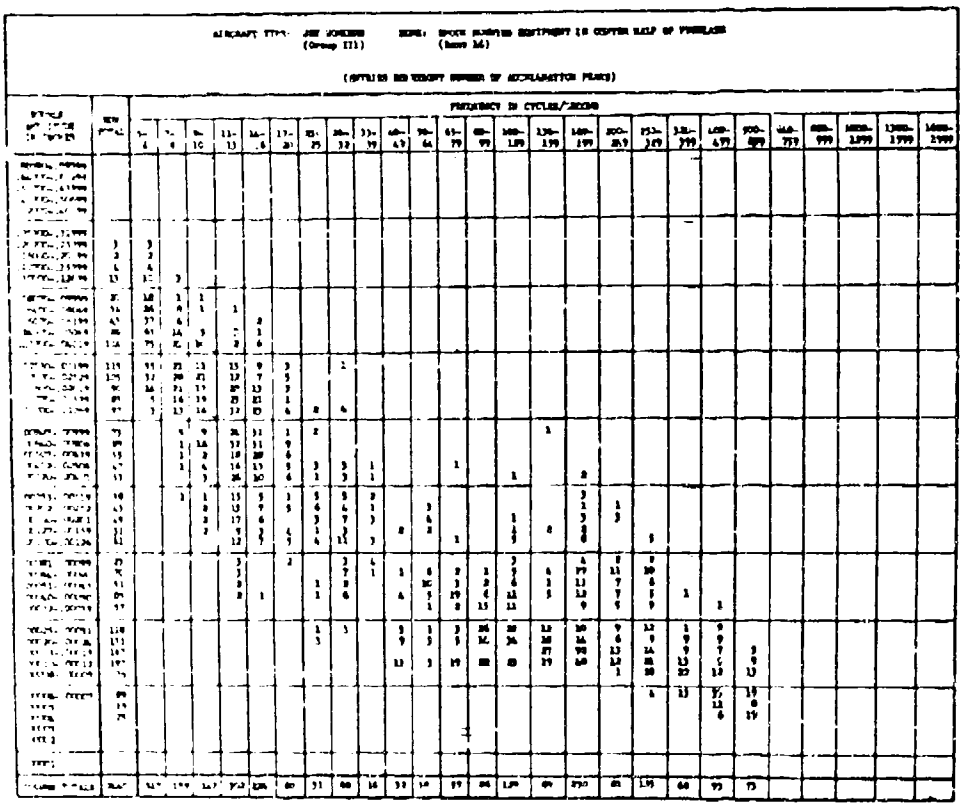
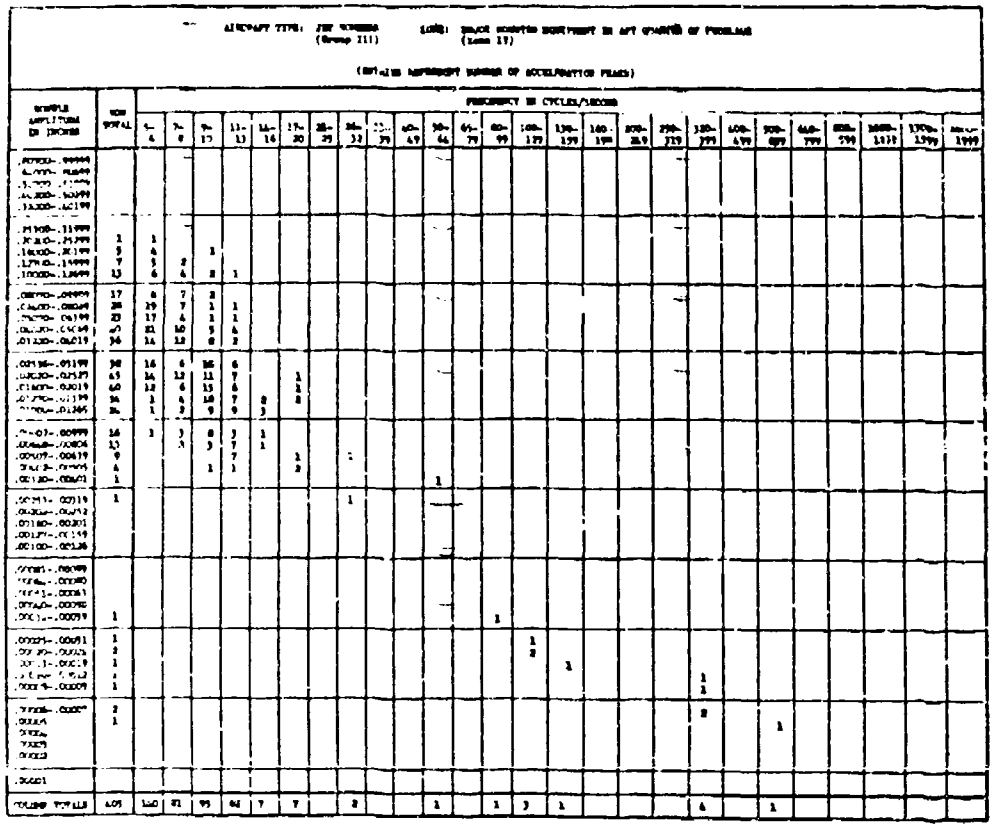


Chart 2. Vibration Environment At Various Locations on Jet Bombers (continued)



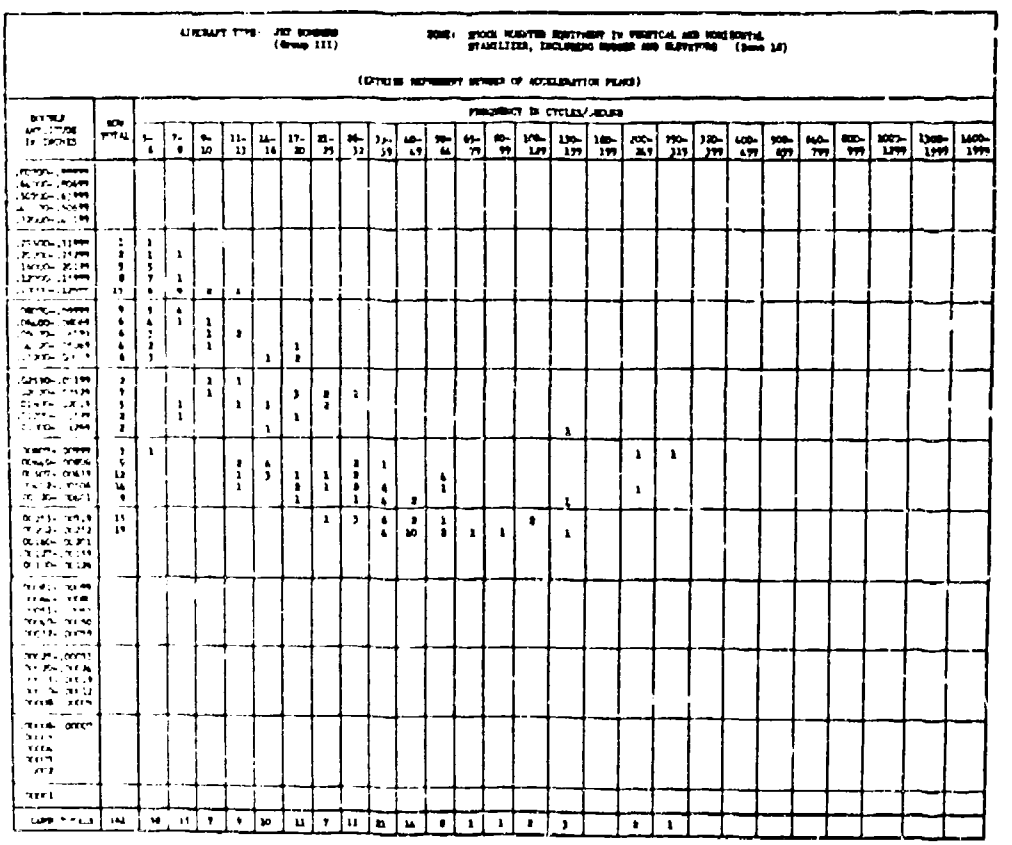
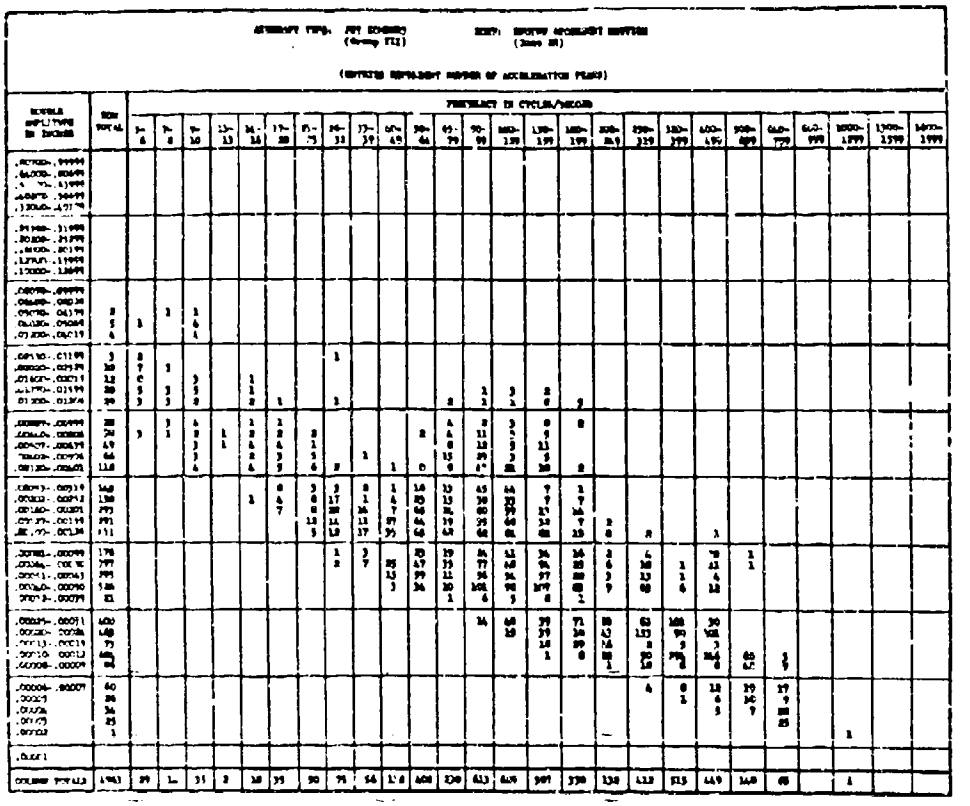


Chart 2. Vibration Environment At Various Locations on Jet Bombers (continued)



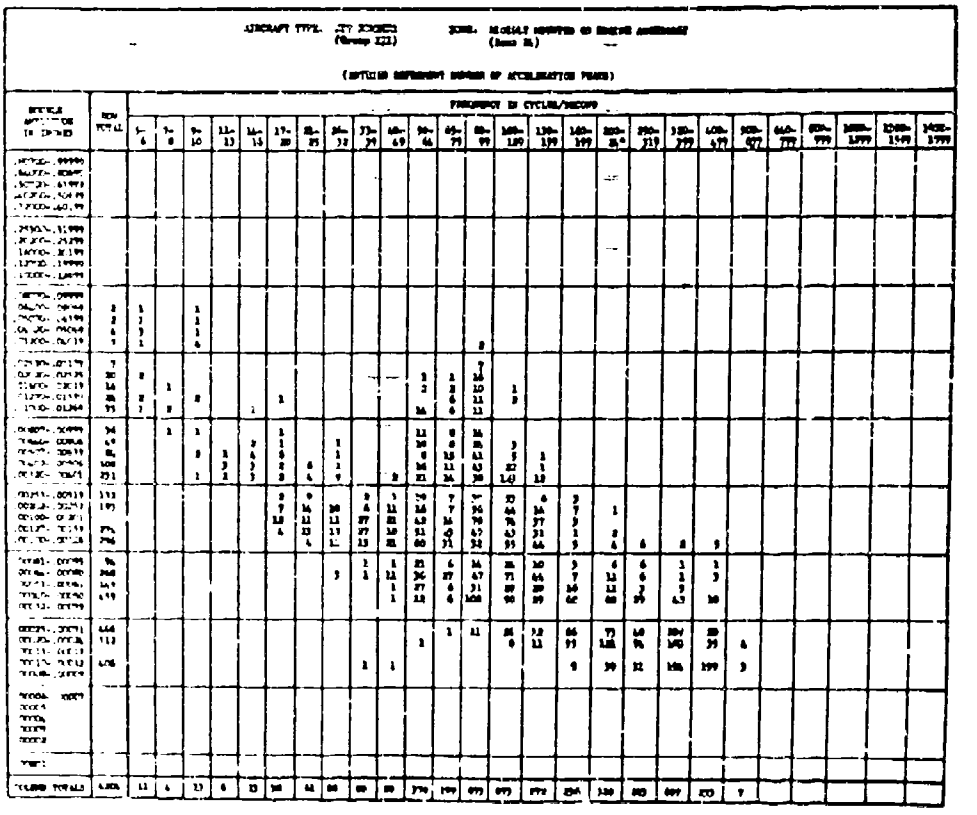
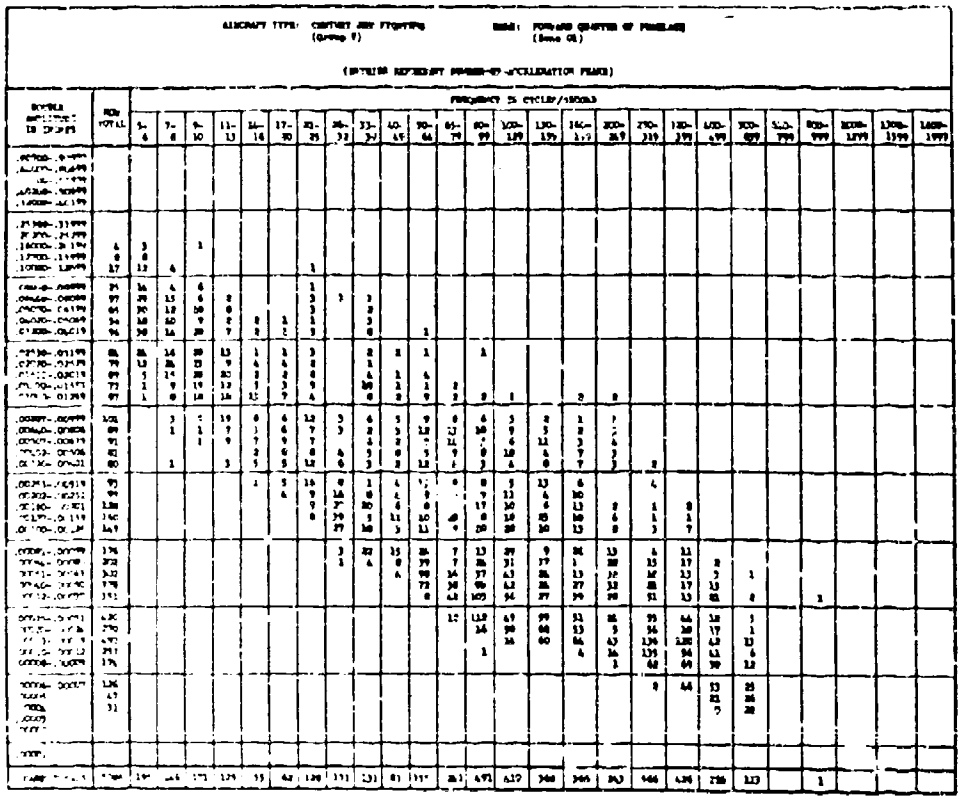


Chart 3. Vibration Environment At Various Locations on Century Jet Fighters



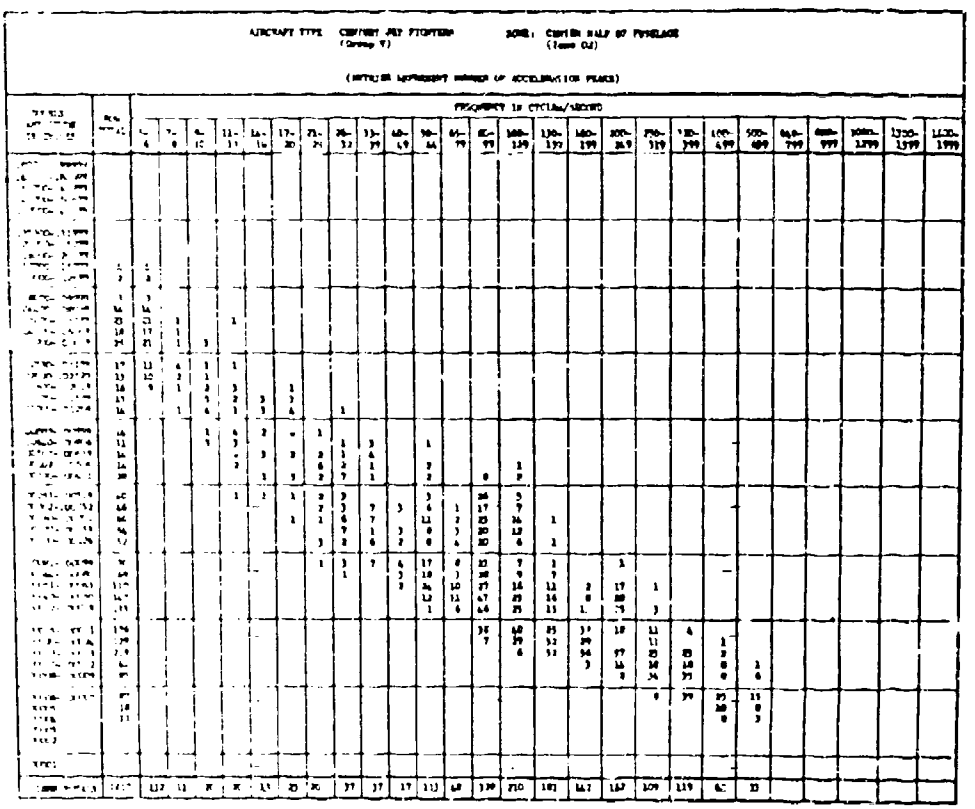
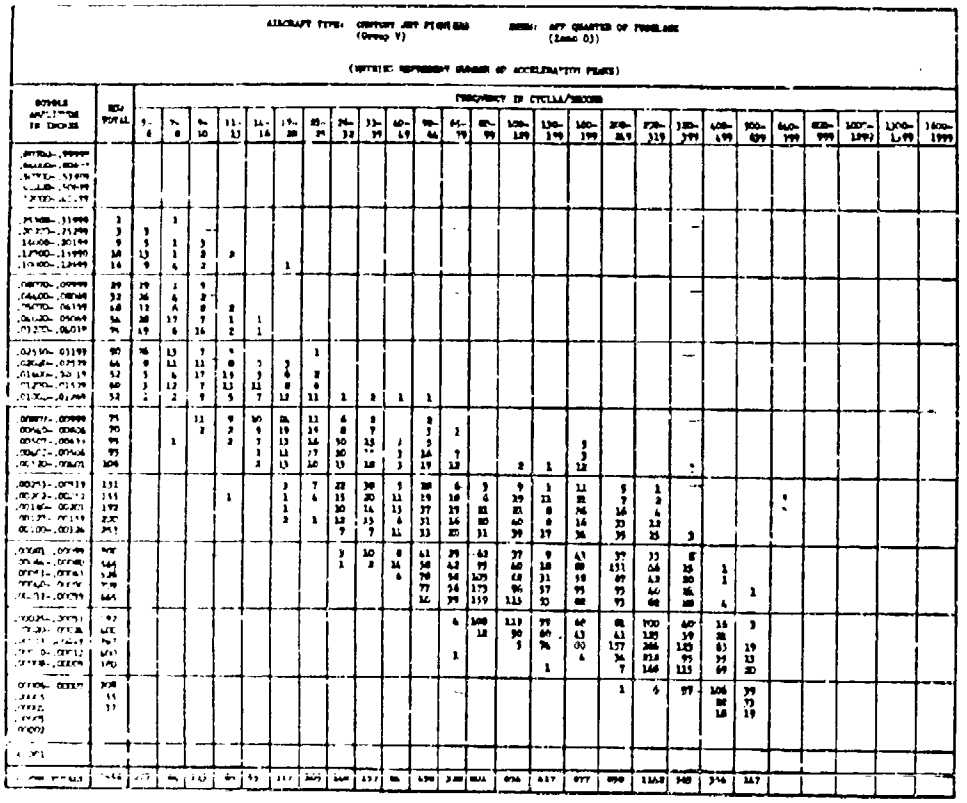


Chart 3. Vibration Environment At Various Locations on Century Jet Fighters (continued)



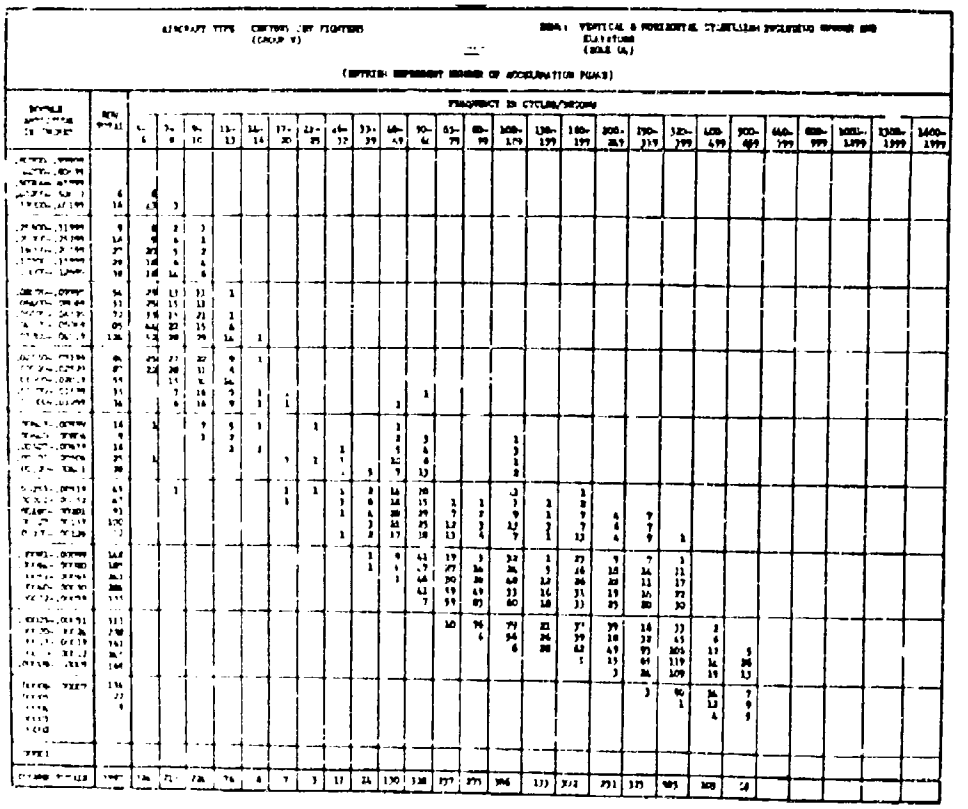
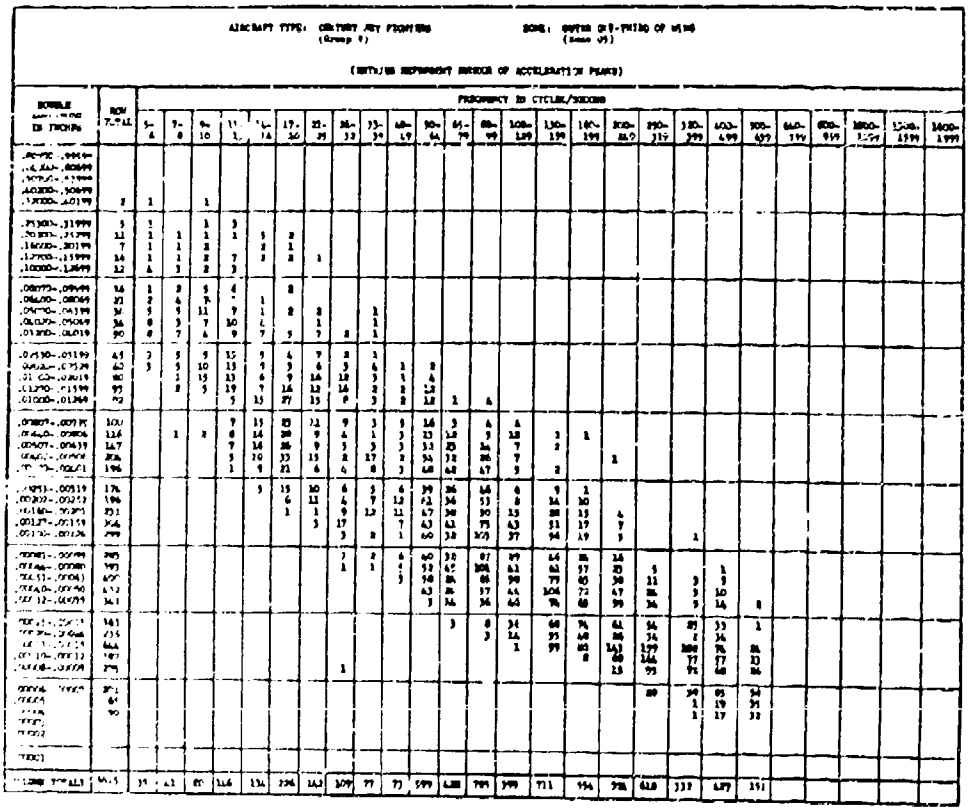


Chart 3. Vibration Environment At Various Locations on Century Jet Fighters (continued)



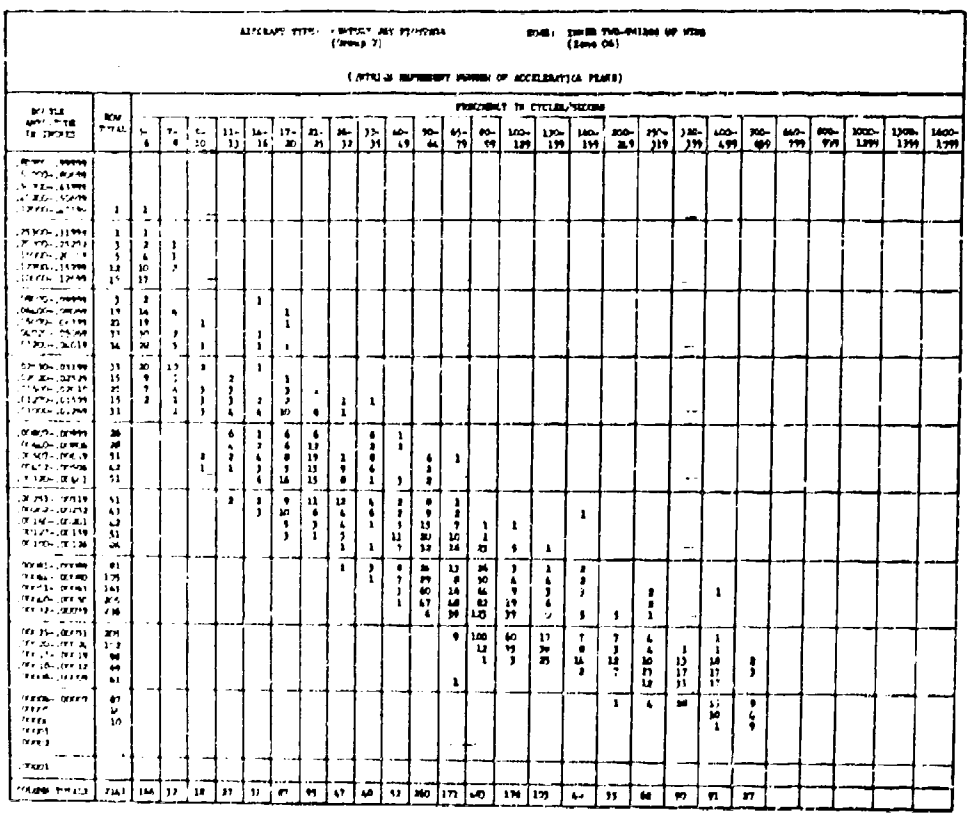
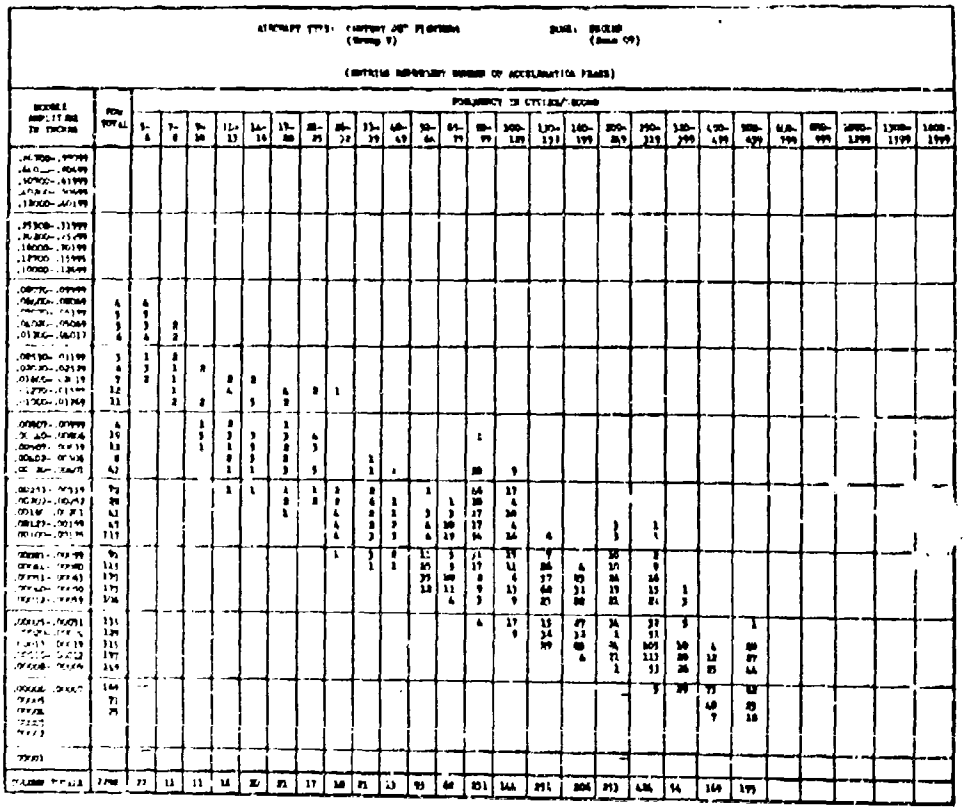


Chart 3. Vibration Environment At Various Locations on Century Jet Fighters (continued)



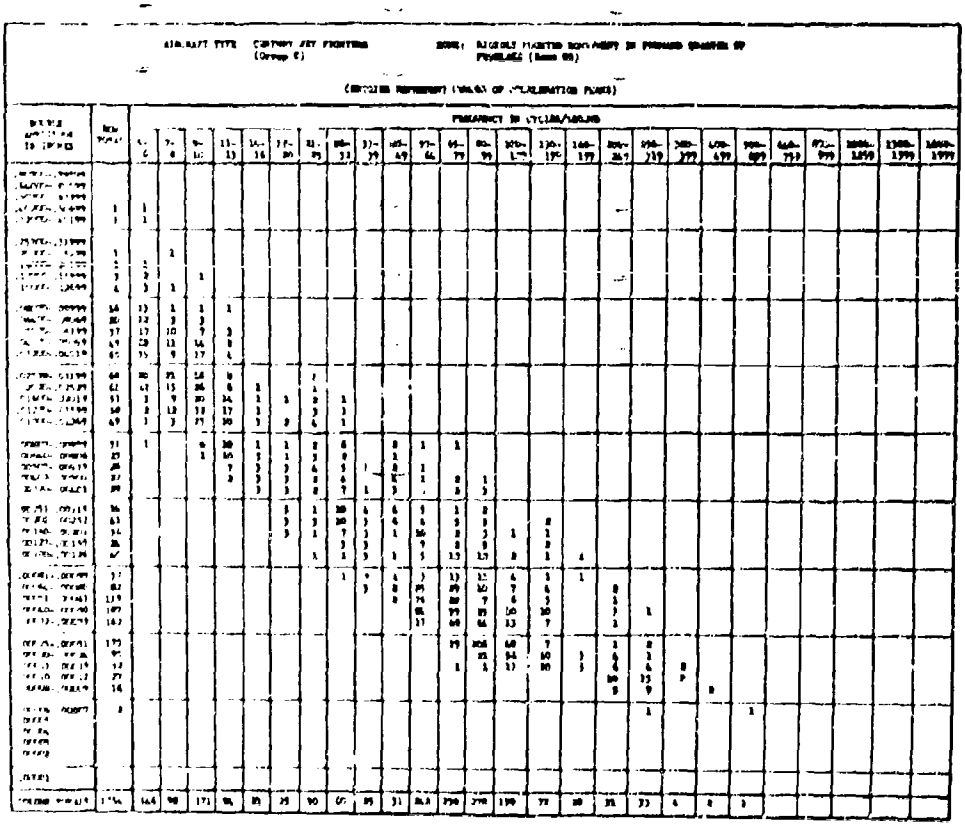
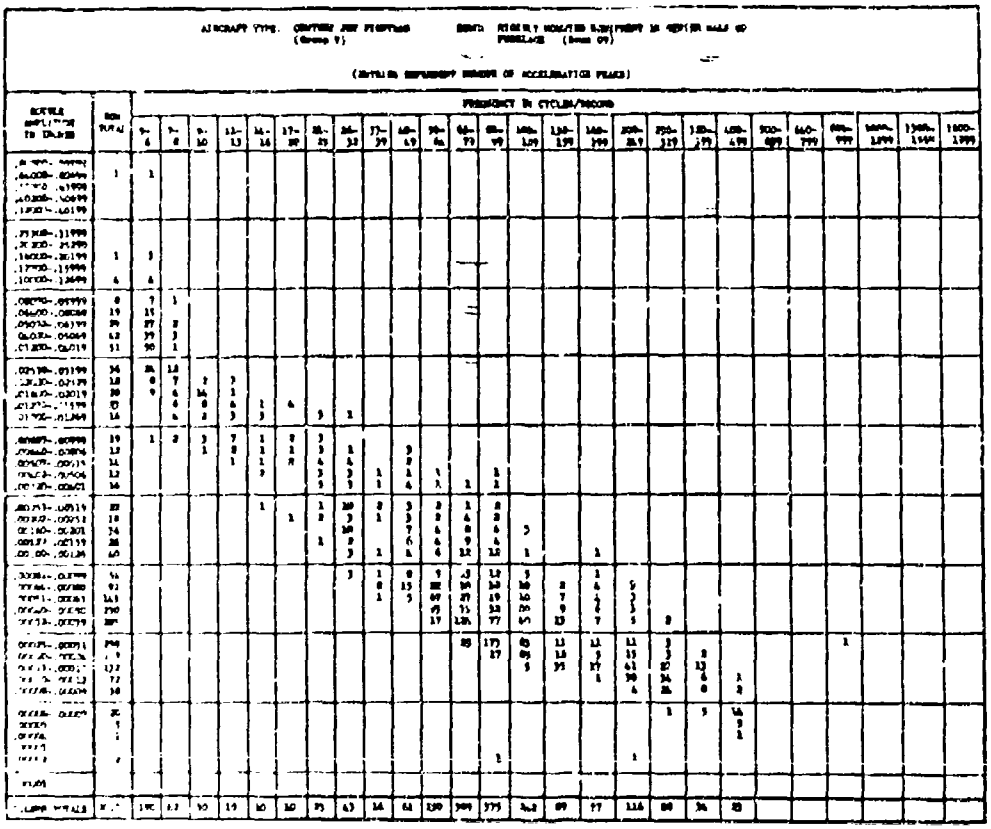


Chart 3. Vibration Environment At Various Locations on Century Jet Fighters (continued)



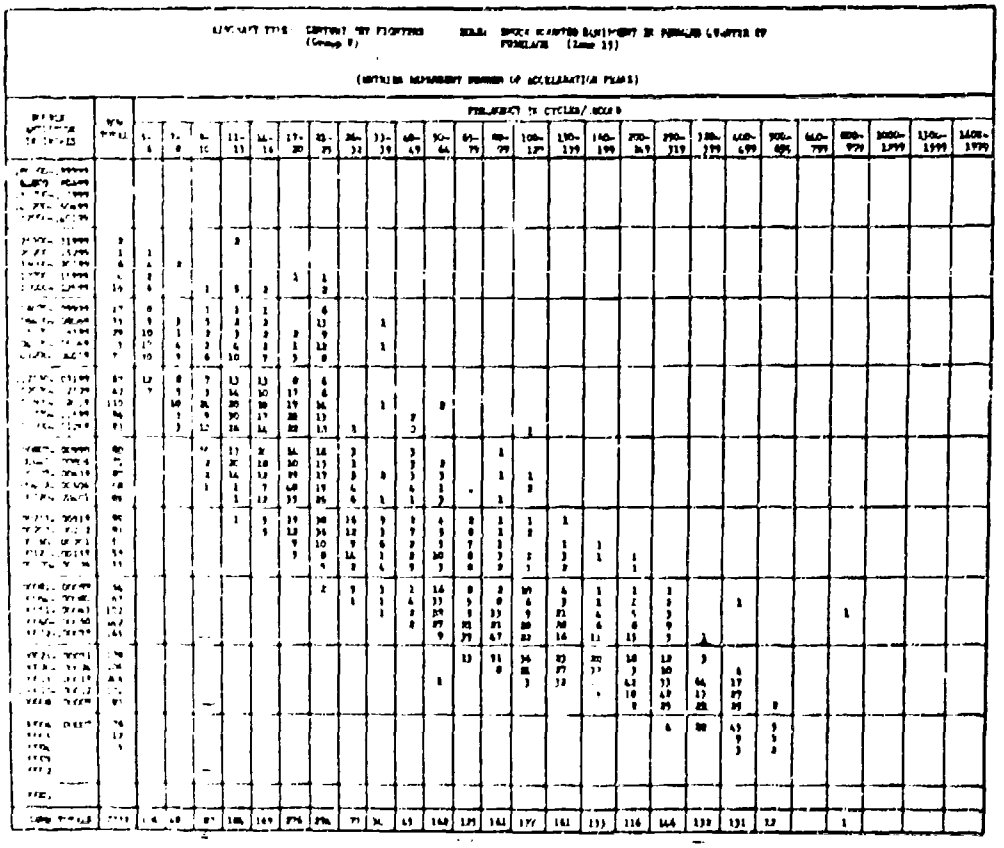
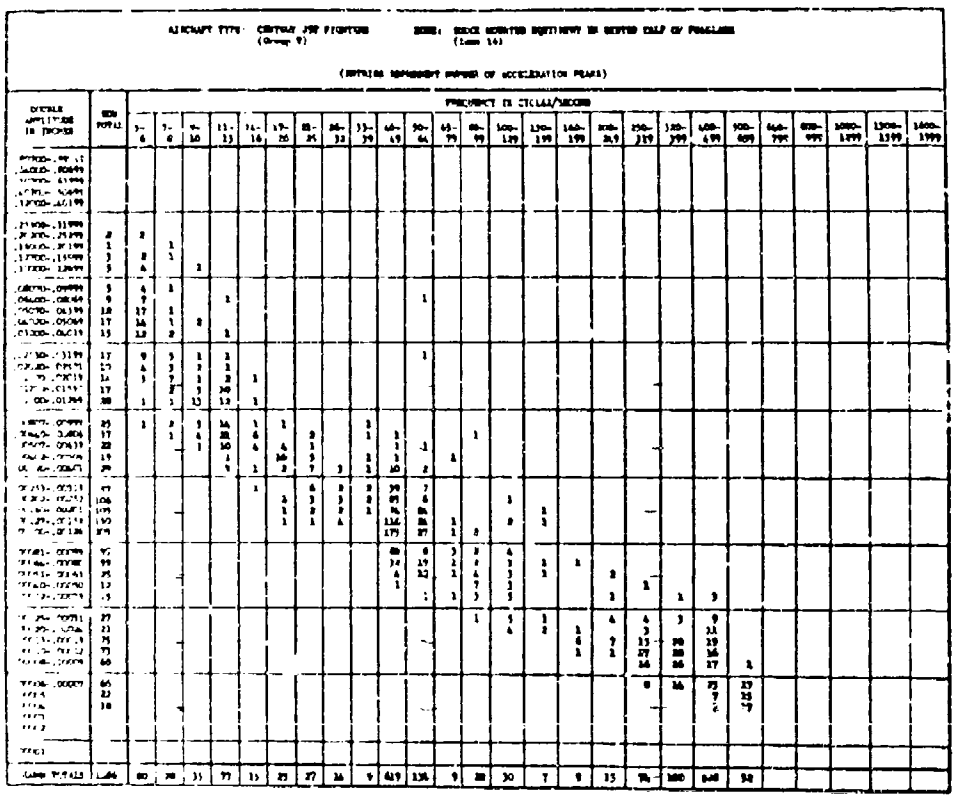


Chart 3. Vibration Environment At Various Locations on Century Jet Fighters (continued)



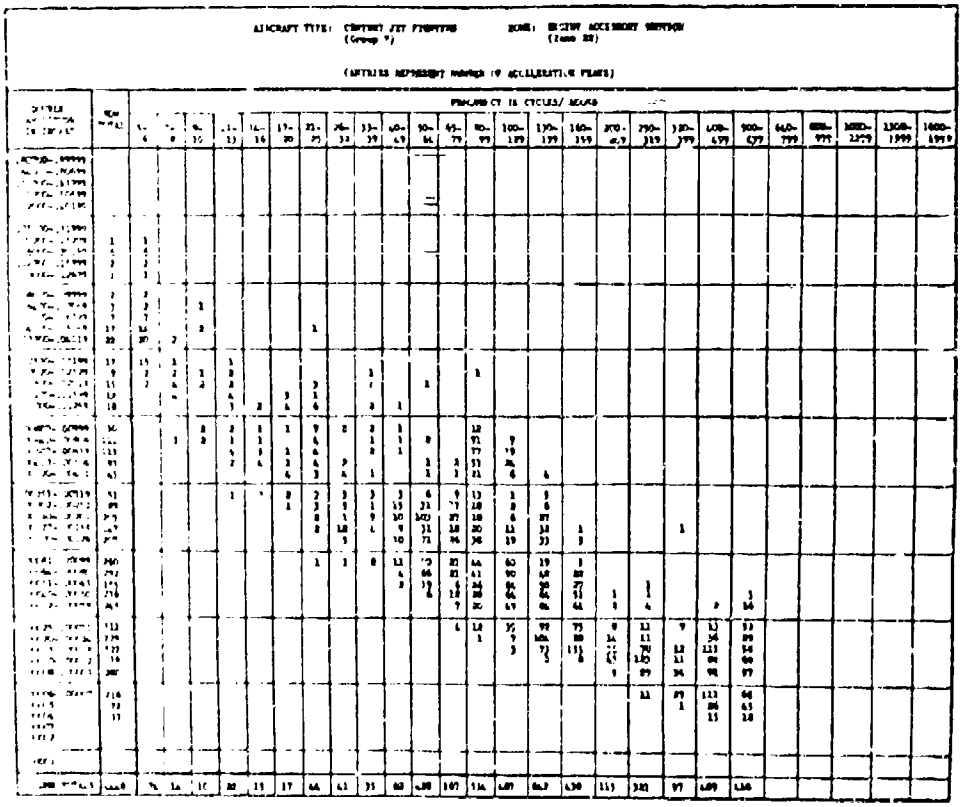


Chart 3. Vibration Environment At Various Locations on Century Jet Fighters (continued)

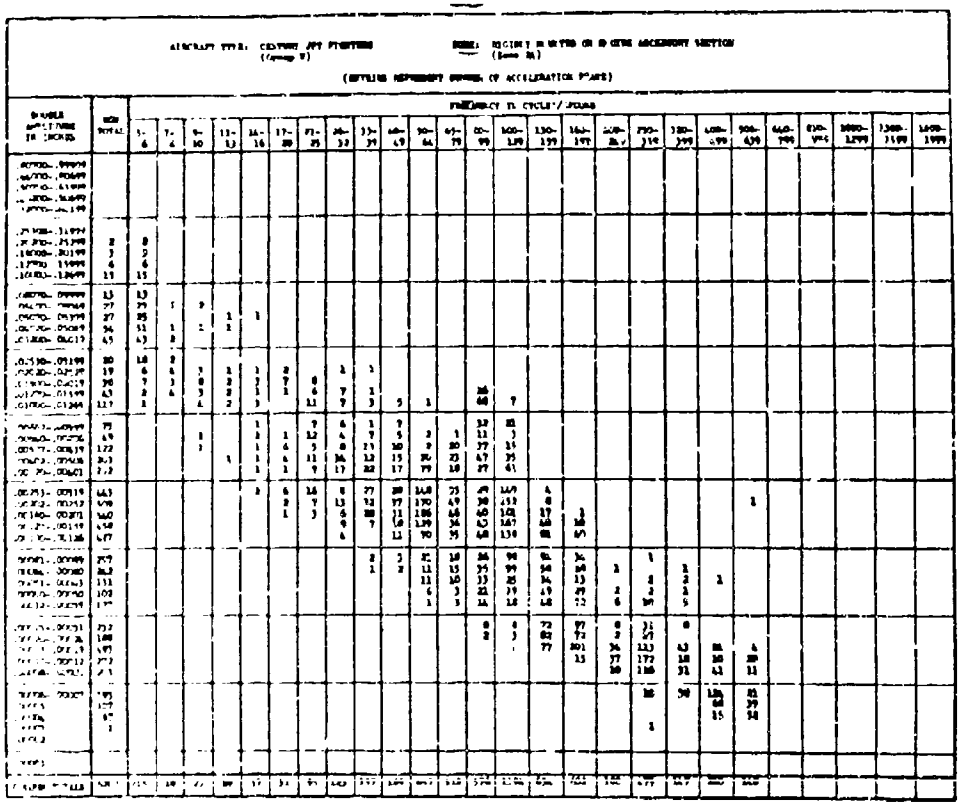
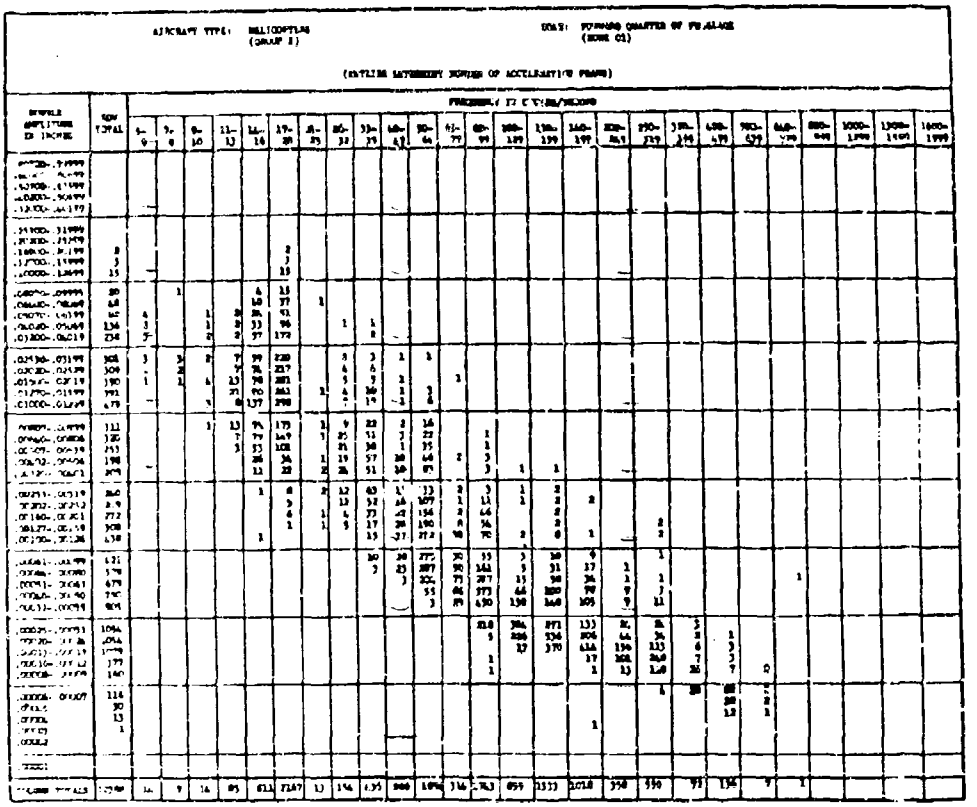


Chart 4. Vibration Environment At Various Locations on Helicopters



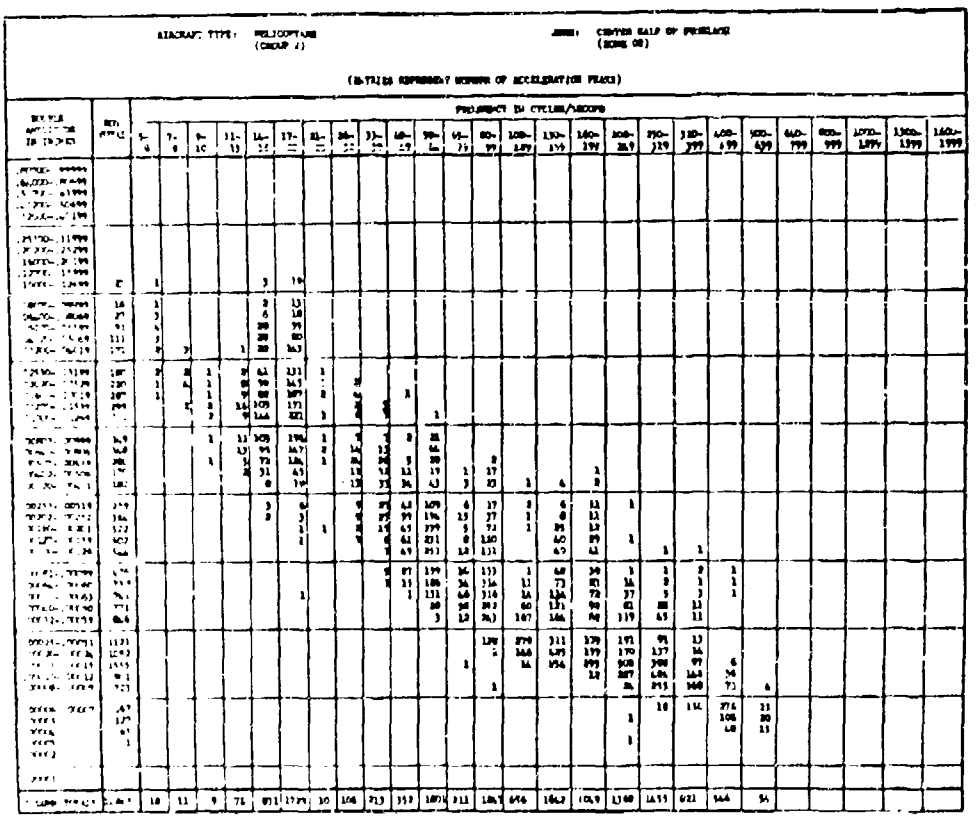
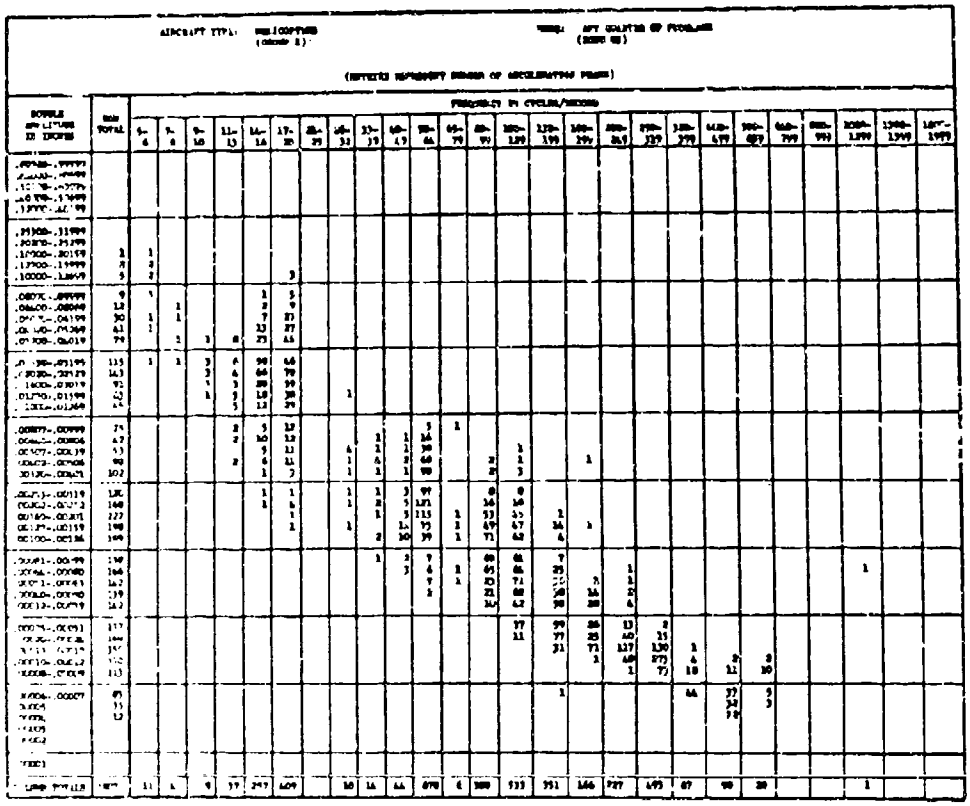


Chart 4. Vibration Environment At Various Locations on Helicopters (continued)



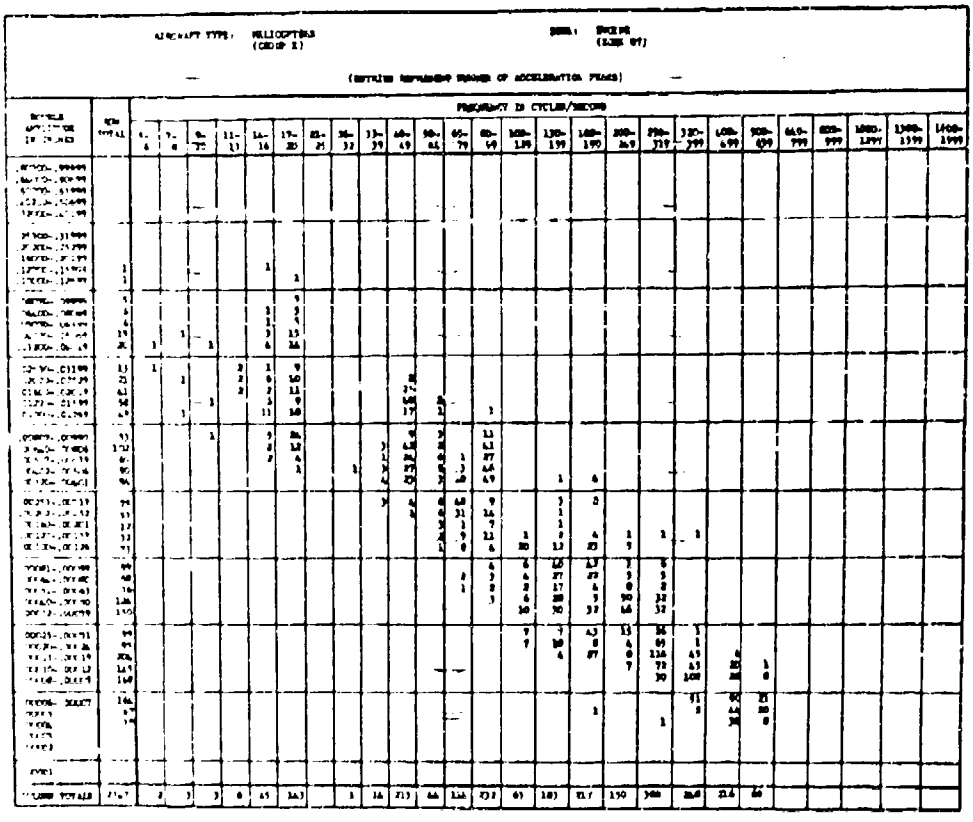
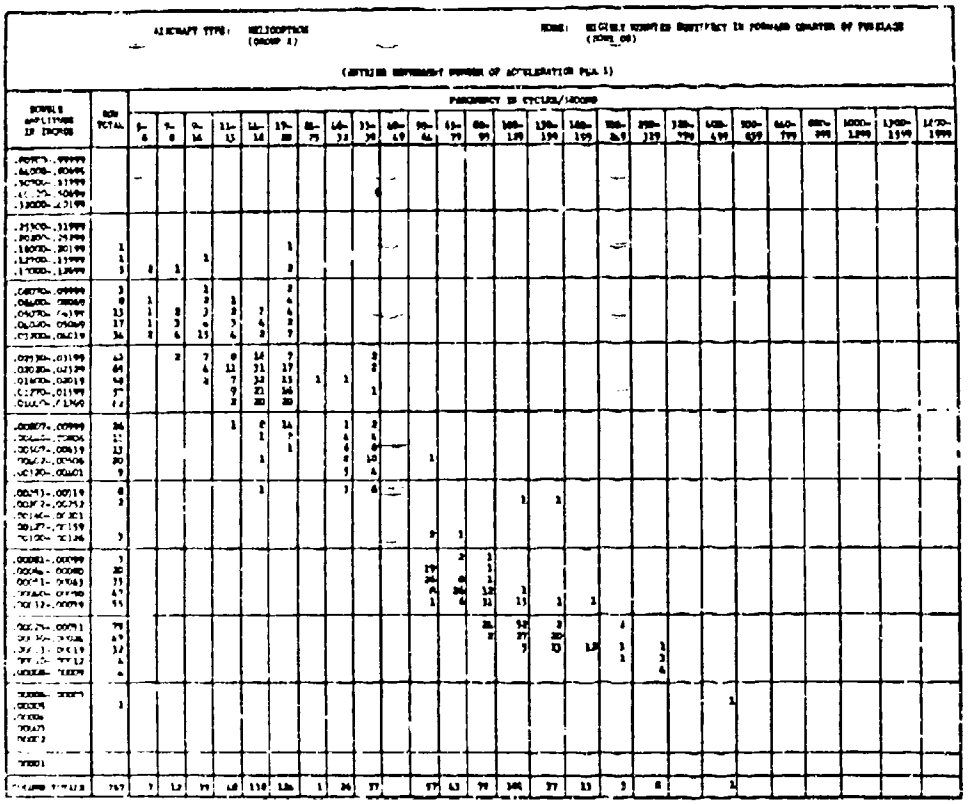


Chart 4.—Vibration Environment At Various Locations on Helicopters (continued)



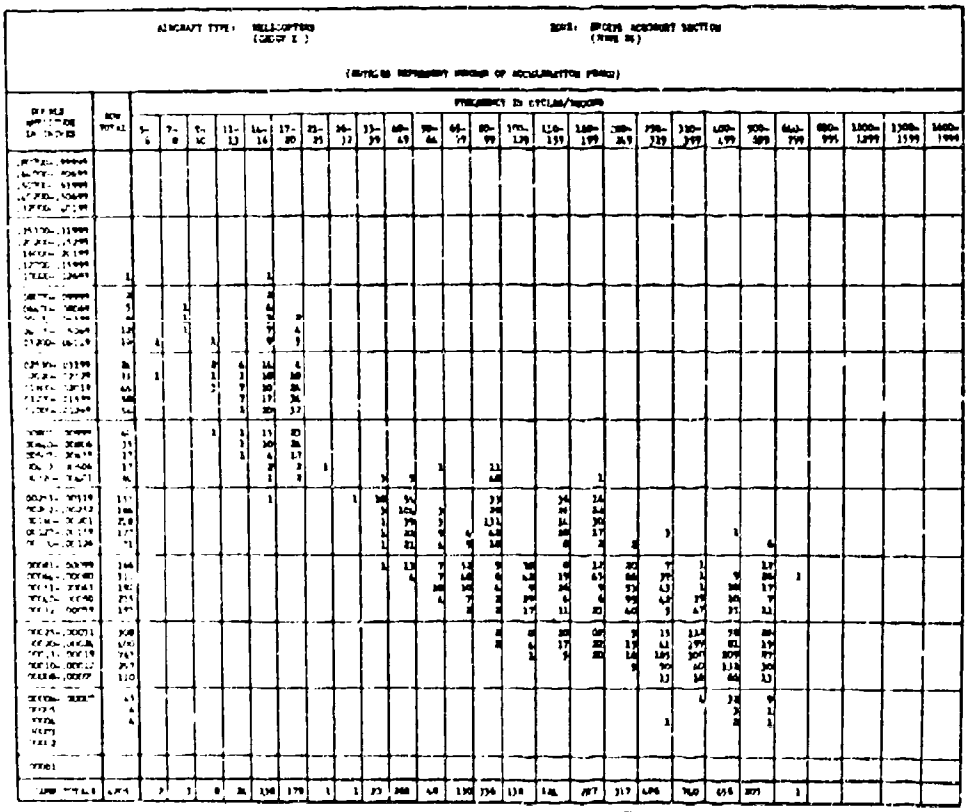
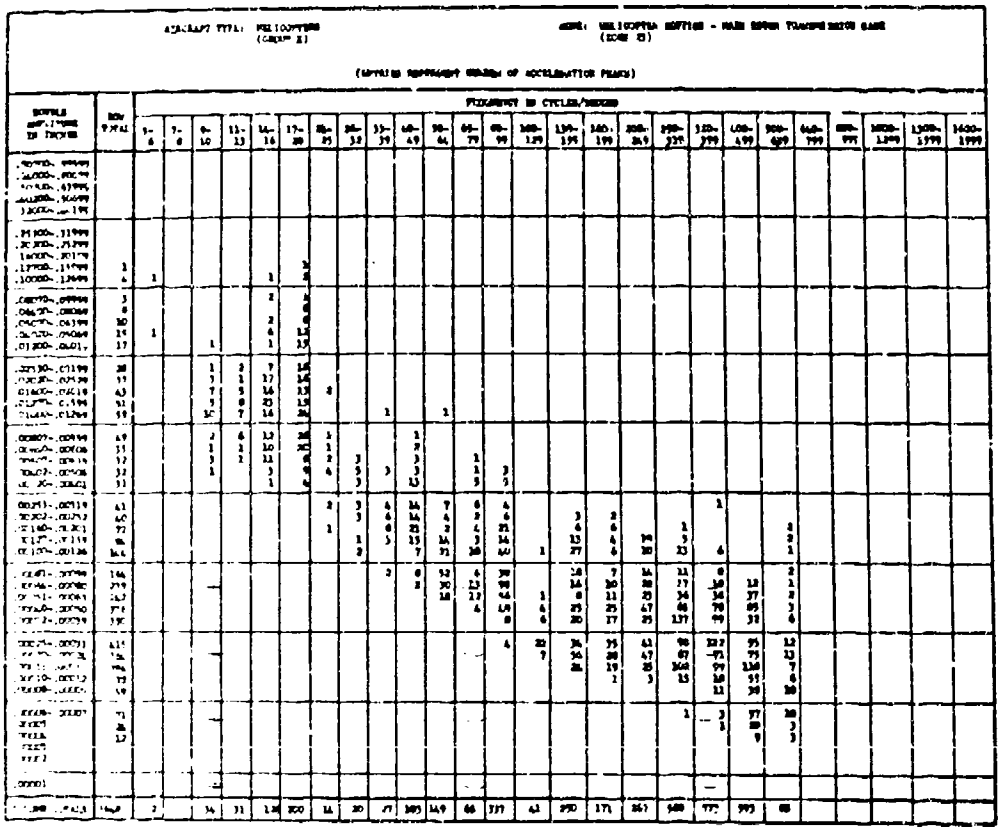


Chart 4. Vibration Environment At Various Locations on Helicopters (continued)



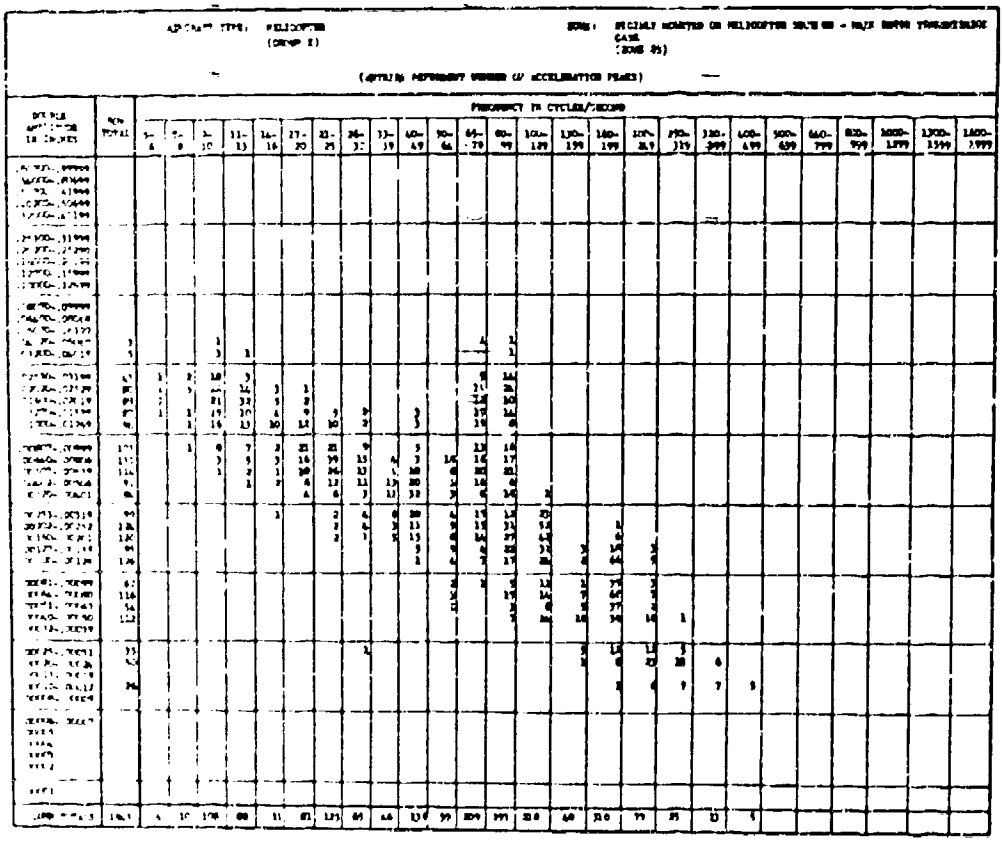
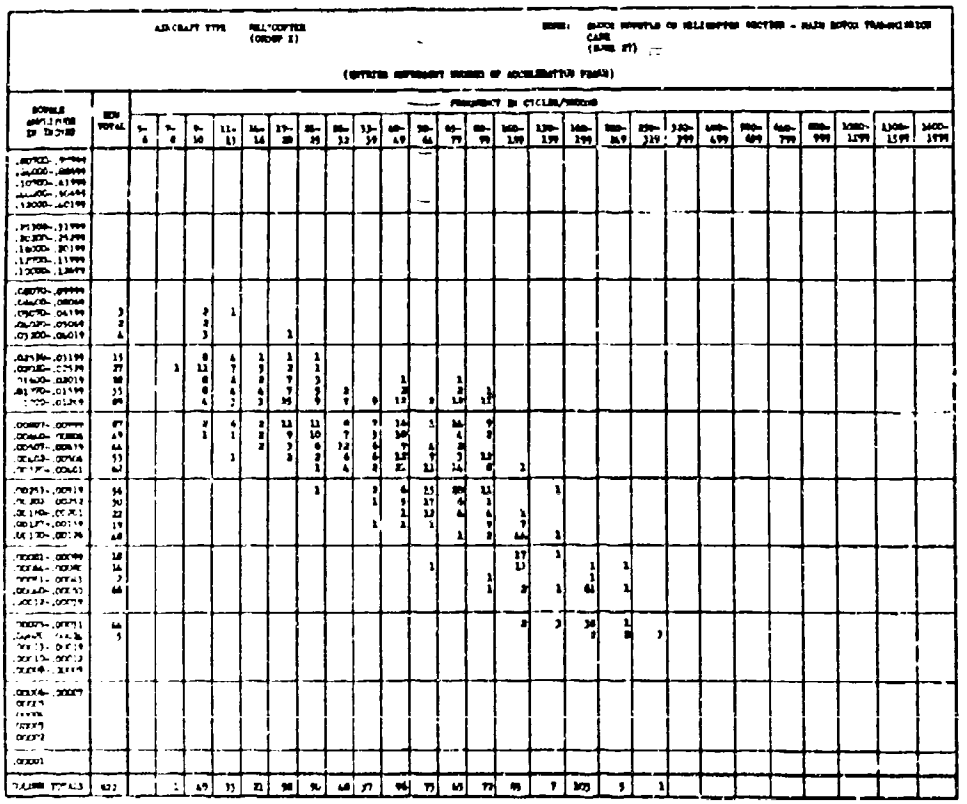


Chart 4. Vibration Environment At Various Locations on Helicopters (continued)



REFERENCES

1. Trewartha, G. T., An Introduction to Climate, McGraw-Hill Book Co., 1954.

2. Grimm, J. R., Effect of Desert Environment on B-47B Aircraft Compartment Temperatures, WADC TN WCSPE 53-13, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1953.

3. Riley, Frank, C. Jr., and Paul F. Walker, Temperature Criteria for Aircraft and Airborne Equipment, Booz, Allen and Hamilton, WADC TN 55-96, Contract No. AF 33 (616)-2089, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

4. Greathouse, Glenn A. and Carl J. Wessel, Deterioration of Materials, Reinhold Publishing Corporation, 1954.

5. Electronic Components Handbook, Vols, 1, 2 and 3, McGraw-Hill Book Co., 1957.

6. Abstract of Effect of Temperature on Guided Missile Systems, Booz, Allen and Hamilton, AF TR 53-124, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1953.

7. Hopkinson, K., "Effects of Ambient Temperature on Electron Tubes," IRE Transactions on Reliability and Quality Control, July 1959.

8. Di Taranto, R. A. and J. J. Lamb, Preliminary Investigation of Hyper Environments and Methods of Simulation, Radio Corporation of America, WADC TR 57-456, Part 1, ASTIA Document No. AD-142002, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, July 1957.

9. C. Gazley, Jr., W. W. Kellogg and E. H. Vestine, Space Vehicle Environment, Report P-1335, the Rand Corporation, Santa Monica, California, 7 July 1958.

10. Bershader, D., "Laboratory Studies of Missile Reentry Aero-Thermodynamics," ISA Journal, Vol. 5, No. 11, November 1958.

11. Hoglund, R. and Dr. J. Thale, Recovery from a Satellitic Orbit, paper presented at semi-annual meeting of American Rocket Society, Los Angeles, California, 9-12 June 1958.

12. Schroeder, Fred E., Edward E. Towe, Phillip H. Lake and Robert L. Wunderman, Study of Equipment Cooling Systems, Aeronautical Accessories Laboratory, WADC TR 59-253, Contract No. AF 33 (616)-5784, Task No. 61221, Project No. 8(15-6146), U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, November 1959.

13. Barbiere, Robert E. and Wayne Hall, Electronic Designers Shock and Vibration Guide for Airborne Applications, WADC TR 58-363, ASTIA Document No. AD 204-095, RCA Service Company, Contract No. AF 33 (616)-3257, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1958.

14. DOD Guided Missile Packaging Handbook, RD 219/3, July 1955.

15. Roehm, J. M., Paper No. 52-SA-41, presented at semi-annual meeting of American Society of Mechanical Engineers, Cincinnati, Ohio, 15 June 1952.

16. Rogers, O. R. and R. F. Cook, Environmental Aspects of Sonic Fatigue, WADC TN 57-58, ASTIA Document No. AD 118C-72, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, February 1957.

17. Eldred, Kenneth M. and Demos T. Kyrazis, 1/Lt., USAF. Noise Characteristics of Air Force Turbojet Aircraft WADC TN 56-280, ASTIA Document No. AD110680, Aero Medical Laboratory, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1956.

18. Crede, Charles E. and Edward J. Lunney, Establishment of Vibration and Shock Tests for Missile Electronics as Derived from the Measured Environment, WADC TR 56-503, ASTIA Document No. 118133, Electronic Components Laboratory, Contract No. AF 33(616)-2188, Task No. 41772, Project No. 4148, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1 December 1956.

19. Clevenson, Sherman A. and George W. Brooks, Considerations of Vibration Environments In Space & Flight Systems, paper presented at annual meeting of Institute of Environmental Sciences, Los Angeles, California, 6, 7, 8, April 1960.

20. Jacobson, R. H., Vibration and Shock Evaluation of Airborne Electronic Component Parts and Equipments, WADC TR 56-301, Armour Research Foundation, Contract No. AF 33(616)-233, Electric Components Laboratory, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1956.

21. Abstract of Effects of Vibration, Shock and Acceleration on Guided Missile Systems, Booz, Allen and Hamilton, AF Technical Report 53-124, Appendix D, June 1953.

REFERENCES (continued)

22. Riley, C. Frank, and Paul F. Walker, Moisture Criteria for Aircraft and Airborne Equipment, WADC TN 55-97, Booz Allen and Hamilton, Contract No. AF 33(616)-2689, Project No. 1111, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

23. Abstract of Effect of Moisture on Guided Missile Systems, Booz, Allen and Hamilton, AF Technical Report 53-124, Appendix B, June 1953.

24. Henney, Keith and Craig Walsh, Electronic Components Handbook Vol. 1, McGraw-Hill Book Co., Inc., 1957.

25. Maron, William, Temperature-Humidity Tests, United States Testing Company, Inc., for Signal Corps Engineering Laboratories, Contract No. DA-36-039 SC-63088, File No. 218-PH-54-91 (3430), 1 July 1954 - 30 June 1957.

26. Henney, Keith and Craig Walsh, Electronic Components Handbook, Vol. 2, McGraw-Hill Book Co., Inc., 1958.

27. Henney, Keith, Craig Walsh and Harry Mileaf, Electronic Components Handbook, Vol. 3, McGraw-Hill Book Co., Inc., 1959.

28. Arthur, Gilbert Jr., Hail as a Flight Hazard, Environmental Criteria Branch, Directorate of Laboratories, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 22 April 1959.

29. Jailer, Robert W., Potential Aircraft Icing Probabilities in the Northern Hemisphere, WADC TR 56-659, ASTIA Document No. AD 110676, American Power Jet Company, Contract No. AF 33(616)-2605, Project No. 1111, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, November 1956.

30. Pauly, James, The Dust Environment and Its Effect on Dust Penetration, WADC TR 56-556, ASTIA Document No. AD110472, Southwest Research Institute, Contract No. AF 33(616)-3280, Project No. 1111, Task 11115, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

31. Clower, J. I., "Oil Filters in Public Utility Fleet Operation", SAE Journal, Vol. 41, No. 2, September 1937.

32. Kayse, J. R., "Graphical Selector for Air Cleaners", Heating and Ventilating, Vol. 50, No. 7, July 1953.

33. Abstract of Effects of Sand and Dust on Guided Missile Systems, Booz, Allen and Hamilton, AF Technical Report 53-124, Appendix F, June 1953.

34. Riley, F. C., Jr. and P. F. Walker, Atmospheric Pressure Criteria for Aircraft and Airborne Equipment, Booz, Allen and Hamilton, WADC TN 55-98, Directorate of Laboratories, Contract No. AF 33(616)-2689, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

35. Lopatin, I. and H. Mileaf, Design Factors for Aircraft Electronic Equipment, Technical Writing Service, McGraw-Hill Book Company, WADC TR 56-148, ASTIA Document No. AD 142204, Aerial Reconnaissance Laboratory, Contract No. AF 30(635)-2844, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1956.

36. Abstract of Effects of Atmospheric Pressures on Guided Missile Systems, Appendix O, Booz, Allen and Hamilton, AF TR 53-124, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1 June 1953.

37. Riley, F. C., Jr. and P. F. Walker, Atmospheric Contaminant, Radiation, and Electricity Criteria for Aircraft and Airborne Equipment, Booz, Allen and Hamilton, WADC TN 55-118, ASTIA Document No. AD92498, Directorate of Laboratories, Contract No. AF 33(615)-2689, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

38. Babicz, D. J., Determining the Effect of Pressure, Humidity, Temperature, Fuel/Air Ratio on the Explosiveness of the Atmosphere, Inland Testing Laboratories, Division of Cook Electric Company, WADC TR 56-5, ASTIA Document No. AD 90043, Directorate of Development, Contract No. AF 33(616)-2691, Project 1111, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1955.

39. Abstract of Effects of Atmospheric Pressure on Guided Missile Systems, Appendix G, Booz, Allen, and Hamilton, AF TR 53-124, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1 June 1953.

40. Saletan, D. I., "Static Electricity Hazards", Chemical Engineering, 1 June 1959.

41. Merrill, G., Missile Engineering Handbook, D. Van Nostrand Company, Inc., Princeton, N. J., 1958.

42. Singer, S. F., The Effect of Meteoric Particles on a Satellite, University of Maryland, Physics Department, College Park, Maryland, Physics Department Technical Report No. 41, ASTIA No. AD 102634, May 1956.

43. Hoenig, S. A., "Meteoric Dust Erosion Problem and its Effect on the Earth Satellite," Aeronautical Engineering Review, July 1957.

44. Space Handbook: Astronautics and its Applications, Staff Report of the Select Committee on Astronautics and Space Exploration, U.S. Government Printing Office, Washington, D. C., December 1958.

45. McCoy, T. M., The Hyper Environments and Their Significance, Northrop Corporation.

46. Draxner, A. H., "Cosmic-Ray Effects and Transistors," Military Electronics, 3:24-27, July 1958.

47. Broadway, N. J., M. A. Youtz, M. L. Zaring and S. Palinchak, The Effects of Nuclear Radiation on Elastomeric and Plastic Materials, REIC Report No. 3, ASTIA Document No. AD 149552, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 31 May 1958.

48. Broadway, N. J. and S. Palinchak, The Effect of Nuclear Radiation on Elastomeric and Plastic Materials, First Addendum, REIC Report No. 3 (Addendum), ASTIA Document No. AD 210759, Battelle Memorial Institute, Columbus 1, Ohio, 31 May 1959.

49. Reinsmith, G., "Nuclear Radiation Effects on Materials," ASTM Bulletin, September 1958.

50. Leininger, R. I., The Effect of Nuclear Radiation on Fluorinated Elastomers in Different Environments, REIC Memorandum No. 1, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Project No. 2133, Task No. 60001, 31 October 1957.

51. Broadway, N. J. and S. Palinchak, The Effect of Nuclear Radiation on Fluoroelastomers, REIC Memorandum No. 17, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-6564, Continuation of AF 33(616)-5171, Task No. 60001, Project No. 2133, 30 June 1959.

52. Javitz, A. E., "Impact of High-Energy Radiation on Dielectrics," Electrical Manufacturing, June 1955.

53. Broadway, N. J., The Effects of Nuclear Radiation on Metallo-Organic Compounds and on Polyethylene, REIC Memorandum No. 3, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33 (616)-5171, Project No. 2133, Task No. 60001, 15 February 1958.

54. Wyant, R. E., The Effect of Nuclear Radiation on Organic Heat-Transfer Materials, REIC Memorandum 13, Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, 28 February 1959.

55. Allen, B. C., A. K. Wolff, A. R. Elsea and P. D. Frost, The Effect of Nuclear Radiation on Structural Metals, REIC Report No. 5, ASTIA Document No. AD 157170, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 31 May 1958.

56. Riley, W. C., W. G. Copping and W. H. Duckworth, The Effect of Nuclear Radiation on Glass, REIC Memorandum No. 9, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33 (616)-5171, Task No. 60001, Project No. 2133, 30 November 1958.

57. Wieder, H. H., Performance of Solid State Materials and Devices Subject to a Nuclear Radiation Flux, NAVORD Report 374, ASTIA Document No. AD 143467, Research Department, U.S. Naval Ordnance Laboratory, Corona, California, 6 August 1957.

58. Reid, F. J. and J. W. Moody, The Effect of Nuclear Radiation on Magnetic Materials, REIC Memorandum No. 12, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Project No. 2133, Task No. 60001, 31 December 1958.

59. Moody, J. W., The Effect of Nuclear Radiation on Electrical Insulating Materials, REIC Memorandum No. 14, Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, 31 March 1959.

REFERENCES (continued)

60. Lamale, G. E. and P. Schall, Electrical Leakage in Insulators Exposed to a Nuclear Environment, REIC Memorandum No. 2, Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Project No. 2133, Task No. 60001, 15 January 1958.

61. Harsen, J. F., Effect of Nuclear Radiation on Electronic Transformers and Transformer Materials, REIC Memorandum No. 7, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 30 November 1958.

62. Hansen, J. F., S. E. Harrison and W. L. Hood, The Effect of Nuclear Radiation on Electronic Components and Systems, REIC Report No. 2, ASTIA Document No. AD 149551, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Project No. 2133, Task No. 60001, 31 December 1957.

63. Dvorak, H. R., "Radiation Environments," Space Aeronautics, December 1958.

64. Robinson, C. C., "Nuclear Effects on Electronic Components," Electrical Manufacturing, August 1956.

65. Effects of Ionizing Radiation on Certain Materials: Final Summarizing Report, ASTIA Document No. AD 42185, The Sarah Mellon Scaife Radiation Laboratory, University of Pittsburgh, Pittsburgh, Pennsylvania, Contract No. DA 18-108-CML-3429, Project No. 4-12-30-002, March 1954.

66. Broadway, N. J. and S. Palinchak, The Effects of Nuclear Radiation on Seals, Gaskets and Sealouts, REIC Memorandum No. 8, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 30 November 1958.

67. Schroeder, M. C., The Effects of Nuclear Radiation on Hoses and Couplings, REIC Memorandum No. 13, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 31 March 1959.

68. Cosgrove, S. L., The Effect of Nuclear Radiation on Lubricants and Hydraulic Fluids, REIC Report No. 4, ASTIA Document No. AD 154432, The Radiation Effects Information Center, Batelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 30 April 1958.

69. Cosgrove, S. L., The Effect of Nuclear Radiation on Lubricants and Hydraulic Fluids (First Addendum), REIC Report No. 4 (Addendum), ASTIA Document No. AD 210760, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(666)-5171, Task No. 60001, 31 March 1959.

70. Hillembrand, L. J., The Effect of Nuclear Radiation on Hydrocarbon Fuels, REIC Memorandum No. 11, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 30 November 1958.

71. Surosky, A. E., D. A. Hill and J. S. di Rende, Gravity-Zero Gravity--Environmental Continuum, Paper Delivered at Institute of Environment Engineers Convention in Chicago, April 1959.

72. Handbook of Geophysics, Geophysics Research Directorate, Air Force Cambridge Research Center, ARDC, U.S. Air Force, 1957.

73. Leary, F., "Communications of the Future," Electronics, 3 July 1959.

74. Bucheim, R. W., S. Herrick, E. H. Vestine and A. G. Wilson, "Some Aspects of Astronautics," IRE Transactions on Military Electronics, December 1958.

75. Swerling, P., "Space Communications," IRE Transactions on Military Electronics, December 1958.

76. McCoy, T. M., The Hyper Environments and their Significance, Northrop Corporation.

77. Arthur, Gilbert F., Investigation of the Concurrence of Natural Environmental Elements, Environmental Criteria Branch, Engineering Services Division, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1957.

78. Humphreys, W.J., Ways of Weather, 1944, Lancaster, Pa., pp. 295-296.

79. Development of Combined Environment Qualification Test Program for Air Force Equipment, Monthly Progress Report III, United States Testing Co., Inc., Contract AF 33 (616)-6315, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

80. Combined Environmental Testing Based upon Logistic and Mission Characteristics of Weapon Systems, Bell Aircraft Corporation, Report No. 9020-11-001, November 1957.

81. Handbook of Instructions for Aircraft Designers (HIAD) Volumes I, II and III, ARDCM 80-1, U. S. Air Force, Wright Patterson Air Force Base, Ohio.

82. Handbook of Instructions for Ground Equipment Designers (HIGED), ARDCM 80-5, U. S. Air Force, Wright-Patterson Air Force Base, Ohio.

83. Handbook of Instructions for Aircraft Ground Support Equipment Designers (HIAGSED), ARDCM80-6, U.S. Air Force, Wright Patterson Air Force Base, Ohio.

84. Rosenblith, W. A. and K. A. Stevens, Handbook of Acoustic Noise Control, Volume II, Noise and Man, Bolt, Beranek and Newman, WADC TR 52-2-4, ASTIA Document No. AD 18260, Aero Medical Laboratory. Contract No. AF 33(038)-20572, RDC No. 695-63, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1953.

85. Dole, S. H. Internal Environment of Manned Space Vehicles, RAND Corporation Report P-1309, 1700 Main Street, Santa Monica, California, 24 February 1958.

86. Bondurant, S., N. P. Clarke, W. G. Blanchard, H. Miller, R. R. Hessberg and E. P. Hiatt, Human Tolerance to some of the Accelerations Anticipated in Space Flight, WADC TR 58-156, ASTIA Document No. AD151172, Aero Medical Laboratory, Project No. 7216, Task No. 71712, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1958.

87. Schock, G. J. D., Sensory Reactions Related to Weightlessness and Their Implications to Space Flight, AFMDC TR 58-6, ASTIA Document No. AD 135012, Aeromedical Field Laboratory, Directorate of Research and Development Project No. 7851, U. S. Air Force, AFMDC, Holloman Air Force Base, New Mexico, April 1958.

88. Gerathewohl, S. J., "Medical Problems in Space, The Peculiar State of Weightlessness," Instructors Journal, ASTIA Document No. AD 156352, Published by the Air Training Command, Air University, USAF School of Aviation Medicine, Randolph Field, Texas, August 1959.

89. Houssay, B. A. and others, Human Physiology, McGraw-Hill Book Company, 2nd Edition, New York City, N.Y. 1955.

90. Schueller, Otto, Space Environment Facility for Life Support Systems, Aerospace Medical Laboratory, Wright-Patterson Air Force Base, Ohio, January 1960.

91. Brown, W. S., Jr., Physiological Hazard of Non-Ionizing Radiation, ASTIA Document No. AD 139961, Lockheed Aircraft Corporation, Burbank, California, 20 August 1952.

92. Casarett, G. W., Acceleration of Aging by Ionizing Radiation, ASTIA Document AD 133226, Atomic Energy Project, P.O. Box 267, Station 3, Rochester 20, New York Contract W-7401-eng-49, 20 June 1957.

93. McGee, John and Chester Polak, The Development of Standard Environmental Test Specimens, WADC TR 59-697, Inland Testing Laboratories Division, Contract No. AF 33(616)-6116, U. S Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1959.

BIBLIOGRAPHY

Acoustical Terminology (Including Mechanical Shock and Vibration), American Standards Association, approved 25 May 1960.

An Evaluation of the Psychological Problem of Crew Selection Relative to the Special Hazards of Irradiation Exposure, ASTIA No. AD 146563, NEPA Medical Advisory Panel, Subcommittee No. 9, Washington, D.C. 22 July 1949.

Anderson, K.G., H.B. Merrell, and J.M. Durham, Aerodynamic Heating and Heat Transfer Phenomena at Mach Numbers 3 to 4, Rosemount Research Center of the University of Minnesota, AF TR 58[illegible]. ASTIA Document No. AD 93637, WADC Equipment Laboratory, Contract No. AF 33(038)-10673, Project No. 1367, Task No. 61294, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1951.

Aukerman, L. W. and F. J. Reid, Energy Levels Produced in Semiconductors by High-Energy Radiation, REIC Memorandum No. 4, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, 15 July 1958.

Aukerman, L. W., The Effect of Nuclear Radiation on Semiconductor Materials (First Addendum), REIC Report No. 1 (Addendum) ASTIA Document No. AD 210758, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, 31 March 1959.

Bakanauskas, S., Resistance of Microorganisms to High Vacuums, WADC TN 59-142, Materials Laboratory, Project No. 7312, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1959.

Behrens, W. V. and J. M. Shaull, "The Effect of Short Duration Neutron Radiation on Semiconductor Devices," Proceedings of the IRE, March 1958.

Berks, W. I., Temperature and Thermal Stresses in Missile Structures, North American Aviation, Inc., Report No. AL-1933, ASTIA Document No. AD 60729, March 1954.

Bopp, C. D. and O. Sisman, Radiation Stability of Plastics and Elastomers, Supplement to ORNL-925, ASTIA No. AD 25395, 18 February 1954.

Circolo, James M. and Robert W. Jaller, A Mission-Oriented Analysis of Aircraft Icing - An Extension of Methodology, WADC TR 57-60, ASTIA Document No. AD 118016, American Power Jet Company, Contract No. AF 33(616)-2605, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Conference on Radiation Cataracts and Neutron Effects, National Research Council, Division of Medical Sciences for the U. S. Atomic Energy Commission, National Academy of Sciences Building, Washington, D. C., ASTIA No. AD 4[illegible]66, 17 February 1950.

Curtis, H., Effects of the Primary Cosmic Radiation on Matter, AFCRC-TN-56-200, Air Force Surveys in Geophysics No. 78, Atmospheric Physics Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Massachusetts, January 1956.

DeCoursin, D. G., W. G., Bradfield, and J.J. Sheppard, Aerodynamic Heating and Heat Transfer Phenomena at Mach Numbers 2.7 through 5.7, Rosemount Research Center of the University of Minnesota, WADC TR 53-379, ASTI Document No. AD 87274, WADC Equipment Laboratory, Contract No. AF 33(038)-10673, Project No. 1367, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, February 1954.

Drennan, J. E. and S. E. Harrison, The Effect of Nuclear Radiation on Semiconductor Diodes, REIC Memorandum No. 6, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 31 December 1958.

Edelman, S., E. Jones, E. R. Smith, B. D. Simmons and R. C. Braunberg, Self-Noise of Projectiles, National Bureau of Standards, NBS Project 0601-20-3527, NBS Report 3465, ASTIA Document No. 46770, July 1954.

Gordon, W. E., "Incoherent Scattering of Radio Waves by Free Electrons with Applications to Space Exploration by Radar," Proceedings of the IRE, November 1958.

Guide Manual of Cooling Methods for Electronic Equipment, Navships 900,190, Bureau of Ships, Navy Department, Washington 25, D. C., For Sale by Supt. of Documents, U. S. Government Printing Office, Washington 25, D. C., Price $2.00, 31 March 1955.

Hansen, F. C., "Some Characteristics of the Upper Atmosphere Pertaining to Hypervelocity Flight," Jet Propulsion, Volume 27, Number 11, 1957.

Hassler, K. E., J. F. Hansen and E. N. Wyler, The Effect of Nuclear Radiation on Transistors, REIC Memorandum No. 5, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Task No. 60001, Project No. 2133, 30 November 1958.

Hausner, H. H. and H. C. Friedemann, Effect of Irradiation on Solids, A Bibliography, ASTIA No. AD 89082, Atomic Energy Division, Sylvania Electric Products Inc., Bayside, New York.

Hess, R. E. and R. F. Badertscher, The Effect of Nuclear Radiation on the Performance of a Hydraulic Flight-Control System, REIC Memorandum No. 18, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-6584, Continuation of AF 33(616)-5171, Task No. 60001, Project No. 2133, 15 June 1959.

Hess, Robert W., Robert W. Fralich and Harvey H. Hubbard, Studies of Structural Failure Due to Acoustic Loading, National Advisory Committee for Aeronautics, Technical Note 4050, July 1957.

Hibbs, A. R., The Temperature of an Orbiting Missile, ASTIA Document No. AD 92240, Jet Propulsion Laboratory of the California Institute of Technology, ORDCIT Project, Contract No. DA-04-495-Ord 13, Department of the Army, Ordnance Corps, March 1956.

Jailer, Robert W. and James M. Ciccotti, Aircraft Operation in Icing Weather, WADC TN 55-226, ASTIA Document No. 80236, The American Power Jet Company, Contract No. AF 33(616)-2605, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

Johnson, E. R., Literature Survey on the Effects of Radiation on Electron Tube Materials, ASTIA Document No. AD 134855, The Army Signal Supply Agency, Stevens Institute of Technology, Hoboken N. J., DA Project No. 3-99-13-000, SC Project No. 112B, 1 February 1955.

Kreitner, J. and C. F. Jenkins, Flight Aspects of the Mountain Wave, Air Force Sueys in Geophysics No. 35, AFCRC TR 53-36, ASTIA Document No. AD 24979, Atmospheric Analysis Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass., April 1953.

Lapp, Roy P., Raymond H. Stutzman and Norman L. Wahl, A Study of the Rain Erosion of Plastics and Metals, WADC TR 53-125, ASTIA Document No. 77185, Cornell Aeronautical Laboratory, Contract No. AF 33(600)-6489, Project No. 7340 U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1955.

Lazzaro, C. P. and A. L. Long, "Effect of High Intensity Radiation on Electronic Parts and Materials," Electrical Manufacturing, September, 1958.

Lightfoot, R. P. and W. H. Rivera, Problems Which Arise During Engineering Evaluation of Radiation Effects on Organic Materials, Convair, A Division of General Dynamics Corporation, Forth Worth, Texas.

Mandeville, C. E., Fifth Annual Report of the Work of the Partial Research Foundation of the Franklin Institute, Contract No. N6 ori-144, Task Order I - NR 026-021, Office of Naval Research, 30 September 1955.

Mannogian, H. A., "The Challenge of Space," Electronics 24 April 1959.

"Materials, Effect of Radiation on Metals," Nucleonics, September 1958.

Newton, Wallace S. and Constantine G. Makrides, Effect of Climate and Environment on Ground Support Equipment, Corvey Engineering Company, USAF Contract No. 33(616)-2278, WADC TR 54-132, ASTIA Document No. AD 38100, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1954.

Osmanski, Joseph T., Experimental Investigation to Correlate the Recurrence of Fatigue Failures in A Typical Aircraft Structure With Vibratory Amplitude, WADC TR 56-551, ASTIA Document No. AD 110462, Cook Electric Company, Contract Number AF 33(616)-2532, Project No. 1370, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1958.

Oxidation of Materials at High Temperatures, Missile Development Division of North American Aviation Inc., Contract AF33(600)-28469, ASTIA Document No. AD 147907, September 1957.

Pigg, J. C. and C. C. Robinson, "Effect of Radiation on Semiconductors," Electrical Manufacturing, April 1957.

Powell, Alan, The Problem of Structural Failure Due to Jet Noise, Department of Aeronautical Engineering, University of Southampton, ASTIA Document No. 115755, March 1955.

Reich, B. and G. E. Pavlik, A Survey of the Nuclear Radiation Effects on Semiconductor Materials and Devices, U. S. Army Technical Memorandum No. M-1902, June 1957.

Reid, F. J., J. W. Moody and R. K. Willardson, The Effect of Nuclear Radiation on Semiconductor Materials, REIC Report No. 1, ASTIA Document No. AD 147393, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-5171, Project No. 2153, Task No. 60001, 20 December 1957.

Scholose, W. F., Explosion-Proof Test Criteria for Reconnaissance Equipment Part II, WADC TR 57-387, ASTIA Document No. AD 206073, Aerial Reconnaissance Laboratory, Directorate of Laboratories, Project 1111, Task 11115, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, November 1958.

Schmidt, C. M. and A. J. Barawait, "Skin Temperatures of a Satellite," Jet Propulsion, Vol. 27 No. 10, October 1957.

Smith, W. W., Natural Weathering and Indoor Open Shelf Storage Exposure Testing of Air Force Fabric Materials, WADC TR 58-502, ASTIA Document No. AD 210226, Materials Laboratory, Contract No. AF 33(600)-34695, Project No. 7312, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1959.

Stephens, E. D. and K. M. Fuechsel, The Aerodynamic Heating Problem, Technical Note WCRR 53-215, ASTIA Document No. AD 27650, WADC Aeronautical Research Laboratory, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1953.

"Studying Radiation Effects," Electronics, 1 June 1959.

Stuetzer, O., G. Wehner, G. Whitnah and J. Nash, Results of Studies on the Effects of Impaction of Small Particles on Bodies Moving at Hypersonic Speed, Research Department, Mechanical Division of General Mills, Inc., 2003 E. Hennepin Avenue, Minneapolis 13, Minnesota 17 June 1958.

Surosky, A. E. "The Nuclear Jungle," Environmental Quarterly, July 1956.

Techniques for Application of Electronic Component Parts in Military Equipment, WADC TR 57-1, Volume II ASTIA Document No. AD 142275, Volume III ASTIA Document No. AD 208661, Electronic Components Laboratory, Contract No. AF 33(616)-2815, Project No. 4155, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Theiss, E. C., Design Temperature Requirements for Operation of USAF Aircraft and Equipment, AR WCSPE 54-2, WADC Environmental Criteria Branch, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1954.

Tobias, C. A., H. C. Mel and D. G. Simmons, A Summary of the Berkeley Conference on Biological Effects of Cosmic Rays and Accelerated Heavy Ions, ASTIA No. AD 156693, University of California, Radiation Laboratory, Berkley California, Contract No. W-7405-eng-48, 10 March 1958.

Van Allen, J. A., "Geomagnetically Trapped, Corpuscular Radiation," Journal of Geophysics Research, November 1959.

Welsh, J. F. and T. J. Walsh, Handbook of Methods of Cooling Air Force Ground Electronic Equipment, RADC TR 58-126, ASTIA Document No. AD 148907, Rome Air Development Center, ARDC, U. S. Air Force, Griffiss Air Force Base, New York, June 1959.

White, C. S., Temperature and Humidity, Convair Aeromedical Consultant's Report, ASTIA Document No. AD 156985, Lovelace Foundation for Medical Education and Research, Albuquerque, New Mexico, 29 April 1954.

Wilkinson, R. A., The Effect of Solar Radiation on the Breaking Strength of Outdoor Exposed Webbing, WADC TR 58-201, ASTIA Document No. AD 206893, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, November 1958.

Wyant, R. E., The Effect of Nuclear Radiation on Refrigerants, REIC memorandum No. 16, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, Contract No. AF 33(616)-6564, Continuation of AF 33(616)-51.., Task No. 60001, Project No. 2133, 30 June 1959.

Wacholder, B. V. and E. Jayer, Critical Environments Encountered by High-Altitude Vehicles, Proceedings of Institute of Environmental Sciences, National Meeting, Los Angeles, California, 6, 7, 8 April 1960.

CHAPTER 4

ENVIRONMENTAL REQUIREMENTS

The nature of the environments, where and when they occur, and their effects have been covered in previous portions of this handbook. In this chapter, methods are described for establishing environmental criteria for specific systems and vehicles. These criteria are necessary because the designer or engineer must have stated limits in which to work if he is to design or develop anything in a practical manner. He must know the product's exact purpose, its size and weight limitations, and its reliability requirements. He must also know exactly what environments it will be subjected to so that he can make sure that the product will withstand them. In effect, established environmental criteria serve as a target at which weapon system design and development teams can aim.

Most often, environmental requirements are spelled out for the designer by the environmental engineering or reliability groups. On the other hand, if the item is not intended for any specific system, it can be provided with inherent design features for broad application in accordance with one of several design guides published by the Air Force

Environmental requirements, then, can be spelled out in two ways: (1) general environmental requirements for developmental purposes or for subsystems, equipment and components having broad applications; and (2) specific environmental requirements for subsystems, equipment and components for a specific weapon system. Each of these requires an environmental analysis. The first must give consideration to all possible applications, and makes maximum use of published standard environmental criteria. The documents giving such criteria are covered in a later paragraph.

An analysis for a broad application need not be as definitive as that for a specific application, but it will be more complete and cover more environments because of its broader scope. In the broad type of analysis, therefore, it is necessary to analyze the mission profiles of various types of vehicles to determine the associated environments. Pertinent environment values can then be calculated or selected from applicable standards, specifications and bulletins to assure proper design and development and then test procedures from such specifications as MIL-E-5272C can be used to determine whether the vehicle and its components can withstand the projected environments.

An environmental analysis for specific vehicles requires a more refined approach, since more details of the vehicle system are known and definite performance and reliability must be achieved. For this reason, an environmental analysis for a hypothetical weapon system must be carried out, with the analysis covering the flight vehicle and its subsystems, equipments, components and materials for both flight and ground conditions.

In specific cases, it may be found that the state-of-the-art may not allow a design to extend over the entire range of an environment. For instance, it may be impossible to design an actuator that will function reliably from -65 F to 1400 F because no one sealing compound will perform satisfactorily over this temperature range. Under this circumstance, there is a tendency to favor the high temperature requirement. This could be a mistake, though, since for many vehicles and missions, the low temperature requirement may be of equal or greater importance. For example, a great number of tests under arctic conditions are failures because of the failure of seals.

Where there is a doubt concerning the significance of any value, an operational analysis should be performed to determine the significance and validity of that value. An operational analysis might show, for example, that even though the vehicle skin temperature will reach 1400 F, insulating characteristics of the airframe will drop this temperature to 900 F, or with additional insulation, to 600 F in the vicinity of the actuator. It is possible also, that by changing the location of the actuator or by using auxiliary cooling equipment the temperature near the actuator might be reduced considerably. Furthermore, an operational analysis might show that the speeds, altitudes and durations of flight required to produce such skin temperatures would occur very infrequently, or that the period during which such temperatures would exist would be extremely short. On the other hand, the duration of low temperature conditions might be lengthy, so that from a practical standpoint they would be more detrimental than the high temperatures.

Operational analysis is actually a part of the overall environmental analysis but is sufficiently important to deserve separate attention, particularly in doubtful or controversial areas.

SPECIFICATIONS AND STANDARDS

There are many periodicals, books and reports available that cover the subject of environmental requirements. Much of the data are available in this handbook and in the reference and bibliography lists located at the end of each chapter. The most important documents containing military environmental criteria are listed in Table 4-1. Documents containing general requirements are included in the table, as well as those covering specific requirements. Some of the most useful documents of a specific nature are described in the following paragraphs.

The ARDC Model Atmosphere, 1959

This document provides detailed information on a revised model atmosphere. The revision is based on data obtained from satellite and rocket measurements which indicated the necessity for changing the upper atmosphere values contained in the ARDC Model Atmosphere, 1956. In addition, values of the following factors have been computed to an altitude of 2,320,000 feet (or 700 kilometers): temperature, pressure, density, molecular weight, acceleration of gravity, specific weight, scale height, number density, particle speed, collision frequency and mean free path. Because the dissociation of oxygen and nitrogen complicates calculation, values of the following factors are limited to an altitude of 295,000 feet (or 90 kilometers): speed of sound, coefficient of viscosity, kinematic viscosity and thermal conductivity.

Table 4-1. Air Force Policy Documents -- Handbooks, Specifications, Standards, and Reports

Identification	Title	Date
	General	
Hq ARDC Document	Policies and Procedures Governing Approval of Air Force Equipment	1 Aug 1952
ARDCM 80-1	Handbook of Instructions for Aircraft Designers, Volumes I, II, III (HIAD)	1 July 1955
ARDCM 80-5	Handbook of Instructions for Ground Equipment Designers (HIGED)	May 1955
ARDCM 80-6	Handbook of Instructions for Ground Support Equipment Designers (HIGSED)	15 Aug 1956
MIL-D-9310B	Data for Aeronautical Weapon Systems and Support Systems	19 June 1959
MIL-W-9411A	Weapon Systems, Aeronautical, General Specifications for	19 June 1959
WADD TR 60-627	Criteria for Environmental Analysis of Weapon Systems	August 1960
WADD TR 60-785	Hyper Environments Simulation Part I, Definition and Effects of Space Vehicle Environment -- Natural and Induced	January 1961
WADD TR	Preliminary Investigation of Interplanetary, Lunar and Near Planet Environments and Methods of Simulation	1961
	Environmental factors	
AFCRC Handbook	Handbook of Geophysics for Air Force Designers	1957
MIL-STD-210A	Climatic Extremes for Military Equipment	2 Aug 1957
WADC TR 56-456	Preliminary Investigation of Hyper Environments and Methods of Simulation, Part I	July 1957

Table 4-1. Air Force Policy Documents -- Handbooks, Specifications, Standards, and Reports (continued)

Identification	Title	Date
Flight vehicles		
ANC-22 Bulletin	Climatic and Environmental Criteria for Aircraft Design	June 1952
MIL-I-5289	Instrumentation of Climatic Test Aircraft, General Specification for	30 March 1953
USAF Specification Bulletin 106	Environmental Criteria for Guided Missile Design	18 March 1957
USAF Specification Bulletin 323	Space Environmental Criteria for Aerospace Vehicles	1960
WADD TR 60-627	Criteria for Environmental Analysis of Weapon Systems	August 1960
WADD TR 60-785	Hyper Environments Simulation Part I, Definition and Effects of Space Vehicle Environment -- Natural and Induced	January 1961
Airborne equipment		
MIL-E-25647	Electronic Equipment, Airborne, General Specification for the Design of	4 Sept 1956
MIL-E-8189A(ASG)	Electronic Equipment, Guided Missiles, General Specification for	16 April 1957
MIL-E-5400C	Electronic Equipment, Aircraft	15 July 1958
Components		
MIL-STD-446	Environmental Requirements for Electronic Component Parts	28 April 1959
MIL-STD-202A	Test Methods for Electronic and Electrical Component Parts	24 Oct 1956
WADC TR 57-1	Electronic Components Handbook, Volumes I, II, III	I - Jan 1957 II - Apr 1958 III - Jun 1959
Ground support equipment		
MIL-E-4158A (USAF)	Electronic Equipment, Ground, General Requirements for	20 July 1955
MIL-G-008512A (USAF)	Ground Support Equipments, General Requirements for	21 Jan 1957
USAF Spec Bulletin 115	Environmental Criteria for Ground Support Equipment	6 July 1955
MIL-T-945A	Test Equipment for Use with Electronic Equipment, General Specification for	14 May 1953
Materials		
MIL-P-116C	Preservation, Methods of	27 Feb 1959

Table 4-1. Air Force Policy Documents -- Handbooks, Specifications, Standards, and Reports (continued)

Identification	Title	Date
	Test methodology	
MIL-E-4970A (USAF)	Environmental Testing, Ground Support Equipment	3 March 1959
MIL-E-5272C	Environmental Testing, Aeronautical and Associated Equipment	13 April 1959
MIL-A-26669	Acoustical Noise Tests, Aeronautical and Associated Equipment	14 July 1959
MIL-T-5422E (ASG)	Testing; Environmental, Aircraft Electronic Equipment	11 May 1953
MIL-E-26554	Explosion-Proof Test Facility Requirements and Procedures for Reconnaissance Equipment	3 March 1959
MIL-STD-202A	Test Methods for Electronic and Electrical Component Parts	24 Oct 1956
MIL-S-4456	Shock, Variable Duration, Method and Apparatus for	12 March 1953
	Test facilities	
MIL-C-7951A (ASG)	Chamber, Altitude, Humidity and Temperature Test	5 Oct 1953
MIL-C-8811 (ASG)	Chamber, Rain Testing	10 July 1957
MIL C-9435	Explosion Proof Testing Facility	12 Feb 1954
MIL-C 9436A (ASG)	Sand and Dust Testing Facility	5 May 1955
MIL-C-9472	Chamber, Fungus Resistance Testing	8 June 1954
MIL-E-26654	Explosion-Proof Test Facility Requirements and procedures for Reconnaissance Equipment	3 March 1959
MIL-S-4456	Shock, Variable Duration, Method and Apparatus for	12 March 1953
WADC TR 57-456	Preliminary Investigation of Hyper Environments and Methods of Simulation:	
	Part II -- Simulation Methods	Nov 1957
	Part III -- Proposed Hyper Environmental Facility	Jan 1958
WADC TR 60-785	Hyper Environment Simulation Part II, Development and Design of Simulation Facilities for Space Vehicle Environment	1961
WADD TR	Preliminary Investigation of Interplanetary Lunar and Near Planet Environments and Methods of Simulation	1961

Handbook of Geophysics

The "Handbook of Geophysics for Air Force Designers" was prepared by Air Force Cambridge Research Center to present probability and frequency tabulations of many aspects of the natural environments. It is one of the most complete compilations of geophysical data available, and provides factual data on:

Temperature	Surface parameters (Earth)
Atmospheric pressure	Low altitude wave propagation
Atmospheric density	Visibility
Wind	Thermal radiation
Precipitation	The Sun
Clouds	Cosmic radiation
Atmospheric composition	Contrails
Atmospheric electricity	Atmospheric exploratory devices
Geomagnetism	Acoustic propagation in the atmosphere

Other ARDC Handbooks

The Air Research and Development Command has made available a series of handbooks that provide a central source of design data for engineers. These handbooks contain general requirements above the level of the specification requirements, and give the background data and basis for the requirements. Also included are explanations, recommendations, nonmandatory guidance and related data. The handbooks are actually a series of instructions for designers of piloted aircraft, guided missiles, ground equipment and ground support equipment.

Military Specifications

The actual military specifications that equipment and systems are designed to meet contain many environmental requirements. MIL-D-9310 and MIL-W-9411 (USAF) contain requirements for prime contractors to prepare and present an environmental analysis of their missile and aircraft weapon systems. MIL-E-4970, MIL-E-5272 and MIL-A-26669 are primarily test procedure specifications, but they outline environmental requirements for ground support equipment and aeronautical and associated equipment, respectively; however, they should not be used as requirement specifications. Detailed information on test procedures are covered in Chapter 6. MIL-E-5400 and MIL-I-6051 also include environmental requirements for electronic equipment used primarily in aircraft. Detail specifications for equipment and components include environmental requirements pertaining to those specific equipments and components.

Military Standards

A number of military standards contain environmental requirements and associated data helpful in the design of military equipment. MIL-STD-210A, for example, gives the probable surface extremes of the natural environments to which military equipment might be exposed, and establishes uniform limits for normal design requirements. It contains surface extremes of temperature, humidity, precipitation, snow loads, winds, blowing snow, blowing sand, blowing dust and atmospheric pressure on the earth's surface, and the probable atmospheric extremes of temperature, pressure, humidity, winds, speed of sound, density and viscosity. The data on ground conditions are supplied for world-wide, short-term storage, and transit conditions. Hot, cold, polar and tropical standard atmospheres extending to 100,000 feet are included. For analysis involving engine and vehicle performance computations, or other cases where a continuous profile is required, the polar and tropical atmospheres must be used, since the hot and cold atmospheres are constructed on a level-by-level basis, without regard to continuity between levels. The hot and cold atmospheres are required in computations involving variations of temperatures at a given altitude, and are useful in work involving heat transfer and heating and cooling of atmospheric vehicles during flight.

MIL-STD-446 contains projected environmental design requirements for electronic component parts. Values of limits are given for temperature, pressure, humidity, vibration, shock, explosive atmosphere and nuclear radiation. The requirements are divided into the following equipment categories.

- Group I - Ground equipment
- Group II - Ground equipment when electrical stability is of prime importance
- Group III - Shipboard and ground equipment
- Group IV - Equipment for aircraft and missiles
- Group V - Equipment for aircraft and shipboard (specialized application)
- Group VI - Equipment for nuclear-powered aircraft and ballistic missiles
- Group VII - Equipment for specialized application in aircraft and missiles
- Group VIII - Nuclear-powered weapons

Specification Bulletins

Air Force Specification Bulletins 106 and 115 present general information on the ranges of environments that must be considered in establishing requirements for ground support equipment and missile equipments, respectively.

Reports

There are many studies being made to gain more knowledge about design criteria. The results of these studies are made available in reports by the various service agencies. For example, Aeronautical Systems Division (formerly Wright Air Development Division) Reports 57-456, 60-627, and 60 785 present data on hyper environments and methods of simulation that can be used as a basis for estimating future design and test requirements.

ENVIRONMENTAL ANALYSIS

From an overall standpoint, the purpose of environmental analysis is to present as complete a picture of the anticipated environments as is practicable to the system designers, and also to provide sufficient criteria to permit assurance that the system design will withstand the environments. For effective usage of the analysis, the results must be presented in a logical manner. Basically, the resulting data are supplied in two categories:

1. Environmental design criteria.

2. Environmental test criteria.

Environmental Design Criteria

The environmental design criteria developed by the weapon system contractor during the environmental analysis required by specifications MIL-D-9310 and MIL W-9411 must be supplied to all the system designers and the Air Force. The designers use the data to design the system and its parts. The Air Force uses the criteria to insure that the analysis is correct and complete and that other equipment used in conjunction with, or as part of, the system will operate within the same environmental limits.

The environmental criteria supplied must take into consideration all conditions that will be encountered in the life span of the system. It is best, then, to consider environments as being encountered in separate phases. For example, a vehicle such as a spaceship must be launched, traverse the atmosphere, follow a space path, enter or reenter the atmosphere, traverse that atmosphere, and be set down. In addition, both before and after flight, the system and its parts must be transported, stored and serviced. Each of these phases imposes a different set of environments on the system. These environments must be outlined as clearly, completely and accurately as possible.

The environmental analysis will generally be more useful if (1) the environments are presented separately as natural or induced (2) they are described as to what operational and mechanical effects they have, and (3) these data are given for external environments and compartment environments.

Environmental Test Criteria

The environmental test criteria, also developed by the weapon system contractor during the environmental analysis, should be supplied to the test engineer, the test equipment designer and the Air Force. This allows the test engineer to establish realistic and accurate test procedures, so that the reliability of the system can be ascertained. The criteria also permit the test equipment designer to build the equipment required for testing, when such equipment is pushing the state-of-the-art and adequate facilities are not available. As part of the environmental analysis, this data allows the Air Force to ensure that the contractor is reflecting the latest technology, and also permits the Air Force to note environmental state-of-the-art weaknesses and problems and hence allows initiating research and investigations to overcome such weaknesses and problems.

Method of Environmental Analysis

For the analysis to produce sound results, it must follow a systematic plan. The following major steps should be taken:

1. Secure data on mission profiles and alternate mission profiles.

2. Outline significant system data.

3. Establish environmental criteria.

4. Conduct analysis tests to determine environmental values not covered by standard environmental criteria.

5. Prepare an analysis report and environmental test requirements.

Mission Profile. The mission profile is one of the most important factors in making an environmental analysis. The altitudes at which the vehicle must perform, the speeds at which it will travel, and the flight paths and regions in which performance will be expected all provide the environmental engineer with a set of boundaries within which his analytic data provide a complete environmental definition. The word performance is used deliberately here. It is not sufficient that the vehicle operate; it must perform in a planned manner to specified limits of environment and reliability if it is to be a success.

The mission may be simple or complex. A commercial aircraft may be expected to operate world-wide, but only over established routes. The military vehicle, on the other hand, will take many varied routes and encounter different environments, many of which may be extreme. When the speed at which the vehicle climbs, cruises, and descends, and the range of altitudes at which performance is expected are all specified, the area in which the environmental engineer's efforts will be exerted is outlined. Alternate mission profiles should also be covered. Possible as well as expected alternate profiles should be included.

In Chapter 2, typical flight paths are outlined as examples of how profiles provide an analysis tool. The gamut of profiles must be examined to determine the concurrence of natural environments to all locations during the various seasons. Also, the activities of the vehicle during its various phases of flight, such as launch or tackoff, climb, cruise, landing and reentry, must be analyzed to determine the generation of induced environments. The entire list of the environments covered in Chapters 2 and 3 must be covered at every point along each profile.

Subsidiary profiles for the system and all its parts must also be covered. These include: (1) ground handling, (2) storage and (3) transportation. During these profiles, different environment types and levels will be encountered.

System Data. The vehicle system itself should be analyzed to determine (1) what environments will be induced by the vehicle, and (2) what parts of the system are most critical from an environmental effect standpoint. This can be accomplished by outlining:

1. The type of vehicle.

2. The layout of the vehicle.

3. The method of propulsion, and location and size of propulsion unit. (This should include secondary propulsion devices, such as booster or retro rockets, and other devices that have aerodynamic effects, such as drag surfaces or ejection devices.)

4. The type of fuel.

5. Environment-generating equipment.

6. Environment-sensitive equipment.

7. Compartmentation of vehicle (including in each compartment the location of all environment-generating and environment-sensitive equipment).

8. Whether the vehicle will be manned or unmanned.

The type of vehicle, whether a ballistic missile with a short life or a satellite or bomber with a long life, will determine the relative importance of the environmental factors. The layout of the vehicle, method of propulsion, and size and location of propulsion unit will affect the dynamic characteristics of the vehicle. Nuclear propulsion systems present one type of problem; highly volatile fuels create another, and liquid-oxygen fuels still another. A full understanding of the characteristics of environment-generating equipment is required for the determination of the environments induced internally. Relative location of this equipment with respect to sensitive equipment within the vehicle determines the difficulty in securing environmental protection. Human occupancy naturally brings about a new focal point for environmental considerations.

Environmental Criteria. After compiling as much data as practicable about the profiles and the system, the environmental engineer establishes environmental criteria for the system, as required by specifications MIL-W-9411 and MIL-D-9310. When doing this, he must examine the data closely to insure that all ramifications and possibilities are understood. For example, a high-level bomber may find application at lower altitudes, or a space vehicle may have to glide for a considerable distance in the atmosphere. The analysis must be made as accurately as possible, and should delineate the facts for each environment on a phase basis. For example, specification MIL-D-9310B stipulates that "(the environmental) analysis shall consider the operational concept (basic missions, possible bases of operation, performance, etc.) to determine the environmental conditions the weapon system will encounter in its regimes of operation, such as extreme temperatures, ionized gases, meteorites, ozone, etc. Further, for the air vehicle, its regime of flight will also require consideration of the dynamic or induced environments associated with flight and operations, such as skin temperature, internal air pressure, vibration and noise field. It is imperative that a complete exterior and interior analysis, in this regard, be accomplished so that further analysis of the environments to which the equipments are to be exposed is practical. Standard environmental criteria shall be used where applicable." As explained previously, standard environmental criteria can be obtained from the documents described under "SPECIFICATIONS AND STANDARDS." The type of effect, whether operational or mechanical, should also be indicated. An example of an environmental analysis coverage is shown in Table 4-2. These factors should be reviewed for the vehicle as a whole, for each compartment in the vehicle, for each class of equipment, and for component parts which make up equipments.

Analysis Tests. In many instances, particularly for the induced environments, the standard environmental criteria will not be helpful in establishing some of the environmental data. This might be particularly true for deriving exact environment figures for the interiors of separate compartments and equipments. In such cases, the criteria must then be determined by calculation or by empirical methods. Tests may be made by instrumenting the various equipments and compartments under simulated conditions, and measuring the environments directly. Often mock-ups can be used; in other cases it must be recognized that the environments at some locations may have to be hypothesized until full scale tests can be conducted.

Test Report and Requirements. Once all of the environmental data have been compiled and analyzed, they must then be documented in report form. This report is necessary for evaluation by the design engineers and the cognizant military agency. The analysis report should be

Table 4-2. Example of Environmental Analysis Coverage

	Profile analysis								Effect	
	Flight			Takeoff or launch	Landing	Ground handling	Storage	Transportation	Operational	Mechanicle
	Space	Atmosphere	Reentry							
Natural										
Albedo	x	x	x						x	x
Asteroids	x									x
Clouds		x							x	
Cosmic radiation	x	x								x
Density		x	x						x	x
Dew		x		x	x	x	x	x		x
Electricity, atmosphere		x							x	x
Fog		x		x	x				x	
Frost		x		x		x	x	x	x	
Fungi							x			x
Gases, dissociated		x	x							x
Gases, ionized	x	x	x							x
Geomagnetism	x	x	x	x	x				x	x
Gravity	x	x	x	x	x				x	x
Hail		x		x	x	x	x	x	x	x
Humidity		x		x	x	x	x	x		x
Ice		x		x	x	x	x	x	x	
Insects		x		x	x	x	x	x		x
Meteoroids	x									x
Ozone		x								x
Pollution, air		x		x	x	x	x	x	x	x
Pressure, air		x	x	x	x				x	x
Rain		x		x	x	x	x	x	x	x
Salt spray		x		x	x	x	x	x		x
Sand and dust		x		x	x	x	x	x		x
Sleet		x		x	x	x	x	x	x	x
Snow		x		x	x	x	x	x	x	
Solar radiation	x	x	x	x	x	x	x			x
Spores							x			x
Temperature	x	x	x	x	x	x	x	x	x	x
Temperature shock	x	x	x						x	x
Turbulence		x	x	x	x				x	x
Vacuum	x								x	x
Winds and gusts		x		x	x	x	x	x	x	x
Wind shear		x		x	x					x
Induced										
Acceleration	x	x	x	x	x				x	x
Acoustics		x	x	x	x		x	x	x	x
Aerodynamic heating		x	x						x	x
Explosive atmosphere		x							x	x
Gases, dissociated		x	x							x
Gases, ionized		x	x							x
Magnetic fields		x		x	x				x	
Moisture		x		x		x			x	x
Nuclear radiation	x	x	x	x	x					x
Shock, mechanical	x	x		x		x		x		x
Temperature	x	x		x	x				x	x
Temperature shock	x	x								x
Vapor trails		x							x	
Vibration	x	x	x	x	x	x	x	x		x
Zero gravity	x									x

clear, concise and complete. Specific values should be given in a logical form. The methods used to derive all values and the references employed should be explained. Where tests were used to establish some criteria, the test description should be included.

The most important part of the analysis is the preparation of the environmental requirements. Values for each environment must be stipulated for the entire system and each of its parts. These values will be used to develop test procedures and equipments (Chapter 6). The values

should be such that any equipment that withstands the tests can be counted on to give satisfactory performance throughout its operational life.

Typical Steps in Environmental Analysis

The following paragraphs describe some typical steps in an environmental analysis. A proposed aircraft planned to achieve a speed of Mach 2 at an altitude of 50,000 feet will be assumed. The mission of such a vehicle would generally to defined further as encompassing a series of phases such as:

1. Takeoff and accelerate to 500 knots.

2. Climb to 20,000 feet.

3. Accelerate to 800 knots.

4. Climb to 28,000 feet, accelerating to 900 knots.

5. Accelerate to 1000 knots.

6. Climb to 50,000 feet, accelerating to 1148 knots.

7. Level flight at 50,000 feet at 1148 knots.

Each of these flight levels and performance requirements must be reviewed to establish the maximum loads on the vehicle. Depending primarily on the specific mission, the vehicle may be subjected to maximum dynamic loading at low altitude and maximum aerodynamic heating at high altitude. Radiation levels will generally be higher in the upper atmosphere and in space, while maximum noise occurs most frequently at takeoff.

Heating. In predictions of aerodynamic heating, values of ambient temperature, T_0, air density, ρ, and thermal conductivity, k, can be found in reference /1/. The stagnation temperature, T_S, or the temperature of the air whose velocity is changed adiabatically to that of the moving vehicle, is:

$$T_S = T_0 + \frac{V_0^2}{2Jc_p}$$

where: J = mechanical equivalent of heat, ft-lbs BTU

c_p = specific heat at constant pressure, BTU lb

With the value of c_p secured from references such as /2/ and /3/, the stagnation temperature, in degrees Rankin, for a vehicle traveling at Mach 2 can be determined as follows:

$$T_S = 390 + \frac{[(1148)(1.688)]^2}{(2)(778)(.24)(32.02)}$$

$$T_S = 390 + 314$$

$$T_S = 704R$$

Actually, the process is never adiabatic and some losses will occur. If the air is considered to remain a perfect gas, the recovery temperature, T_r, can be expressed by the relation:

$$T_r = r(T_S - T_0) + T_0$$

Taking the recovery factor, r, as .85, the expression reduces to:

$$T_r = .85\ (704 - 390) + 390$$

$$T_r = 657R$$

The Reynolds number, R_e, is determined by the expression

$$R_e = \frac{\rho V \ell}{\mu}$$

where: ρ = air density at vehicle, slugs/ft^3
V = velocity, ft/sec
l = flow length, ft
μ = coefficient of viscosity

The air density at the vehicle can be estimated as:

$$P = P_0 \left(\frac{(T_0)}{(T_r)}\right)$$

$$P = .0003639 \left(\frac{(390)}{(657)}\right)$$

$$P = .000216 \text{ slugs/ft}^3$$

Therefore, if the coefficient of viscosity, μ, is taken as 3.0×10^{-7}, and the flow length is 25 feet, the Reynolds number becomes:

$$R_e = \frac{(.000216)(1148)(1.688)(25)}{(32.02)(3.0 \times 10^{-7})}$$

$$R_e = 1.1 \times 10^6$$

The heat transfer coefficient for laminar flow, h, can then be computed from the expression:

$$h = .026 \frac{k Re^{0.8}}{\ell}$$

$$h = \frac{(.026)(2.3 \times 10^{-6})(1.1 \times 10^{6})^{0.8}}{25}$$

$$h = 1.6 \times 10^{-4} \text{ BTU/sec/ft}^2\text{R}$$

In addition to aerodynamic heating, radiation from the sun produces an increase in the heat input. If the aircraft has a coefficient of absorptivity, α, and an exposed area A, the heat input, Q, due to solar heating is given by the expression.

$$Q = \bar{S}A$$

Values of the solar constant, S, are given in reference /4/ as follows:

At sea level, air mass = 1

$$S = 1.026(927.9) \text{ watts/m}^2$$

In space, air mass = 1

$$S = 1.026(1322.1) = 1360 \text{ watts/m}^2$$

At 50,000 feet, energy levels of radiation with a wavelength shorter than 0.29 microns and longer than 2.5 microns are small, so that only the region within these limits need by considered. The decrease in intensity is a logarithmic function expressed by the relation:

$$I = I_0 \, 10^{-au}$$

where a is an attenuation factor and u is the thickness of the atmosphere. The attenuation factor is wavelength dependent, but for the sake of brevity, an average value of 0.0003 per kilometer will be assumed. Also, the absorption due to ozone below 50,000 feet is considered negligible. Thus, if the radiation energy at sea level is 953 watts per square meter, the level at 50,000 feet is

$$953 = I \times 10^{-\left[(.003)\left(\frac{50{,}000}{3280}\right)\right]}$$

$$I = 965 \text{ watts/m}^2$$

$$= .085 \text{ BTU/sec/ft}^2$$

At the same time, the vehicle will be radiating heat at a rate determined by the fourth power of its absolute temperature, or:

$$Q = \epsilon \sigma T^4$$

The Stefan-Boltzmann constant, σ, is 17.3×10^{-10} BTU/hr-ft^2 R, so that if the emissivity of the vehicle surface, ϵ, is taken as 0.6, the heat radiated per unit area is:

$$Q = 17.3 \times 10^{-10} (.6)(657)^4$$

$$Q = 19.3 \text{ BTU/hr/ft}^2$$

$$= .005 \text{ BTU/sec/ft}^2$$

Adding the various heat inputs, including internal heating, and subtracting the heat the vehicle loses by radiation, conduction, and convection, the resultant heat inputs to sections of the vehicle can be computed. Detailing this information on plan and elevation views permits the designer to visualize the conditions he must consider and enables him to design a suitable structure. As the design progresses the heat transfer to each compartment must be determined so that the environment in which individual equipment will operate is known, and, if required, the auxiliary cooling or heating to maintain specified limits will be evident. The results may be incorporated in detail on a diagram such as shown in Figure 4-1.

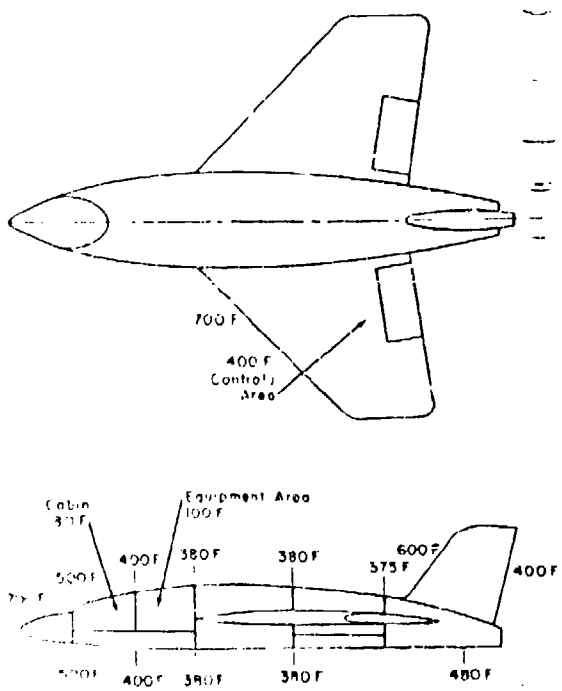


Fig. 4-1. Estimated skin Temperatures at rated speed.

Vibration. The complexity of most vehicle and equipment structures is sufficiently great that a purely analytic solution of the dynamic loading is not generally feasible. A large amount of data on the excitation and response of typical

aircraft and missiles has been accumulated by the U.S. Air Force at the Wright Air Development Division. This information can form the base from which projections may be made to new designs. Typical vibration data for various types of flight vehicles, as well as information on where more detailed vibration data can be obtained are given in Chapter 3.

Vehicle specifications outline vibration environment extremes, and documents such as reference /5/ provide limits for particular types of equipment. When tentative configurations and compositions are selected, testing must be resorted to. In this manner, proof of the conception is obtained, and if necessary, modifications may be made to insure the required level of reliability under the specific conditions.

Noise. Jet and rocket motors produce high intensity noise levels over a wide band of frequencies, thus creating severe dynamic problems. Generally, the effects are most severe at takeoff. Nevertheless, the total noise environment must be investigated during flight also. An example of cockpit noise prediction during flight at 50,000 feet is given in WADC Technical Report 58-343.

To estimate the noise level in the cockpit of an aircraft flying at 50,000 feet, the cockpit being assumed to have a total surface area, s, of 50 square feet and to be pressurized to 5,000 feet with 25 ventilator-defroster system jets (0.23-inch diameter, d, with a total area, A, of 1 square inch) and an exit velocity, V, of 350 feet per second, the following procedure is used.

The power in the air jet stream is:

$$P = 1/2\ \rho A V^3$$

$$P = 1/2 \frac{(0.0659)}{32.2} \frac{1}{144} (350)^3$$

$$P = 300 \text{ ft-lbs. sec} = 400 \text{ watts}$$

The sound power level is given by the expression:

$$PWL = 10 \log P + 88$$

$$PWL = 10 \log 400 + 88$$

$$PWL = 144 \text{ db}$$

The maximum frequency is:

$$f_{max} = 0.2 \frac{V}{d} = 0.2 \left(\frac{350}{0.23/12} \right)$$

$$f_{max} = 3650 \text{ cps}$$

And the overall sound pressure level is:

$$SPL = PWL - 10 \log S + 9$$

$$SPL = 114 - 10 \log 50 + 9$$

$$SPL = 106 \text{ db}$$

Boundary layer noise represents another segment of the flight environment. A number of empirical expressions have been developed for the prediction of the noise level, one of which is the following:

$$SPL = 20 \log \left[\frac{0.003\ \rho V^2}{4.18 \times 10^{-7}} \right]$$

This expression may be reduced to the form:

$$SPL = 120 = 20 \log p M^2$$

where;

p = ambient pressure, lbs/in^2

M = Mach number

Thus, for a vehicle traveling at Mach 2 at an altitude of 50,000 feet, the sound pressure level would be:

$$SPL = 120 + 20 \log (1.692) (2)^2$$

$$SPL = 136.6 \text{ db}$$

On the ground, the engine is the major noise device. The acoustic power of a jet engine is given by the expression:

$$W = 3.66 \times 10^{-5} \frac{\rho_o A V^8}{V_o^5}$$

where ρ_o = ambient air density, slugs/ft^3

V = effective flow velocity, ft/sec

V_o = ambient acoustic velocity, ft/sec

W = power, watts

If sea level conditions are assumed, and the effective flow velocity is 1800 feet per second with an exhaust diameter of 1.5 feet, the acoustic power is:

$$W = 3.66 \times 10^{-5} (.002377) \frac{\pi (1.5)^2}{4} \frac{1800^8}{116}$$

$$W = 9600 \text{ watts}$$

The acoustic power level in decibels above a reference level of 10^{-13} watts is:

$$PWL = 130 + 10 \log W$$

$$PWL = 130 + 10 \log 9600$$

$$PWL = 170 \text{ db}$$

At sea level, with a hemispherical distribution the sound pressure level is given to a practical degree of accuracy by the simplified expression:

$$SPL = PWL - 10 \log S$$

Here, S is the total surface area, or $2\pi r^2$ in the case of a hemispherical distribution. If a distance from the source of 20 feet is assumed, the sound pressure level will be:

$$SPL = 170 - 10 \log 2500$$

$$SPL = 136 \text{ db}$$

Generally, the pattern of jet engine noise will deviate somewhat from a spherical pattern, reaching a peak of about plus 7 db at an angle of 135 degrees off the forward axis.

Electromagnetic Wave Propagation. Wave propagation at operating altitudes must be investigated, particularly when dissociated and ionization take place, as in the case of reentry. If the aircraft has high-frequency equipment that must operate over the flight regime, reference /4/ provides data from which the signal attenuation and back-scattering may be estimated. For example, at an altitude of 50,000 feet, if equipment is operating at a frequency of 16,700 megacycles, reference /4/ gives the following two-way attenuation coefficients:

Water vapor - 0.084 db per mile

Oxygen - 0.040 db per mile

Total - 0.124 db per mile (two way)
- 0.062 db per mile (one way)

If a range of 50 miles is desired, the total attenuation will be 3.1 db one way. Equivalent values are provided for more severe conditions, such as in a polar atmosphere with heavy snow, in an intense thunderstorm, or through a dense water cloud. Each of these conditions must be investigated if the performance of equipment under all conditions is to be realized.

Other Considerations. Wherever a world-wide capability is desired, the limits of MIL-STD-210A should be considered in the design of all items subjected to the natural environment. While certain environmental factors, such as aerosols, insects, precipitation, salt spray, and sand and dust are not a major importance at high altitudes, they are important at low altitudes or on the ground. In general, these factors are defined in references /4/ and /6/. Where prolonged low altitude flight is a consideration, the type and prevalence of insects must be studied in the specific localities concerned. Transit environment is described in reference /7/.

Factors such as dissociated and ionized gases are of importance in the upper atmosphere, and others such as asteroids, cosmic radiation, solar flares, Van Allen radiation, vacuum and zero gravity become of critical importance in space flight. These environments are not as well defined as many others, but current investigations are improving the prediction accuracy. Data on hyper-environmental conditions are contained in reference /8/, as well as in WADC TR60-627, WADC TR60-785 and UASF Specification Bulletin 523.

OPERATIONS ANALYSIS

The Operations Analysis Problem of Environmental Engineering.

The philosophy of operations analysis, like that of the scientific method, is not a single, formal statement that may be followed without thought or insight, but rather a collection of methods that have been found effective.

Operations analysis is based first on the fact that almost any situation can be measured, and that even qualitative measures are an essential step to knowledge; second, that measurements are not certain, since natural and induced environmental encounters are not rigid and predictable, but rather are only probable; and finally, that it is preferable to look at a system as a whole in relation to the environment taken as a whole.

The goal of operations analysis was well put by Sir Robert Watson-Watt -- to obtain "the maximum effect from available resource." In the present context, we might add: "in the study of natural and induced environments." The methods used must insure objective measurement and the prediction of the probabilities connected with (1) natural and induced environments, (2) available resources, and (3) maximum effect. The necessary facts are then available to those who must make the final choice, and decisions may be made with minimum prejudice and maximum foreknowledge of all the pertinent factors.

There is no limited set of tools and techniques to which the operations analyst is restricted, nor is there a specific "canned" approach. Instead, the point of view is the application of scientific method with special attention to the analysis of complex situations. The essential framework is by no means strange to the military. Indeed, the Staff Officers Field Manual gives the following form for the development of a military decision:

1. State the mission. If the mission is multiple, specify priorities. If there are intermediate tasks either prescribed or necessary to the mission, these should be listed.

2. Analyze the situation and state the various courses. Develop the basic data on assumptions. Cover enemy capabilities and list all practical courses of action.

3. Analyze the effect of the philosophy factors on each of the possible courses.

4. Compare the courses of action.

5. Make the decision.

The Field Manual emphasizes the employment of an existing system, while the systems for which environmental requirements must be constructed have available a far wider scope of potential courses of action.

The scope and severity of the environmental problem has paralleled the rapidly increasing complexity of modern weapons systems; specifically:

1. The scope of environments considered has increased.

2. The required operating limits within any one environment or group of combined environments have broadened.

3. The number and complexity of elements affected have multiplied.

The nature of the many new environments under consideration implies that simpler impressions gained from past experience are no longer adequate. The broadening range of performance required within any environment means increased effort and expenditures are necessary to secure test equipment that can handle these ranges. And finally, the consequences of any decision affecting environmental requirements have time, cost, and development effort implications previously unknown.

System Level

It has been aptly said that "One man's system is another man's sub-assembly." Exactly what constitutes a system remains a "gray area." There is the question of systems that share elements, such as two completely unlike aircraft sharing the same ground control or runway. Again, environmental protection may be built into a container, but at the price of increasing weight, so that the item cannot be transported by certain classes of air vehicles. These points are not trivial. The decision made as to what constitutes the essential core of the system is the basis from which trade-offs must be judged.

Since some sort of worthwhile nomenclature (with examples) is necessary to illuminate this gray area, consider the following hierarchy:

1. Part - resistor
2. Component - decision circuit board
3. Equipment - computer
4. Subsystem - terminal guidance group
5. System - missile and guidance
6. Weapon System - air defense

Individual parts make up components that have specific functions in an item of equipment. Equipments are made up of components, and carry out an end function within a subsystem. The subsystem is a worthwhile breakdown when the system is very complex, and several equipments combine to carry out a given function. A system is an assembly of subsystems that has a specific function in a weapon system and is essential for the accomplishment of the weapon system design mission. A weapon system is an assembly of systems essential to accomplish a specific Air Force mission. Not every system will require an complete a breakdown. Nomenclature may be sub-divided, as appropriate, since the insight which recognizes the existence of trade-offs and their interrelationships is the really pertinent factor.

Optimization

A logical consequence of appreciating the above definitions is the level at which a particular weapon system should be optimized. Part of the work in all operations analysis is to select the right level of optimization, and this, perhaps, is the most important single factor in setting up an environmental testing program. Should the program be optimized around the effectiveness of the weapon system as a whole, or around a single system? Is it better to have a piece of equipment that functions excellently in one of the environmental combinations, but not in all to which the unit may be exposed, or moderately well in all and excellently in only a few?

The name given to this problem is "sub-optimization." /9/ On one hand, a too narrow viewpoint of sub-optimization must be avoided, and yet it is possible to formulate the problem in terms so general that no useful answer can be obtained. One guide to the proper course between these two errors is the use of decision criteria that are consistent with those appropriate to the next higher level of the weapon system.

Then there is the matter of limited sample size. Production staging and equipment cost establish the number of available samples. Obtaining the maximum amount of information from the sample is not solely a matter of statistical technique, but of controlling the strategy of the environmental program so that the information is most reliable in areas of major importance to the success of the weapon system.

Environmental engineering does not end with the testing of a component or system. It continues into the field operations phase, reducing the tolerance between assessed environment and actual use. Differences occur not only through inherent variability, but because of the inevitable evolution of the plan for using complex systems.

Moreover, the environment of a weapon is essentially competitive; that is, the enemy seeks its defeat not only by direct means, but also by forcing it to operate where its performance is marginal.

The situation that faces the operations analyst in environmental testing of modern systems may be summarized as follows:

1. Systems are larger and more complex, requiring integrated planning. The performance of the system as a whole cannot be predicted solely from its components.

2. The value of each set of trade-offs must be crosscalculated to determine its value, and the best way of demonstrating its performance devised.

3. Environmental test programs are performed with budget, facility, and sample limitations, all under the pressure of time. The optimum strategy must be decided upon.

4. The results of environmental experience in the field, particularly the effect of hostile competition, must be fed back into system improvement.

Consideration of Uncertainties in Operations Analysis

A trademark of operations analysis is thoroughgoing evaluation of the importance of uncertainties. In the old, classic physical problems, uncertainties were relatively small and accuracy of measurement was high compared with the effects that were being studied. Beginning with the study of the behavior of gases, however, a realization that complex events could only rarely be described in a deterministic form led to the beginnings of statistical mechanics. Precisely because it involves so many variables, all occurring with varying probability, the operational situation is a natural area for statistics, a tool that opens the way to war gaming, simulation, and similar techniques.

Whenever data are brought together and organized in a particular way, a model is implicit. Operations analysis is unique in stressing the importance of the model's nature and characteristics. Thus, the law of gravitation assumes that the force of gravitational attraction falls off as the square of the distance between the masses. Astronomy may treat a planet as a point mass for purposes of predicting its orbit, but the astronaut making a landing must take account of the size of the planet and its physical configuration. The picture of the situation that is valid for guidance in certain computations is not sufficient in others.

Models (for example, Newton's law of gravitation) may be deterministic; that is, if the factors are known, then the results may be accurately computed. But as has been previously pointed out, the role of uncertainty forces the use of stochastic or probablistic models. A model, therefore, may vary in sophistication from a qualitative word picture to a highly developed mathematical theory. The analytic value of choosing a model is that it sharpens our understanding of the points at which experience and predictions are likely to diverge. Its effective value is the strengthening of judgment by conscious measurement and logical analysis.

The Role of Operations Analysis in Environmental Engineering

We have seen that the environmental test program is essentially a compromise between conflicting demands and pressures. The history of operations analysis has shown that it is most useful in spelling out the various conflicting demands and quantifying the relationships among them, so that a course of action can be selected that meets the requirements of the actual situation in the time required. Operations analysis begins with setting the frame of reference and bringing together the informal and formal specifications, developing an envelope of natural and induced environmental encounters, and then reconciling them with the factors that limit the scope, intensity, and duration of the environmental test. Operations analysis is not limited to the test phase alone, however. The results of field experience should be collected and fed back into the test program in the form of modifications in the required environmental envelope. This is a point of real significance in the development of complex weapons systems, where items are tested and introduced into operational use well before the development phase is complete. The final contribution is made when the lessons gained on one weapon system are used to develop the environmental program for its successor.

Mission Effectiveness

In the detailed fulfillment of the environmental program, mission-effectiveness has proved to be a powerful tool in determining how environmental test resources should be allocated to meet program requirements. This is done by setting realistic evaluation criteria (particularly in working out the distinction between the individual and system points of view), developing the envelope of probable environmental encounters, and assigning relative values to various regions of the envelope thereby establishing the trade-offs and figures of merit. In this process, the occurrence of low probability events is a point deserving particular attention. The end result of the first stages is the establishment of the environmental test plan, which may be envisioned as a map of the environmental combinations related to the facilities, testing times, and costs, all of which will be allocated.

The map is accompanied by a recommended strategy and tactics for fulfilling the plan. It is a basis of the strategy that statistical rather than deterministic data are being dealt with. The degree of uncertainty varies so much from one

facet of the problem to another that approximations are not only possible and necessary, but actually desirable. All available knowledge regarding the item and the environment is used in determining the test plan. This involves the application of scientific method, a conscious use of the techniques usually labeled "the design of experiments," and the use of a sequential approach in which knowledge gained at one part of the program is immediately fed back into the other parts. The basic philosophy is to continue the program until the results are stable within the degree of accuracy required by operational use.

Utilization of Results

The final contribution of operational analysis to environmental engineering is in the utilization of results: first, to assist in guiding future research by establishing areas of uncertainty regarding environments, materials, processes, or performances; and secondly, to indicate the payoff areas in which product improvement will be remunerative.

The operational analysis program fulfills its purpose when a reliable model and good predictors are evolved that can cope with changes in requirements. Experience with the natural and induced environments should permit prediction of performance in future situations thereby shortening the weapons development leadtime and extending the period during which the weapon system is effective.

Scope of Operations Analysis Participation

The specification is the starting point for establishing the environmental program. By specification is meant not only the formal documentation and supporting references, but also the very considerable body of knowledge concerning system purposes, user desires, etc., which do not fall within the scope of formal requirements. Thus, specifications, both formal and informal, are given different weights, depending on their importance and the supporting authority. It is therefore appropriate to briefly review here the processes by which a specification comes into being.

Environmental Specifications

Specification of the mission and mission alternatives begins at a national level. The framework for specifying missions may be traced up through the echelons of the Army, Navy, and the Air Force, through the Secretary of Defense, to the National Security Council. At this level, direction in terms of missions and their probable environments is general, but becomes increasingly specific as the directive is translated into specifics by the procuring agency. Thus, the Air Force maintains a structure of ARDC technical objectives, which sets forth in general terms the state of development in key areas and the probable trend of developments. Weapon systems are developed according to general operational requirements, which specify the purpose of the weapon system, and indicates the context of its use. Finally, the contract "statement of work," which is the basis for developing either components or a complete system, refers to specifications and specification bulletins that further define environmental requirements. Even within this convergent chain, however, there is room and, indeed, necessity to translate the mission into its environmental implications, and to review the applicability of a given environmental requirement in terms of the mission.

The scope of the review is dictated by the level concerned. It is a matter of national planning to decide whether to have weapon systems that are suitable for use only in the Temperate Zone, the Arctic, or the Tropics; or whether they shall be omni-environmental. Present policy of the Air Force is to build aircraft for global operations. Missiles and space vehicles depend on the operational concept, and in turn, on the environmental analysis prepared in the early stages of their development. This is not the concern of the analyst investigating the environmental requirement for a component. Working within the framework of the decision, the analyst must assess the probability of encountering given extreme environments, and what cost, weight, or performance penalty is acceptable to overcome a given risk.

Changes in Environmental Specifications

There is a responsibility for establishing environmental requirements at each level of the weapon system development, but this is not a one-way street. Unforeseen limitations determined at each level have a reciprocal feedback. For example, a bomber may have been required for the basic mission of high altitude bombing, and a satisfactory vehicle designed, developed, and made operational. If, because of radar countermeasure developments, it is concluded that low altitude missions are also feasible, the environmental specification is changed and the aircraft must now be further capable of performing in low-altitude turbulence and under new maneuver and load conditions. This is an instance in which technological developments in one field demand a new mission capability in another, and with it a new environmental requirement for the weapon system.

Use of Environmental Data

The importance of informal as well as formal specifications has already been noted. A constant information exchange occurs between the Armed Forces and industry through the media of published articles, briefings, symposia, visits, speeches, etc. The operations analyst must bring these together into a logically organized and usable form. Formal and informal specifications taken together provide a loose envelope from which all of the environments that will be encountered, the relative duration and frequency of such encounters, and the relative value of success in each of the combinations may be established.

Corresponding to each part of the performance requirement, assessments of the natural and induced environments are needed. Data regarding the induced environments come from performance analyses, and data concerning natural environments from other sections of this handbook. This data can then be translated into probabilities of encounter, and made specific according to the mission and geographical location. An example of how this can be done is contained in reference /10/.

Before leaving this discussion, it is necessary to note the differences between those specifications appropriate to the:

1. Research phase.
2. Experimental phase.
3. Prototype phase.
4. Product qualification phase.

During the research phase, every effort is made to obtain data regarding the characteristics of the physical environment and the current developments in physical and engineering principles. It is a period of exploration in which insight and judgment play major roles. Pilot experiments are filled out only to the extent necessary to establish knowledge sufficient for the experimental phase.

The experimental phase concentrates on developing the design principles and mechanical feasibility of the physical equipment. Here, environmental test results become useful for predicting performance of the end system. For this reason, the trend towards increasing participation of the environmental analyst in this phase has proven profitable in reducing total lead-time.

The prototype is the system embodiment which, if successful, will be brought to full scale production. The operational analyst contributes by planning the environmental program so that the very limited set of sample items are utilized to obtain information on the most critical parts of the operating regime.

During production, emphasis shifts to the following areas: (1) maintenance and adjustment of quality control for the environmental stresses, (2) utilization of feedback from the applications phase to modify environmental boundaries, and (3) establishment of bases for continued product improvement and growth.

Summary

The scope of operations analysis participation begins with working out the frame of reference of the environmental program by bringing together all of the relevant specifications and translating them into consistent details. Formal and informal specifications must be considered and relative weights assigned to each. These specifications are translated into an environmental envelope, which is usually far too complex for testing within the facilities, budget, time, and samples available. The task of reconciling these factors is the operations analyst's contribution. His participation is sequential; that is, it begins with the specifications and carries on through the research, experimental, prototype, and end product phases, utilizing data and insights obtained at each stage as reciprocal determinants of future steps. Environmental engineering does not end with the production item, but continues through the system improvement and application phases.

Establishment of Mission Effectiveness and Trade-offs

It has been seen that the key goals of operations analysis, in terms of facilities, time, and money, are the optimum environmental design and the best possible allocation of environmental test effort. This "environmental competence" of the design is attained by making the relative value of each environmental design feature an integral factor in attaining capability in the mission. To do this, two major questions must be answered: (1) what is the probability of a given set of environmental encounters, and how important are they, and (2) what are the trade-offs among the mission capabilities? The answers to these questions form the basis of environmental engineering in any specific context.

Lest the task of specifying so complex a series of interrelations seem too formidable for practical use, it should be noted that, in practice, the decision is always made, even if only by neglect. Thus, during World War II much electronic equipment shipped to England had to be rebuilt before it could be rendered serviceable. This neglect of the storage and logistic environment was an environmental design decision having unfortunate results; had the designers considered the subject, they would have realized that the equipment would have to survive handling and ocean shipment before it would ever be used. This rather obvious instance suggests the importance of actually making an explicit and detailed statement or "map" of the distribution of environmental encounters and their importance, as well as the trade-offs among them.

Definition of Scope. In any particular case, the first logical step is to define the scope of the item of system. Too broad a definition leads to unnecessary complication; too narrow a definition omits relevant factors. A practical choice is to select a functional entity that depends on the level at which the environmental design is performed. Thus, a navigational system must be all-weather, but a specific optical component may be restricted to a daylight function. Hence, the designer of the entire navigational system must consider how the various elements fit together to give him all-weather capability, but the designer of the optical element of the system may restrict his attention to day operations. Failure to attain the goal of the element has an immediate repercussion at the sys-

tem level. Thus, if the optical device fails to achieve the desired resolution under, say, conditions of temperature inversion, then there is an immediate feedback for the system designer, who must seek an alternate solution.

Assignment of Values. The value of a given environmental capability depends, first, on the probability of encountering the environment and, second, on the importance of functioning under the given conditions. Information on the probability of environmental encounters is increasingly available, and sources are given in other sections of this handbook. Thus, equipment intended to function in alternative environments and locations may have computed for them the probability of encountering given environments, and, what is of equal importance, the probability of encountering given combined environments. In cases where detailed values are lacking, a simple range estimate may suffice, or else advantage may be taken of the possible correlation with better-known environments. The important thing is that the nautre of the assumptions be made explicit so that it is possible to relate the decision made to the assumptions on which it is based.

The "weighting" of the environmental encounter regions by their importance to the mission follows logically from specifications and the preliminary system studies. As equipments have become more complex and systems increasingly large-scale, such values are increasingly difficult to assign. One reasonable way of assigning them is based on the consequence of failure (or success) to the user. Thus, failure of one part of a redundant flight power system may be a nuisance, but failure of one in series with the other equipments may be catastrophic. The value of environmental survival is complicated by the question of establishing bounds of "satisfactory" performance. Thus, the environmental engineer must be aware of just what limits of performance are acceptable from the standpoint of the mission. By making use of such evaluations, he can arrange the required environmental tolerances to attain the desired functional life of the system.

Making Decisions. Given the weighted probability of environmental encounters, the stage is set for the appropriate decision in the particular case. A decision is always made in the light of a given task, time and circumstance. Hence, the time, resource and facilities available for development and test enter as truly into the environmental decision as do conditions of a specifically engineering or mission function nature. Environmental design and testing may profitably take the point of view of decision theory, in which the weighted joint probability of environmental encounter is matched against the available resources and time to give at least a figure of merit to relative design or testing effort. [11, 12, 13, 14]

Statistical decision theory attempts to isolate the crucial points of the decision-making process by identifying the possible outcomes and penalties. Taken literally, it involves foreseeing and setting forth all of the probabilities of environmental encounter and all of the outcomes that correspond to a given degree of environmental capability, and then computing the contours of the outcome.

It is assumed that the environment will be encountered in a reasonably denumerable number of simple combinations (A in the following equations). The designer may select alternative courses of action; that is, choose to design his equipment to meet certain environments (B in the equations). Obviously, a table can be set up that gives the probability of encountering each of the environments specified in the matrix during the mission phase. To do this, a series of solutions of the following form is obtained:

$$X_1 = A_1B_1, X_2 = A_2B_2, X_n = A_nB_n$$

The alternative courses of action are now set forth numerically in terms of the unit effort to cope with requirements of intensity associated with different probabilites of encounter, and a minimum may be sought.

There are three criticisms of this procedure. The first is simply the unavailability of sufficiently detailed information regarding the environment to specify the probabilities involved. This is a factual matter and the answer may be obtained by referring to other sections of this handbook and to other literature. When factual data are lacking, it is an immediate indication of an area for research; however, in the interim, estimates may frequently be made provided that the analyst is conscious of the uncertainties in his estimation.

The second problem is that of placing envelopes on the outcomes associated with each course of action. But this judgment is always made, even if by default. Thus, the decision to state equipment specifications such that the system must operate at -40 F involves the value judgment that the need for operating at -40 F is worth the design, development and fabrication costs involved.

The third objection concerns the very considerable and difficult computations required in a particular case. This is in many ways a powerful criticism and is best answered by using the decision theory approach only for bounds, or extremes, of the probable environmental encounters.

There is an important point to remember in any probabilistic or trade-off analysis; systems must frequently operate in a hostile environment; that is, in situations where there is an intelligent opponent who strives to defeat the system. One resource against him is to operate under environmental conditions unfavorable to the defender. Therefore, low probability events must not be neglected; instead, they require careful detailed study in the light of the hostile environment.

The result of the foregoing process is a map of trade-offs and figures of merit that indicates to the designer and the test engineer just what performance must be attained, what the consequences of failure are, and how much effort should be allocated to its attainment. The map also indicates the interrelationships between the respective mission, environment and resource inputs.

Establishment of Environmental Plan

The establishment of the environmental plan follows as a consequence of the figure of merit and trade-off map. There are areas, particularly in the primary mission, in which complete environmental competence must be attained; that is, in which the equipment must have substantially zero probability of failure. Equally, however, there is a feedback between the desire to make this region as broad as possible, and the need for remaining within the resources and time available to complete the system and make it fully operational. Failure to assess this region during the course of development is paid for in terms of long lead times and excessive costs. The procedure recommended in the preceding paragraphs is desirable in this respect, in that it makes available to the designer and to the test engineer the consequences of the decision.

It must be remembered that the appropriate plan will differ according to whether the equipment is in the experimental, prototype or production stage. In the experimental stage, feasibility is being established and fundamental knowledge gained regarding the technical possibilities and the natural and induced environments. The test plan then may seek to follow only the environments deemed critical, taking wide intervals so as to obtain quantative knowledge of the system response to the environment and at least a single bound. During the prototype stage, the envelope is more closely specified, and the steps are closer together and are pointed specifically to weak spots in the design. In the production phase, environmental testing has as its goals at least the following: (1) performance demonstration and product qualification, (2) quality control, (2) quality assurance, and (4) failure analysis and trouble-shooting. The first seeks to demonstrate the inherent quality of the design, and implies that close attention has been given to the item under test. Moreover, the experimental and prototype test results are available for back-up. Hence, a small number of samples may be tested at a few critical check points. In the second and third cases, tests should not only cover critical points but also screen for process degradation. The subject is well covered in standard works on quality control, such as references /15/, /16/ and /17/. Failure analysis and trouble-shooting is obviously focused on the particular source of trouble.

It is not necessary to discuss the plan for environmental design, since it is a consequence (as noted above) of the figure of merit and trade-off analysis. The designer will, however, consider the consequences of failure on other parts of the program and select the most conservative values (upper confidence limit) during the experimental stages of the program; for it is during this phase that the extra cost is modest in comparison with the effect on the program as a whole. Then, as knowledge regarding the operational environment is fed back and a more precise knowledge of the requirements for mission effectiveness is gained the requirement itself may be optimized.

It is emphasized that the environmental goal must recognize and distinguish between the required and the discretionary elements at each stage, and that the map of required environmental competence must be fulfilled.

Strategy and Tactics of Environmental Program Fulfillment

The scope of environmental strategy is to utilize the characteristics of the technical problem, previous knowledge, and the resources of scientific method to achieve the desired goals in the required time and with the available resources. No fixed procedure can be recommended; instead, there is a body of viewpoint, insights and techniques from which only those that seem especially relevant in the present context can be selected. /18/.

In regard to the technical problem, first, it is clear that in the practical situation there are many more factors involved than can be measured or experimented with. Therefore, it is necessary to find means of unifying or "collapsing" these extensive sets of observations into regions of securely won knowledge. Second, test measurements and assessments of environmental conditions are likely to differ from those actually encountered in practice. Therefore, actual experience must be fed back to calibrate and scale the test. Program fulfillment must be iterative; that is, the environmental engineer must use each stage in learning about and solving his problem as a platform from which to achieve the next stage.

The formulation of fruitful questions and lines of attack requires that the data and assumptions that are used be actually chosen and not merely arrived at by accident. Since really serious errors and misconceptions emerge early, it is best to stay as simple as possible, and to begin with a series of exploratory runs, preferably beginning in an area of known response. As soon as irrelevant, undesired or highly correlated factors are isolated, they can be eliminated, since their effects either do not matter or can be predicted from the known.

The decision and evaluation criteria selected at any level should be consistent with those at higher levels, and the level of sub-optimization should be chosen carefully. Finally, there is a caution that cannot be overstressed: "it is the real world and not the model or the specification that is your object."

Use of Available Knowledge. The role of previous knowledge has already been noted. The environmental design and test engineer has available a considerable body of physical knowledge and theory from which to begin. The degree of certainty may vary, but he will almost never start totally in the dark. It is therefore possible to run check points in known areas, intensifying and detailing the coverage where technological surprise is encountered.

The existing body of knowledge regarding the physical universe provides physical laws that may be interpolated and, with rather more caution, extrapolated to a first estimate. Also, as has been noted previously, the goals in each phase of environmental test differ; those during basic research have a primary exploratory nature; these are followed by the other phases, which yield increasingly specific knowledge. The formulation of the strategy of testing first involves a survey of the physical laws and engineering data applicable to the item*. Thus, the properties of given metals in high temperature are so well-known that the degree of variability to be expected would be much less than that for, say, certain elastomers.

In many cases, it is possible to extrapolate from other similar items. Here again, the stage of the program is important. Much less extrapolating and estimating may be necessary during the prototype stage than in the research and experimental stages; and the end product performance estimate depends even less upon judgment.

Selection of Test Method. It is at this point that a decision can be made as to whether the appropriate test is a single test, or a combined or hurdle test. If there are no interactions among the environments or functions, then single tests are appropriate. The degree of the interaction determines the necessity for a combined approach.

The decision to simulate the actual environment, or to employ accelerated or hurdle testing depends on the availability of a scale for measuring the effect of the acceleration or of the hurdle. The response of most items under environmental stress is linear under only a portion of the regime, and in setting the hurdle or acceleration test it is necessary to avoid violent discontinuities in the response. For the best use of accelerated and hurdle testing, it is desirable to have the possibility of an interval scale; that is, a way in which a given increment in the environmental stress can be related to corresponding changes in the response of the item.

Environmental testing is, of course, performed on a sample, even when only one item is being tested, and the same item is used both for test and operation. This is true because, while we may not be sampling the equipment, we are in fact sampling the equipment-and-its-operating-time. The decision to regard successive operation at different times as equivalent may, of course, be made, but should be a conscious one.

The desire to extract the maximum amount of meaningful information from given tests implies a sequential approach, in which data and conclusions from one test are used to decide the course of action in the next; that is, whether to increase the sample size, conclude the test, or narrow the test interval. Modern experimental design strongly stresses this "evolutionary" approach. An excellent account is given in reference /15/; sequential methods are well treated in reference /19/. Much of this material is primarily within the professional competence of the statistician; however, the environmental designer and test engineer will find the underlying viewpoint well worth assimilating. It will aid him in attaining the benefits of doing the statistical design before, and not after the experimental work is done. If he follows this course, he will avoid the regrets common to much work in this field.

A Note on Statistical Technique

The ready availability of statistical texts at almost all levels makes it possible to dispense with a lengthy discussion of basic statistics in this handbook. As a minimum, the environmental engineer will want to be able to communicate with the operations analyst and statisticians who support his work, and others who must integrate his results into system evaluation. The following is a check list of recommended topics with which he should be familiar:

1. The idea of a random variable.
2. Statistical notation.
3. Definitions and properties of the average variance and standard deviation.
4. Standard statistical distributions, including the normal, lognormal, rectangular, x^2 (chi-square), binomial, Poisson, t, and f distributions.
5. Curve fitting and least squares.
6. Confidence interval estimation.
7. Tests of hypotheses.
8. Analysis of variance.
9. Nonparametric statistics.

An excellent general introduction to the application of statistical methods may be found in reference /18/. This book also provides useful and wise advice on almost the entire range of problems encountered in practical scientific and engineering investigation.

* The word "item" is used here to avoid the cumbersome enumeration of the hierarchy—part, component, assembly, unit, subsystem and system.

Other useful references are listed at the end of this chapter. Particularly recommended is reference /20/, one of the most complete and yet useful works. More elementary, but excellent, are references /21/ and /22/. The important field of non-parametric statistics is covered in an introductory, but thoroughly useful, fashion in reference/23/.

Statistical estimation also has its trade-offs in technique, and the analyst will always want to consider the relative value of a rapid estimate based on a few measurements with a larger confidence interval as opposed to large sample techniques. A useful pocket guide in this area is reference/24/.

The design of experiments is dealt with from a philosophical, yet practical, point of view in reference /25/, and a large number of experimental designs are given in reference /16/. Reference /15/ is worthwhile reading for the environmental engineer, whether or not he participates directly in designing the underlying statistical structure of the test sequence. Reference /26/ is a classic. Because of the frequent relevance of the lognormal distribution to experimental data, reference /27/ is also listed.

Assessment of Environmental Plan Fulfillment

The purpose of system development is to insure effective performance in the mission environment. Therefore, the implementation of the environmental plan must be followed at each stage, first to assess prospects, then to insure the actual fulfillment of the plan, and finally to gain a basis for predicting the future. The evaluation is performed at two different levels: across time as the system is developed; and for a given item in a given test. The two aspects are sufficiently different to merit separate consideration.

Figure 4-2 presents a block diagram of a typical system development sequence. The process begins with the mission, which is translated by means of operations research studies into the desired system characteristics. These characteristics then lead to an engineering selection of the technical alternatives, which are either in the realm of available technology or else constitute a research area. The two taken together lead to a technical solution. The solution is implemented by prototypes and production quantities, which go to service test and operational use. The mapping of the environment-mission-value, previously discussed, is the basis of the evaluation process. As shown in Figure 4-2, opportunities for assessment occur in at least six stages, beginning with the engineering consideration of the technical alternatives, on through the operational use stage. For most large scale developments, this process may be envisioned as of the order of four to eight years (corresponding to the actual development cycle). The results of this sequential consideration are fed back to the mission and the desired system characteristics blocks. The environmental plan should receive the same intense scrutiny as the other key system aspects. The information obtained at any one stage may then be fed back to guide the succeeding stages or, if necessary, to appropriately adjust the mission or the means.

At the detail level of assessing test fulfillment, the environmental engineer must determine, for the particular problem, the allowable uncertainties and, by utilizing appropriate statistical techniques and engineering analysis, select the proper cut-off point. The price of increasing confidence comes high. Figure 4-3, for example, gives reliability levels for a series of tests with and without failures. The rapid increase in the number of test samples for high-confidence coefficients is evident. The decision as to when the test plan has been fulfilled, there-

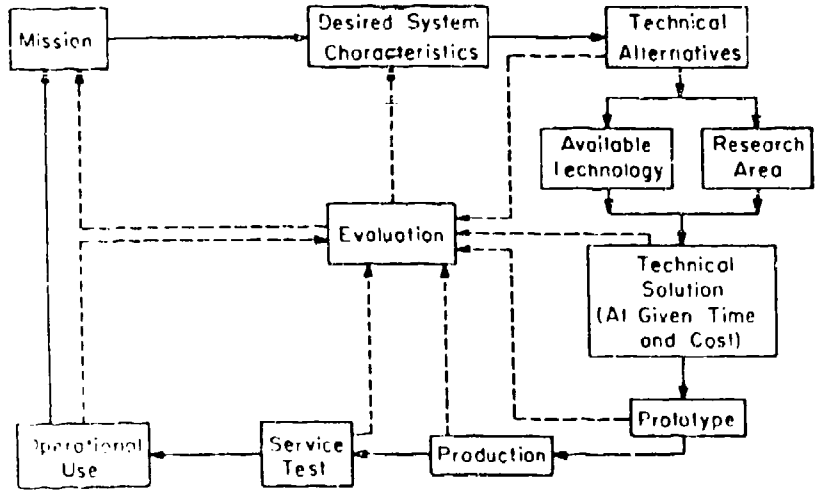


Fig. 4-2. System development interrelations.

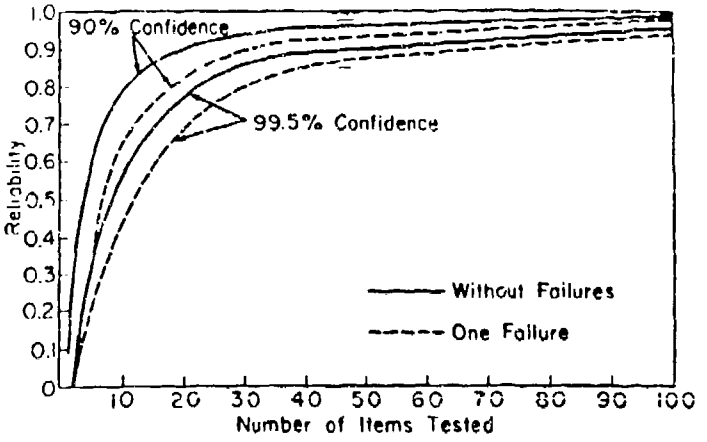


Fig. 4-3. Reliability levels for series of tests with and without failures

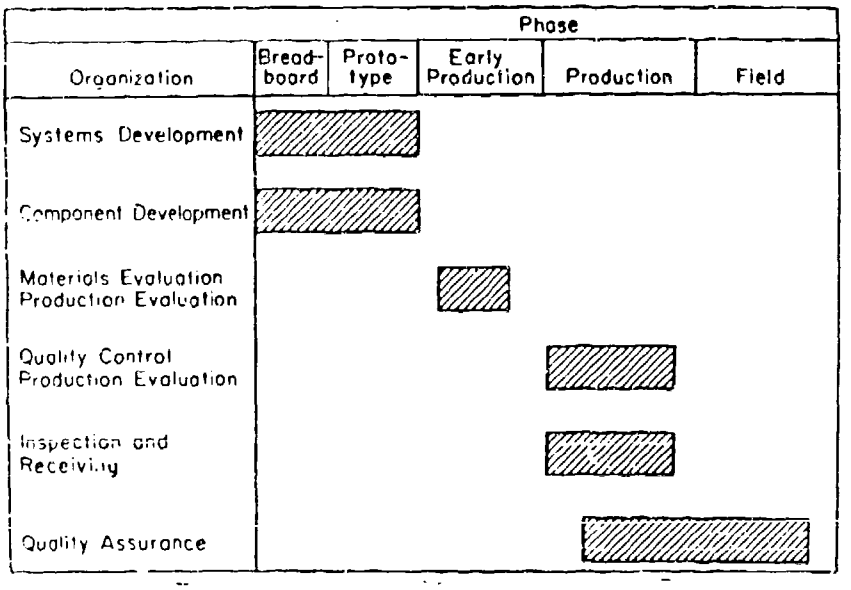


Fig. 4-4. Organizations requiring use of environmental facilities./28/

fore, is an integral part of choosing the allowable level of uncertainty commensurate with the grand design of the system.

Utilization of Results

Figure 4-4 shows some of the various groups that require test evaluation work in the various phases of design and development.

The systems point of view applied to the utilization of environmental test results is highly profitable in the following areas:

1. Determination of further research directions.
2. Product improvement.
3. Quality control.
4. Formulation of environmental models and predictors.
5. Changes in mission value weights.
6. Bases for future environmental planning.

The system of comparisons and feed-backs brings to the fore areas of ignorance or uncertainty. Moreover, the value weights give the relative importance that should be attached to a given increase of knowledge of any given point. Therefore, not only are research areas distinguished, but also a relative priority is indicated.

Product improvement areas follow logically from failure to attain the mission goals. Here again, the weights play an important part in guiding the allocation of resources. Conversely, the approach also provides a measure of protection against the disease of tinkering with the design, and expending resources on product improvement for its own sake.

Quality control is made effective by relating competence in a given environment to the tolerances which must be maintained at the manufacturing level. The evaluation procedure discussed above may be integrated with the conventional, well-established quality control techniques to adjust the acceptable tolerances (and hence the cost) to the purpose at hand. Here the designer will want to consider not only the immediate mission but also the secondary and future missions to which the equipment may be assigned during its useful life.

A major pay-off area lies within the scope of environmental technique itself. The present assortment of single, combined, accelerated and hurdle tests may be systematized into an established series of environmental models and predictors.

Evidently, the sequential assessment of environmental competence through the life history of a system ultimately leads to a comparison of the initial judgment of the mission environment with that encountered in practice. The corresponding changes in the mission values act to shorten development lead time and attain the goal of an effective system at minimum cost. The same process lays the basis for planning future environmental requirements. These become increasingly consistent, explicit, predictable and responsive to the needs of modern technological development.

The Future of Environmental Operations Research

Operations research methods are capable of making a profitable contribution to environmental engineering. The preceding discussion has given hints as to its proper utilization at each stage of the research, development and use phases. It has shown how the approach leads to an explicit understanding of the environmental plan in relation to the system as a whole, and provides a basis for working out the optimum trade-offs. It leads to increasing information regarding the operational environment and models appropriate for its simulation.

Environmental operations research will evidently grow and develop within the scope of environmental engineering, and the contributions it may make will grow as systems and environments become more complex and demanding.

REFERENCES

1. Minzner, R. A., K. S. W. Champion and H. L. Pond, The ARDC Model Atmosphere, 1959, AFCRC-TR-59-267, Air Force Surveys in Geophysics No. 115, Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, Bedford, Massachusetts, August 1959.

2. Hilsenrath and Beckett, Tables of Thermal Properties of Gases, National Bureau of Standards Circular No. 564, 1955.

3. Keenan, J. A. and J. Kaye, Gas Tables, Thermodynamic Properties of Air, John Wiley and Sons, Inc., New York, 1948.

4. Handbook of Geophysics, Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, Bedford, Massachusetts, 1957.

5. Environmental Requirements for Electronic Component Parts, Military Standard-441, Superintendent of Documents, U.S. Government Printing Office, Washington 25, D. C.

6. Climatic Extremes for Military Equipment, Military Standard-210A, Superintendent of Documents, U.S. Government Printing Office, Washington 25, D. C., 2 August 1957.

7. Klein, Elias, Fundamentals of Guided Missile Packaging, Shock and Vibration Factors, OASD (Rand E) Publication RD219/3, July 1955.

8. DiTarranto, R. A. and J. J. Lamb, Preliminary Investigation of Hyper Environments and Methods of Simulation, Parts I, II and III, WADC TR 57-456, ASTIA Document Nos. AD 142002, AD 142167, and AD 142338, Contract No. AF 33(616)-3915, Project No. 1111, Task 1300, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1957-1958.

9. Hitch, C., "Sub-optimization in Operations Research," Operations Research, 1953.

10. Thompson, James K., Fifth Phase Hot Weather Flight Test Criteria, WADC TN 57-387, ASTIA Document No. AD 142155, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, November 1957.

11. Davies, M. and M. Verhulst, Operational Research in Practice, Pergamon Press, New York, 1958.

12. Flarle, C. D., W. H. Huggins and H. Roy (Editors), Operations Research and Systems Engineering, The Johns Hopkins Press, Baltimore, 1960.

13. Goode, H. H. and R. E. Machol, System Engineering, McGraw-Hill Book Company, Inc., New York, 1957.

14. Williams, J. D., The Complete Strategyst, McGraw-Hill Book Company, Inc., New York, 1954.

15. Box, G. E. P., L. R. Connor, W. R. Cousins, O. L. Davies, F. R. Himsworth and G. P. Sillitto, Design and Analysis of Industrial Experiments, Hafner, New York, 1956.

16. Cochran, W. G. and G. M. Cox, Experimental Designs, Second Edition, John Wiley and Sons, Inc., New York, 1957

17. Shewart, W. A., Statistical Method from the Viewpoint of Quality Control, Graduate School, Department of Agriculture, Washington, 1939.

18. Wilson, E., Jr., An Introduction to Scientific Research, McGraw-Hill Book Company, Inc., New York, 1952.

19. Wald, A., Sequential Analysis, John Wiley and Sons, Inc., New York, 1947.

20. Kendall, G., The Advanced Theory of Statistics, Charles Griffin and Co., Ltd., London, 1948. Two Volumes. Vol. I revised 1958, Two Additional Volumes in preparation.

21. Mood, A. M., Introduction to the Theory of Statistics, McGraw-Hill Book Company, Inc., New York, 1950.

22. Dixon, W. J. and F. J. Massey Jr., Introduction to Statistical Analysis, McGraw-Hill Book Company, Inc., New York, Second Edition, 1957.

23. Siegel, S., Non-Parametric Statistics, McGraw-Hill Book Company, Inc., New York, 1956.

24. Quenouille, M. H., Fundamentals of Statistical Reasoning, Stechert-Hafner, Inc., New York, 1959.

25. Cox, D. R., Planning of Experiments, John Wiley and Sons, Inc., 1957

26. Fisher, Sir R. A., The Design of Experiments, Sixth Edition, Oliver and Boyd, London, 1951.

27. Aitchison, J., and J.A.C. Brown, The Log-normal Distribution, Cambridge University Press, London, 1957.

28. Hooper, R. S., Evolution of Environmental Testing, presented at annual meeting of Institute of Environmental Science, Chicago, Illinois, April 1959.

BIBLIOGRAPHY

Anderson, R. L. and T. A. Bancroft, Statistical Theory in Research, McGraw-Hill Book Company, Inc., New York, 1952.

Bartlett, M. S., An Introduction to Stochastic Process with Special Reference to Methods and Applications, Cambridge, London, 1955.

Churchman, C. W., R. L. Ackoff, and E. L. Arnoff, Introduction to Operations Research, John Wiley and Sons, Inc., New York, 1957.

Deming, W. E., Some Theory of Sampling, John Wiley and Sons, Inc., New York, 1950.

Ezekiel, M., Methods of Correlation Analysis, Second Edition, John Wiley and Sons, Inc., New York, 1941.

Fisher, Sir R. A., Statistical Methods for Research Workers, Thirteenth Edition, Oliver and Boyd, London, 1958.

Goldman, S., Information Theory, Prentice-Hall, Inc., 1953.

Hannan, E. J., Times Series Analysis, John Wiley and Sons, Inc., New York, 1960.

McCloskey, J. F., and J. M. Coppinger, (Editors) Operations Research for Management, Volume II, Second Edition, Johns Hopkins Press, Baltimore, 1956.

Merrill, G., H. Goldberg and H. Helmholz, "Operations Research, Armament, Launching," Principles of Guided Missile Design, Volume III, D. Van Nostrand Company, Inc., 1956.

Nichols, N. B., and R. S. Phillips, Theory of Servomechanism, McGraw-Hill Book Company, Inc., New York, 1947.

Saaty, T. L., Mathematical Methods of Operations Research, McGraw-Hill Book Company, Inc., New York, 1959.

Sasiene, M., A. Yaspan and L. Friedman, Operations Research, John Wiley and Sons, Inc., New York, 1959.

Methods of Operations Research, Volume 2A, Summary Technical Report of Division 6, National Defense Research Committee, Washington D. C., 1946.

"Statistical Procedures for Determining Validity of Suppliers' Attributes Inspection, "Quality Control and Reliability Handbook (Interim) H109, Superintendent of Documents, Washington D. C., 1960.

CHAPTER 5

ENVIRONMENTAL PROTECTION

Designing flight vehicle systems to operate reliably under the many expected adverse environments presents many problems. The problems are generally more difficult to solve for a flight system than for a land or sea-based system because (1) the flight system usually has severe weight and size restrictions imposed on it, and (2) the high velocity of flight vehicles often results in more extreme combinations of environments. To further complicate the problems, flight systems are rapidly becoming more complex and sophisticated, so that not only do hyperenvironmental combinations become problematical, but much more equipment is being used, which also requires protection.

There are two basic approaches to environmental protection;

1. Use of materials and designs that can withstand the environments.

2. Control of the environments to within limits where they can be withstood.

The first method is the most desirable, since it generally does not require the use of additional equipment; added equipment increases cost and weight, uses needed space, and increases the protection problem because the additional equipment is also exposed to the environments. The use of proper materials and design calls for constant awareness on the part of the designer of the continuing new developments and studies made by industry and the military.

When it is not practical or possible to design equipment to withstand the environments, environmental control should be exercised. This includes measures such as temperature control, shock and vibration isolation, radiation shielding, etc. It is important to note that control of environments does not always require additional equipment. Many of the induced environments are created by the vehicle system itself. Heat, shock and vibration are some examples of such environments. By the careful choice and design of some pieces of equipment, less heat, shock and vibration will be produced.

In many instances, the design complexities and weight and space limitations are so great that neither one of the protection approaches will suffice by itself. In these cases, judicious compromises will have to be made. Proper choice of materials and design may be carried out to a practical point where only a minimum of environmental control equipment is needed.

MATERIAL STUDIES

To aid designers in choosing the proper materials for various applications, military agencies continually sponsor material studies. Various types of studies are conducted: Some determine the general reaction of certain materials to various environments; others determine the environmental limitations of materials; and still others investigate the feasibility of using certain materials and alloys for future applications. Some studies are highly specialized, investigating only such items as parachute materials. Others are broad in scope, covering a large number of materials such as:

Plastics	Antiseize compounds
Metals	Gasket materials
Metallo-organic compounds	Hydraulic fluids
Ceramics	Chemicals
Transparent materials	Sealing compounds
Textiles	Semiconductor materials
Coating materials	Dielectric materials
Lubricants	Insulating materials
Adhesives	Hydrocarbon fuels
Magnetic materials	

The results of the studies can be obtained in reports made available by the Armed Services

Technical Information Agency or from the original service organizations that sponsored the studies. For example, abstracts of 270 technical reports written for the Materials Laboratory of Wright Air Development Division from July 1956 to June 1957 can be obtained in WADC TR 53-373, supplement 4 (ASTIA Document No. AD 131001). These abstracts present a review of the Air Force materials research and development program during that period. A complete list of all known organizations or agencies, both military and industrial, that may be designated as materials information centers on the basis of their collecting and disseminating up-to-date data on materials research and development is contained in WADD TN 60-246. Specific problems concerning new types of materials or application of materials should be directed to the Materials Central, Directorate of Advanced Systems Technology, Aeronautical Systems Division (formerly WADD).

HIGH-TEMPERATURE PROTECTION

The following paragraphs describe methods and techniques for protecting flight vehicles and their associated equipment from the degradative effects of high temperatures. First, the selection of materials and components capable of withstanding high temperatures is discussed. Then, passive protection techniques, such as compartmentation, use of insulation, and choice and location of equipment, are covered. Next, a discussion is given of the various means of heat removal and the equipment used with each. And finally, the different cooling systems that might be used in flight vehicles are discussed, together with the advantages and disadvantages of each, and the considerations involved in selecting one of the systems for a particular application.

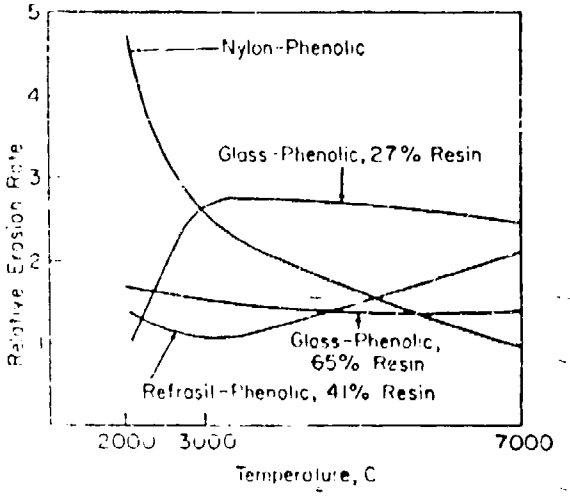


Fig. 5-1. Relative erosion rates for different plastics as a function of temperature./1/

MATERIALS

Selection of Materials

Two points must be considered when choosing materials for high-temperature operation. The first is to choose a material with a low specific heat rating, which denotes the heat-absorbing quality of the material. Choose the material that will operate coolest in a given temperature environment. The second is to choose materials that will still have the needed physical properties at the anticipated temperatures.

Plastics/1/

Plastics decompose slowly, and in doing so they absorb large amounts of heat and generate a considerable volume of gas that interferes with the convective transfer of heat to their surface. Erosion of plastics varies markedly with temperature. This is shown for a selected group of plastics in Fig. 5-1. The group includes a nylon-reinforced phenolic resin, which contains no inorganic materials; two glass reinforced phenolic resins, with one rich in glass and the other rich in resin; and a Refrasil-reinforced phenolic resin. At each of three temperatures, the best material is rated "1" on the graph, and the others are then rated according to their relative erosion rates. The curves indicate relative performance of each material compared to the others at a particular temperature. Actually, the nylon-reinforced material does not erode more slowly as the temperature is raised; on the contrary, its erosion rate at 7000 C is greater than it was at 2000 C, but is less than the others at 7000 C.

Plastic Laminates

Phenolic-formaldehyde laminates are able to withstand temperatures up to 390 F (200 C). These phenolics are always reinforced with various fibers, such as glass, silica, nylon or asbestos. The fiber reinforcement aids in preventing catastrophic failure under extremely high temperatures. The high-temperature performance of phenolics is due to phenol-formaldehyde condensation products decomposing more slowly at higher temperatures than the other organic polymers. The condensation products are simple gases and a refractory carbon residue. The residue protects the underlying material, to a certain extent, from the heat. A composite laminate, consisting of alternate laminations of asbestos-phenolic and nylon-phenolic, shows possibilities for use in missile nose cones under reentry conditions. Figure 5-2 shows the thermal insulation characteristics of this laminate in comparison with other types of laminates. The curves were obtained by embedding a thermocouple in the center of 1/4-inch thick sheets, and applying a temperature of about 2300 F (1260 C) to the surface of the sheets.

For service under extremely high temperatures and corrosive action due to flames, modifications with styrene, diallyl phthalate, diallyl

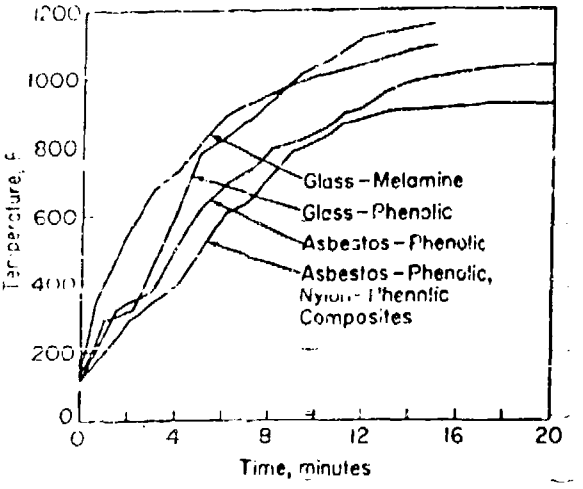


Fig. 5-2. Thermal insulation comparison of high-temperature phenolic laminates./2/

isophthalate and triallyl cyanurate have shown good results up to about 5000 F (2760 C).

Several plastic laminate materials with the ability to survive temperatures from 4500 to 6000 F (2500 to 3300 C) for a fraction of a second are in production and are intended for short-time application in missiles or rockets.

Compounds, Fillers and Fibers

Few, if any, of the basic resins can withstand a temperature greater than 480 F (250 C). With some modifications, temperature resistance may go up to about 660 to 700 F (350 to 375 C), but for higher-temperature service, suitable loading or reinforcement with inorganics is essential. Tests of TFE-fluorocarbon resin with various concentrations of quartz, mica, glass and asbestos (10, 20, 30, and 40 percent of weight) have shown that a 20-percent glass-filled TFE-fluorocarbon provides an optimum combination of resin and filler. This was determined in a test that simulated the thermal effects of missile reentry; the filled samples were exposed to 2700 F (1500 C) for a period of 30 seconds./3/

Ceramic encapsulants for use from about -75 to 2000 F (-60 to 1100 C) can be applied in the same manner as most conventional encapsulants. Ceramic spheres, either hollow or solid, bonded with phenolic resins or inorganic binders provide low-density materials for a variety of applications, including light-weight potting and embedment. A family of such low-density moldable compounds is reported to have given satisfactory service for 30 to 60 seconds at temperatures exceeding 4000 F (2200 C). Ceramic materials for 930 F (500 C) operation have been developed for coatings, cements to bond insulating surfaces to metal parts, ceramic-base sheet insulation, refractory-type fillers and castables for hermetic construction, and encapsulating compounds for protecting entire units.

Some commercially available electrical materials that are able to withstand high temperatures, together with suggested applications, are given in Table 5-1./2/

Metals/4/

For flight vehicles, the ideal metal would be one with a high melting point, excellent strength and ductility, and near zero density. Unfortunately, such a metal does not exist. The next best thing is to modify existing metals and search for new ones that will approach the desirable properties. Some of the better temperature resistant existing metals are listed in Table 5-2, together with the source from which data can be obtained concerning each metal. The specific heat ratings of these metals at various temperatures are given in Table 5-3.

Aluminum

Aluminum Alloy X2020 T-6 contains copper and lithium. Its room-temperature properties are somewhat higher than those of 7075 T-6, which up to now has been the strongest standard aluminum alloy. Alloy X 2020 has superior tensile properties in the lower temperature range; up to almost 400 F (205 C) for a 1000-hour exposure. For shorter exposure times, its superiority is extended to over 400 F.

Table 5-1. Commercially Available High-Temperature Materials /2/

Material	Application	Evaluation temperature F (C)
Alumina microspheres	Encapsulation	950 (510)
Reconstituted phlogopite mica	Interlayer insulation	950 (510)
(a) Glass braid (b) Ceramic	Magnet wire insulation	950 (510)
(a) Magnesia (b) Boron nitride (c) Alumina	Capacitor dielectric	950 (510)
(a) Pyroceram glass ceramic (b) Alumina	Radomes	1300 (704)
(a) Forsterite (b) Alumina	Metal-ceramic electron tube structures	750 (399)
Tin dioxide plus antimony oxide	Resistor film	950 (510)

Table 5-2. Some Better Temperature-Resistant Metals /4/

Metal	Source
K-Monel	International Nickel Co.
Inconel	International Nickel Co.
Inconel X	International Nickel Co.
Stainless steel, Type 301	Republic Steel Corp.
Stainless steel, Type 316	Timken Roller Bearing Co.
Stainless steel, Type 347	Timken Roller Bearing Co.
SAE 1010 mild steel	United States Steel Corp.
Magnesium alloy, Type AN-M-29	Dow Chemical Co.
Aluminum alloy, Type 24S-T6	Aluminum Company of America
Aluminum alloy, Type 75S-T6	Aluminum Company of America

Alloy X 2219 T-6 was developed for high-temperature service. It contains copper, manganese, and small amounts of vanadium and zirconium. This alloy is best in the range of 400 to 600 F (205 to 315 C). Although primarily a forging and extrusion alloy, it can be rolled into sheets and plates. Figure 5-3 shows the strength-to-weight ratios for the best aluminum alloys.

A significant aluminum development is the sintered aluminum powder (SAP) type of products, which use aluminum flakes containing various amounts of aluminum oxide. The properties of these powder products vary with particle size and volume of oxide. In general, they are usable up to about 1000 F (537 C). One such composition is M257. The creep and rupture properties of the aluminum powder products at 600 F (315 C) are superior to conventional aluminum alloys.

Magnesium. Alloys containing thorium have increased the usable temperature of magnesium up to 900 F (482 C) for short-time, low-stress applications. Figure 5-3 shows the best magnesium alloys in their recommended temperature ranges. Alloy AZ-31, the standard sheet alloy, has the highest room-temperature properties,

Table 5-3. Specific Heats* of Ten Metals /4/

Temperature C	K-Monel	Inconel	Inconel X	Stainless steel, Type 301	Stainless steel, Type 316	Stainless steel, Type 347	SAE 1010 mild steel	Magnesium alloy, Type AN-M-29	Aluminum alloy, Type 24S-T6	Aluminum alloy, Type 75S-T6
-200	0.062	0.065	0.064	0.070	0.069	0.071	0.053	0.160	0.112	0.115
-150	0.73	0.075	0.075	0.081	0.080	0.081	0.069	0.182	0.141	0.142
-100	0.083	0.084	0.085	0.091	0.089	0.090	0.082	0.200	0.165	0.164
-50	0.091	0.092	0.093	0.099	0.098	0.098	0.093	0.216	0.184	0.182
0	0.097	0.099	0.100	0.107	0.105	0.105	0.102	0.299	0.198	0.196
100	0.107	0.110	0.110	0.118	0.117	0.116	0.115	0.248	0.218	0.216
200	0.114	0.117	0.116	0.127	0.125	0.124	0.126	0.263	0.231	0.231
300	0.117	0.122	0.120	0.132	0.130	0.130	0.134	0.274	0.243	0.248
350	---	----	----	----	----	----	----	0.279	----	----
400	0.120	0.126	0.124	0.136	0.134	0.134	0.145	----	0.262	0.270
450	----	----	----	----	----	----	----	----	0.276	0.286
500	0.123	0.130	0.128	0.139	0.136	0.138	0.159	----	----	----
600	0.128	0.135	0.133	0.142	0.139	0.142	0.179	----	----	----
700	0.135	0.141	0.143	0.145	0.143	0.146	0.209	----	----	----
800	0.146	0.150	0.156	0.149	0.148	0.152	0.203	----	----	----
850	0.153	0.156	0.167	0.152	0.152	0.156	0.283	----	----	----

* Specific heat given in gram calories per gram per degree C.

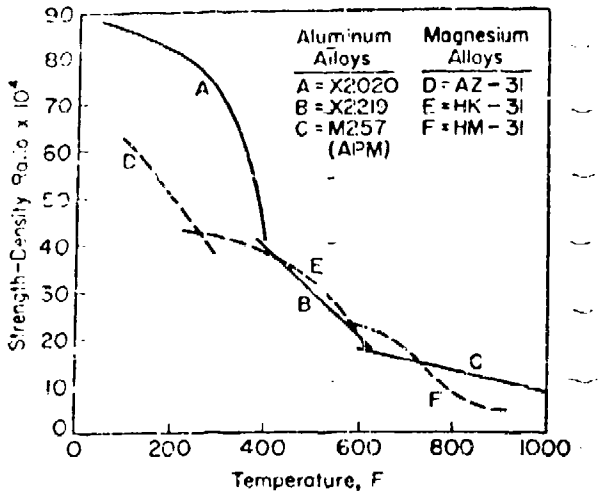


Fig. 5-3. Capabilities of aluminum and magnesium alloys for high-temperature applications. Strength-density ratio is ultimate strength psi to density in pounds per cubic inch./4/

but it is exceeded in high-temperature properties by HK-31 H-24 in the range 300 to 550 F (150 to 288 C), and by HM-21 XA T-8 above 550 F. Alloy HM-21 is exceptionally stable at elevated temperatures. For example, exposure for as long as 100 hours to 700 F (371 C) has very little effect on its properties. Its creep properties at 400 F (205 C) and above are better than those of HK-31.

Thorium additions also extend the temperature range for magnesium castings. EZ-33 is typical of the rare-earth-zirconium alloys, and HK-31 of the thorium-zirconium composites. The former has applications in the 350 to 550 F (177 to 288 C) range, while the alloys containing thorium are definitely superior above 400 F (205 C). Magnesium alloys work out well for thin-walled castings. Wall thicknesses as low as 3/32-inch are now approved for aircraft use.

Titanium. The strength-to-density ratio of titanium is its most publicized property. In this respect, it is superior to many metals over an intermediate, although wide, temperature range. Figure 5-4 gives a comparison of yield strength-to-density ratio as a function of temperature for titanium, beryllium and ferrous-base alloys. On this basis, the hot work die steels are the most competitive materials. Beryllium, with its low density, will be competitive when it becomes available in greater quantities. The top curve in Fig. 5-4 represents the new all-beta titanium alloy. It has the potential of being heat treated to an ultimate tensile strength of over 250,000 psi.

The maximum temperature at which titanium can be used appears to be about 2000 F (1093 C) for very short-time exposure and 1100 F (593 C) for long-time exposure. Creep strength is not necessarily the limiting factor at high temperatures. Above 1100 F (593 C), titanium absorbs oxygen and nitrogen at rates sufficient to interfere with its usefulness.

Beryllium. The thermal properties of beryllium, with a melting point of 2343 F (1280 C), make it highly desirable for heat-sink applications. Its strength-to-weight ratio is high; few metals can approach it. A unique advantage of beryllium is its great stiffness, with a modulus of elasticity exceeding that of many other metals, including steel.

Despite its advantages, beryllium is presently utilized in limited, but important, applications because of inherent undesirable properties as well as scarceness. Joining beryllium to itself and to other metals presents a problem, as does the entire area of fabrication when it is compared to the more common structural metals. In addition, beryllium is toxic, and specialized equipment is required when working with it.

Transparent Solids. Some transparent solids with possible high-temperature applications are listed in Table 5-4 together with sources from which information concerning them may be obtained. The specific heat ratings of these transparent solids are given in Table 5-5.

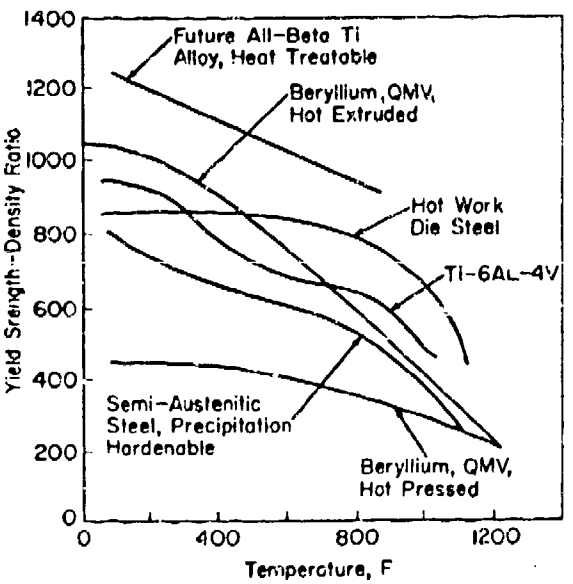


Fig. 5-4. All-beta titanium alloy compared with beryllium and ferrous-base materials on a strength-to-density basis at high temperatures. Strength-density ratio is yield strength in 1000 psi to density in pounds per cubic inch./4/

Table 5-4. Some Transparent Solids /5/

Material	Source
Clear fused silica (quartz)	Hanovia Chemical Co.
Vycor	Corning Glass Works
White (clear) plate glass	Pittsburgh Plate Glass Co.
Pyrex clear chemical glass No. 774	Cincinnati Gasket and Packing Co.
Solex "S" plate glass	Pittsburgh Plate Glass Co.
Solex 2808X plate glass	Pittsburgh Plate Glass Co.
Plexiglass, AN-P-44A, aircraft quality	Rohm and Haas Chemical Co.

Magnetic Materials /3/

The curie temperature of metallic core materials is relatively high, and for the present, silicon steel has been used successfully for 935 F (500 C) operation. For higher temperatures, it may be necessary to investigate cobalt-iron alloys, which have a higher curie temperature and very desirable magnetic characteristics, although their activation characteristics under nuclear radiation might be prohibitive. Nickel alloys have curie temperatures in the vicinity of 935 F (500 C). At temperatures above 935 F, grain growth in the material is expected, which will change its magnetic properties. Its usefulness depends upon the resulting orientation and size of grains, and the application for which it is used. Better core materials should be developed for operation above 935 F.

Ferrite materials are available over a range of -240 to 480 F (-150 to 250 C). Nickel-zinc ferrites with additives are used up to 390 F (200 C), and it may be possible to extend the operating temperature to 480 F (250 C). Curves indi-

Table 5-5. Specific Heats* of Seven Transparent Solids /5/

Temperature (C)	Clear fused silica (quartz)	Vycor	White (clear) plate glass	Pyrex Type 774	Solex "S" plate glass	Solex 2808X plate glass	Plexiglass Type AN-P-44A
-200	0.047	0.041	0.075	0.045	0.072	0.071	0.102
-150	0.081	0.080	0.102	0.084	0.101	0.103	0.174
-100	0.112	0.114	0.129	0.117	0.127	0.130	0.219
-50	0.138	0.142	0.153	0.145	0.151	0.155	0.252
0	0.161	1.166	0.174	0.170	0.173	0.176	0.288
50	---	---	---	---	---	---	0.340
100	0.199	0.202	0.210	0.208	0.208	0.210	0.425
200	0.226	0.221	0.236	0.235	0.235	0.234	---
300	0.245	0.240	0.255	0.255	0.254	0.251	---
400	0.059	0.251	0.266	0.271	0.264	0.262	---
500	0.269	0.262	0.270	0.289	0.268	0.271	---
600	0.277	0.277	---	---	---	---	---
700	0.286	0.302	---	---	---	---	---
800	0.299	0.338	---	---	---	---	---

*Specific heat given in gram calories per gram per degree C.

cating permeability, magnetic Q, and their product, μQ, rise linearly from -240 to 480 F (-150 to 250 C) for some compositions, while for others the curves tend to peak around 390 F (200 C). There is need for additional work to improve the characteristics of ferrites for practical applications.

Dielectric and Insulating Materials/6/

Lead barium-titanate with additives shows promise for use as a dielectric at 480 F (250 C). It exhibits a 25 to 50 percent variation in dielectric constant over the temperature range of -85 to 480 F (-65 to 250 C). Silicon monoxide maintains good dielectric properties up to 390 F (200 C), and indicates possible future operation at 570 F (300 C).

Teflon may be used as a dielectric up to 390 F (200 C). Its temperature capabilities may be increased by operation in an atmosphere of oxygen or nitrogen. In a range of frequencies from 60 cps to 10^8 cps, the dielectric constant of Teflon is from 2.0 to 2.2 and the dissipation factor is less than 0.0005.

Films of zirconium dioxide formed on substrates of aluminum, highly polished on one side for test purposes, have been investigated as a possible dielectric material for 930 F (500 C) operation. Lead zirconate-titanate with an additive also appears feasible for use at high temperatures. Disks of this material have been held at 480 F (250 C) under normal atmospheres with an applied field of 30 volts per mil for 1000 hours without excessive deterioration.

Various forms of mica afford good electrical insulation properties at high temperatures. The best grades of natural muscovite mica bonded with glass will withstand temperatures from about 645 to 690 F (340 to 370 C) without distortion; with fluor-phlogopite mica, the range is 790 to 895 F (420 to 480 C). Reconstituted sheet mica, obtained by binding small flakes with an organic or silicone binder, is subject to temperature limitations of both the binding medium and the type of mica. Fine particles of synethetic mica hot pressed into homogeneous blocks result in a dense, ceramic-like dielectric material that is soft and machinable, and has transverse strengths of 8000 psi at temperatures up to 735 F (390 C). Its dielectric constant varies a little with temperature for most compositions, changing less than five percent when heated to 735 F. The power factor remains less than one percent up to 535 F (280 C).

Coefficient of Expansion of Materials

When different materials are used together, the coefficients of expansion must be known. If joined materials have widely different coefficients of expansion, buckling or rupturing may occur as the materials pass through a range of temperatures. From the information given in Table 5-6, metals, plastics, ceramics and natural insulators with similar coefficients of expansion can be quickly selected. This table is useful for narrowing the choice of materials, but more specific data should be obtained from manufacturers.

COMPONENTS

Selection of Components

The problems associated with operation of components at high ambient temperatures are basically those of obtaining suitable materials, and, where necessary, finding suitable fabrication techniques for materials that may be unique for the application. For data on the application of existing components in military equipment, refer to reference /8/. The following information deals with the feasibility of obtaining components for 500 C (930 F) operation. /9/

Capacitors. Operation of capacitors at 500 C (930 F) at present appears difficult, particularly with gas-dielectric and electrolytic capacitors. All present-day electrolytes boil below 500 C, and gas-filled units develop bad seals and become severely unstable.

Paper or plastic dielectric capacitors, too, are unsuitable for 500 C operation. The only present day dielectrics that show promise are the ceramic, glass, and mica types, but the electrodes still present a problem. Zinc and aluminum are now used almost exclusively. Zinc melts at 420 C (788 F) and aluminum at 660 C (1220 F). The internal temperature of a capacitor in a 500 C environment would probably be higher than 660 C (1220 F).

To produce capacitors that will operate at 500 C will most likely require the use of materials not previously considered.

Resistors. As with other components, the operation of resistors at 500 C (930 F) becomes primarily a materials problem. One of the more common construction methods suitable for 500 C application is as follows: a ceramic tube is metallized in a band at each end, both inside and outside. The resistance film, coating, or composition is then deposited on the ceramic, making contact with the bands. Either the inside or outside of the tube, or even both sides, may be used depending upon the resistance value and wattage rating desired. The feasibility of this type of resistor has been demonstrated using a special forsterite ceramic form with titanium end-caps. The expansion coefficients of these materials are almost identical up to 900 C (1650 F).

Variable resistors have problems identical with fixed resistors, in addition to mechanical problems. If the variable resistors are to be sealed for protection, the great problem of a rotary seal at high temperatures is also of concern. The upper operating temperature of presently available variable resistors is 200 C (390 F), with investigations under way to extend this limit.

Table 5-6. Coefficients of Linear Expansion in Descending Order (in inch/inch/degree C X 10^{-6}) /7/

100 and over		95 to 55 (continued)	
Vinyl acetate	265 ±25	Vinyl carbazole	65 ±15
Vinylidine chloride	190	Polystyrene, prefoamed	65 ±10
Mercury	182	Vinyl formal	64
Vinyl chloride, flexible	160 ±90	Polymethy alphachloroacrylate	62
Polyvinyl butyral	150 ±70	Polysulfide-epoxy	60 ±40
Polyethylene	140 ±35	Epoxy, flexible	60 ±40
Cellulose propionate	140 ±30	Lithium	56
Cellulose acetate butyrate	140 ±30	Glyceryl phthalate	55
Cellulose acetate	120 ±40	Hard Rubber, mineral filled	55
Nylon	115 ±35	Casein, molding	55 ±15
Polypropylene	110	Polychlorotrifluoroethylene (Kel-F)	55 ±10
Vinyl chloride, rigid	110 ±60	Epoxies, unfilled	55 ±10
Polytetrafluoroethylene (Teflon)	100	Silicones, mineral filled	54 ±4
Cellulose nitrate	100 ±20	**45 to 25**	
95 to 55		Cellulose acetates, foamed rigid	45
Styrene copolymer blends	95 ±35	Phenol formaldehyde laminates	45 ±25
Chlorinated polyether	80	Urethane, prefoamed rigid	45 ±20
Polyester, unfilled	80 ±20	Wood, across fiber	45 ±15
Urethane, foamed-in-place	80 ±10	Phenol-formaldehyde, unfilled	45 ±15
Allyls, cast	75 ±25	Vulcanized fiber	42
Hard rubber, unfilled	75 ±5	Melamine-formaldehyde, cellulose filled	42 ±2
Polyvinyl alcohol	70	Polyester laminates	40 ±5
Methyl methacrylate	70 ±20	Silicone rubber foamed-in-place	40 ±5
Phenolics, unfilled	70 ±10	Selenium	37
Styrene, heat resistant	70 ±10	Micas	37 ±10
Polystyrene, unfilled	70 ±10	Diallyl phthalate, mineral-filled	35
Modified acrylic molding	70 ±10	Polyester, filled	35 ±15
Teflon laminates	65		

Table 5-6. Coefficients of Linear Expansion in Descending Order (in inch/inch/degree C X 10^{-6}) /7/ (continued)

45 to 25 (continued)	
Epoxy, prefoamed	34 ±5
Phenolics, asbestos filled	33
Zinc	33
Indium	33
Epoxy laminate, glass-filled	30 ±15
Epoxy, silica-filled	30 ±10
Lead	28 ±1
Urea-formaldehyde, filled	27
Magnesium	27
Rubber phenolics	27 ±12
Solder, 50/50 lead-tin	25
Phenol-formaldehyde, filled	25 ±15
Melamine-formaldehyde laminate	25 ±10
24 to 10	
Aluminum and alloys	24 ±2
Magnesium	23
Diallyl phthalate, glass-filled	22
Tin	20
Zinc alloys	20
Phosphor bronze	18.9
Silver	18.5 ±0.4
Copper alloys	18 ±1.5
Copper	17 ±0.4
Cobalt	15
Melamine-formaldehyde, filled	15
Diallyl phthalate, fiber-filled	15
Stainless steel	14
Silicone Laminates	14 ±5

24 to 10 (continued)	
Gold	14 ±0.2
Nichrome	13.4 ±0.3
Steel	13.3 ±1.8
Nickel	12.8
Thorium	12
Nickel alloys	12 ±1
Palladium	11.8
Iron	11.7
Beryllium	11.5
Gray cast iron	11.2
Glass-bonded mica	10
Under 10	
Soda-lime glass	9.2
Lead silicate glass	9
Quartz crystals	9 ±4
Alumina cermets	9 ±0.5
Platinum	8.8
Forsterite	8.5
Tourmaline	8.5 ±0.8
Rhodium	8.4
Silicones, glass-filled	8
Alumina ceramics	7 ±0.3
Iridium	6.8
Steatite	6.6 ±0.6
Tantalum	6.5
Osmium	6.1
Wood, parallel to fiber	6 ±3.5
Zirconium	5.5
Germanium	5.5 ±0.5
Silicon	5 ±2.2
Silicon carbide	4.3

Table 5-6. Coefficients of Linear Expansion in Descending Order (in inch/inch/degree C X 10^{-6}) /7/ (continued)

Under 10 (continued)		Under 10 (continued)	
Molybdenum	4	Invar	0.8
Tungsten	4	Silica glass	0.87
Cordierite	3.7	Fused quartz	0.58
Porcelain	3.5 ±0.5	Opaque fused silica	0.56 ±0.03
Boron carbide	3.1	Vitreous silica	0.5
Carbon	3	Clear fused silica	0.49

Values for plastics are generally approximate, obtained by ASTM test method D696, and are applicable over a temperature range of -22 to +86 F (-30 to +30 C); for higher temperatures, more detailed data should be obtained from manufacturers since the coefficients change abruptly for some plastics at a certain temperature. Values for other materials generally apply over the entire range from room temperature up to at least 750 F (400 C), and much higher for most metals. Whenever coefficients vary with formulation or purity of a material, the average value is given, followed by a value indicating the range of variation above and below this value that can be expected with commercial materials.

Wire and Cable. To date, copper is still considered to be the general-purpose conducting material at 500 C (930 F). /9/ Because of its inherent property of progressive oxidation, however, it cannot be used unless provisions are made for protection against oxidation. The most likely approach to this protection is to exclude the atmosphere by surrounding the copper with a material impervious to oxidation damage. If this material is applied in a sufficiently thin layer, the conductivity of the entire conductor is not much less than the conductivity of an equivalent unclad copper conductor.

In general, the use of aluminum as a conductor material at 500 C is limited by the fact that it has a relatively low melting point, and operation near the melting point would undoubtedly result in a degradation of its mechanical properties. Nevertheless, some special-purpose, high-temperature applications of aluminum conductors are anticipated.

Other materials with relatively good conductivity that might be considered for conductor applications at high temperatures are silver, gold, magnesium, molybdenum and tungsten.

Both gold and silver have good electrical conductivity, as well as excellent corrosion- and oxidation-resistance properties at elevated temperatures. However, unsatisfactory mechanical properties, high cost and procurement difficulties will probably limit the use of gold and silver.

Magnesium has fair electrical conductivity and good corrosion-resistance properties; but, like aluminum, it has a relatively low melting point which may prohibit its use at 500 C.

Molybdenum and tungsten have only about one-third the conductivity of copper, fair oxidation-resistance characteristics, and poor workability. However, due to their high melting points, they have been used in special high-temperature applications. The oxidation characteristics of molybdenum can be improved by using a siliconized coating. With this technique, molybdenum can be protected against oxidation in air up to 980 C (1800 F).

Some of the more important high-temperature characteristics of various conductor materials are listed in Table 5-7.

Electromechanical Components. Electromechanical components include restricted motion components (relays, solenoids, switches etc.) and rotary motion components (motors, generators, synchros, etc.) The spring action of restricted motion components is greatly hampered at temperatures of 500 C (930 F), and lubricants become a formidable problem in the rotary motion units at that temperature. In both types of components, arcing at 500 C reduces contact, brush, commutator, and slip-ring life. It appears that a complete re-evaluation of materials and methods is necessary for the development of electromechanical components for 500 C operation.

Printed Wiring and Terminal Boards. Suitable materials for use as bases for printed wiring or as terminal boards at 500 C (930 F) are available. Both "Supramica 500" and "Micaramic" are adequate for this purpose. Many ceramic materials are also useful. Silver conductor strips, etched or plated on the boards with binding posts of platinum, magnesium silver, or some other mechanically stronger materials, should be considered. The metal and ceramic combinations must match expansion coefficients as closely as possible.

Table 5-7. Some High-Temperature Characteristics of Conductor Materials /9/

Material	Melting point C (F)	Resistivity at 500 C (10^{-6} ohm-cm)	Resistivity ratio 500 C/20 C	Volume ratio* material at 500 C/copper at 500 C	Weight ratio** material at 500 C/copper at 500 C	Comments on operation at 500 C ambient
Silver	960.5 (1760.9)	4.1	2.52	0.81	0.96	Suitable; more costly and heavier than copper.
Aluminum	660 (1220)	10	3.82	1.96	0.6	Temperature rise in apparatus is critical.
Aluminum-clad copper	660 (1220)	6.3	3.1	1.23	1.20	Melting point of aluminum is limited.
Silver-magnesium nickel	970 (1778)	6.8	2.96	1.33	1.63	Easily brazed; ductile before heating.
27 % nickel-clad copper	1083 (1981)	7.9	3.35	1.55	1.55	Permanent change in resistance.
Copper	1083 (1981)	5.1	2.90	1	1	Must be protected against oxidation.
Magnesium	650 (1202)	13.8	3.0	2.72	0.53	Good corrosion resistance.
Gold	1063 (1945.4)	6.62	2.71	1.3	2.82	Costly; may have limited application.
Platinum	1773 (3224)	29.1	2.9	5.7	13.7	Suitable for contacts and binding posts.
Palladium	1555 (2829)	31.3	2.9	6.15	8.4	Soft; corrosion resistant.
Tungsten	3370 (6098)	18.5	3.4	3.53	7.46	Good arc and pitting resistance.
Molybdenum	2620 (4748)	15.8	2.77	3.1	3.56	Oxidizes at elevated temperatures.
Titanium	1725 (3137)	76	1.6	14.9	7.50	Ceramic- and glass-to-metal seals.
Nickel	1455 (2651)	78.3	10	15.3	15.1	Useful as electrode or cladding material.

* Volumes per unit length yielding the same electrical properties.

** Weights per unit length yielding the same electrical properties.

TEMPERATURE CONTROL OF FLIGHT VEHICLES

The primary objective of temperature protection is to prevent excessive temperature rise on and within the vehicle. When heat buildup is kept down to a practical minimum the excess heat is then removed by removal systems which may be either of the passive or active type. Passive systems make use of natural heat sinks, while active systems use apparatus such as heat pumps or refrigeration units to create artificial heat sinks.

Methods of Temperature Control for Atmospheric Vehicles /10/

Application of aerodynamic design, especially of the nose, airfoil, and control sections, will reduce the temperature of the vehicle skin. A blunt or rounded nosed vehicle or airfoil will build up lower stagnation temperatures than sharp nosed vehicles or airfoils, particularly at supersonic flight speeds.

Beyond the atmosphere, the primary source of external heat is solar radiation, which may be kept to a minimum with suitable reflective skin coatings.

Within the vehicle, temperatures can be kept to a minimum by compartmentation, insulation, intercompartment and intrawall airflow, and the choice and location of components, subassemblies, and equipments.

Compartmentation. If the interior of the vehicle is one large open space, the heat from hot equipment will flow toward cooler equipment and overheat them. By dividing the interior of the vehicle into compartments and properly locating heat-generating equipment, it is possible to direct the heat to the skin, where it may be dissipated, provided that the skin is not at a higher temperature than the equipment, which may be the case for very high-speed flight.

Merely dividing the interior of the vehicle into compartments does not automatically solve the heat-buildup problem. The temperature may still rise in the cooler compartments because of conduction through the walls. This may be reduced by insulating the walls to reduce conduction, and/or reducing the temperature differential across the individual portions of the walls by the use of intercompartment or intrawall air flow.

Insulation of Compartment Walls. In order to effectively reduce the heat transfer to a compartment, the amount and placement of thermal insulation becomes important. Just an airspace in a hollow wall has good insulating qualities, but the use of insulating material is better. The thicker the material, the better the insulation, but the greater the weight.

The emissivity of the insulating material is also significant, since radiation can contribute a considerable portion of the thermal load of a compartment. Where appreciable temperature gradients exist over large areas, such as between the belly skin and the compartment floor, the use of aluminum foil-back insulation will substantially reduce the interchange of radiant energy.

In practice, the effectiveness of insulation is reduced somewhat by moisture absorption and compacting. To account for this, it is conventional to assume the effective thickness of the insulation to be somewhat less than actual.

The effects of insulation on the total thermal load of a compartment are illustrated by evaluating a production aircraft with several different amounts of compartment insulation. Table 5-8 shows that the total heat transfer through the walls, Qw, is reduced about 40 percent by completely insulating the compartment walls with 1/2-inch of Fiberglas. It is reduced another 24 percent by doubling the thickness of the insulation.

Intercompartment and Intrawall Air Flow. The use of intercompartment and intrawall air flow is very effective for rapid heat removal. Intercompartment heat removal is accomplished by discharging cooling air into adjacent compartments to reduce heat transfer through common walls. Table 5-9 shows the effectiveness of intercompartment air flow.

Table 5-8. Reduction in Wall Load for Production Aircraft With Varying Degrees of Insulation /10/

Amount of insulation	Heat flow, Qw (Btu/hr)
Standard insulation - 1/2 inch of Fiberglas over 25% of compartment area.	35,200
1/2 inch of Fiberglas overall.	20,070
1 inch of Fiberglas overall.	12,200

Table 5-9. Effect of Intercompartment Air Flow on Compartment Floor Heat Transfer /10/

Condition	Heat flow, Q (Btu/hr)
No intercompartment air flow; belly skin and floor uninsulated.	11,560
No intercompartment air flow; belly skin insulated only.	5,450
Intercompartment air flow; belly skin and floor uninsulated.	9,620
Intercompartment air flow; belly skin insulated only.	1,785

The heat-flow rate from one compartment to the next can often be further reduced by discharging the cooling air through intrawall ducts. A view of a section of intrawall duct is shown in Fig. 5-5. Air from the compartment enters the duct at A, flows through the duct, and is discharged at B. As the air flows along the duct, it prevents heat transmission from the outer wall, with the object being to reduce the temperature of the inner wall. Because of the difficulties in equalizing flow through the ducts, as well as the need for leakage control, the intrawall system is considered a practical possibility only for small compartments in high-speed vehicles for which efficient use of the available cooling is very important.

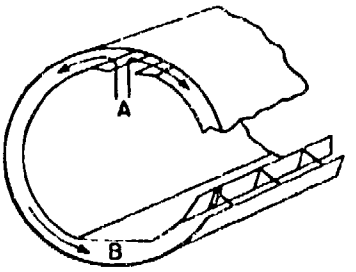


Fig. 5-5. Intrawall duct system./10/

Choice and Location of Equipment

The amount of heat generated by equipment can be markedly influenced by the choice of components, while the location of the equipment can determine the problems that result from generated heat. Every item should be studied from two viewpoints: (1) can a substitute be found that will generate less heat? or (2) can the item be located so that heat from it will not be directed to other items?

Some components produce less heat than others and should be used where heat buildup is a problem. For example, transistors generate less heat than electron tubes, fluorescent lamps produce less heat than incandescent lamps, and rotating power-supply components produce less heat than electronic types. It should be noted, however, that replacing a component with another that generates less heat is not always feasible, since it is possible that the replacement component has a lower maximum operating temperature and would not perform satisfactorily at the particular ambient temperature.

In certain applications, it may be possible to substitute pneumatic or hydraulic equipment for electrical equipment. Such a substitution is likely to be dictated by systems consideration as well as by environmental consideration.

To prevent excessive temperatures at any location, the placement of one equipment with respect to another, as well as the placement of subassemblies within an equipment, should be carefully considered. Equipment with high heat output should be located as far as possible from cooler units. Heat shields should be used between hot and cooler units, and conduction paths to the heat sink for high-heat units should be as short and direct as possible. Also, heat-producing equipments should not be bunched, unless a forced convection heat-removal system is used, in which case bunching might be highly desirable.

Methods of Temperature Control for Space Vehicles

Most of the passive methods of temperature control previously described for atmospheric vehicles apply also to the inside of pressurized space vehicles. However, methods that employ natural convection will be ineffective unless an artificial gravity environment is created. Even then, the strength of natural convection will depend upon the gravity-force system.

If a cooling system that depends upon liquid and vapor phases is used, such as a refrigeration unit, special care will have to be taken to separate the vapor bubbles from the liquid, since the bubbles will not rise without the influence of gravity. Likewise, if a closed, pressurized-liquid circulating system is used, care would be required to eliminate all gas pockets from the system so that the pump will not become vapor locked. Heat removal systems are discussed in later paragraphs.

HEAT REMOVAL

In spite of passive temperature protection methods, the complexity of present-day vehicles is such that heat will still build up in the equipment to interfere with satisfactory performance and life. This heat must be removed by some means at the same rate at which it is generated. Heat removal is a process of transmitting heat from a heat source to a heat sink.

Thermal Systems

A complete thermal system involves the object from which heat is removed, a transmission medium to carry the heat, and a heat sink to receive the heat. Actually, thermal systems are seldom that simple. Usually, intermediate sinks are required, along with combinations of the three modes of heat transmission. These three modes of heat transmission are: conduction, convection, and radiation.

Conductive Heat Transfer. Heat is transferred by conduction from one object to another when they are in direct mechanical contact with each other.

Convective Heat Transfer. The process of heat transfer from the surface of a solid to moving masses of fluids, either gaseous or liquid,

constitutes convection. This mode of heat transfer is brought about mainly through circulation of the fluid. When the circulation is caused only by differences in density, the process is called natural or free convection. When the circulation is forced mechanically by blowers, pumps, etc., it is called forced convection.

Radiant Heat Transfer. Objects emit thermal radiation ranging in wavelength from the long infrared to the short ultraviolet. Radiation from an object can travel through a vacuum or through gases with relatively little absorption. When radiation is intercepted by another object, part of it may be absorbed as thermal energy, part of it may be reflected, and part of it will be reradiated.

Conduction Cooling

For conduction cooling to be effective, high-conductivity materials must be used. Thermal conductivity of metals is generally directly proportional to electrical conductivity. Table 5-10 gives the relative thermal conductivity of various materials. When employing conduction cooling, good metal-to-metal bonds are important.

Table 5-10. Relative Thermal Conductivity of Various Materials at Approximately 150 F (65 C) /12/

Material	Thermal conductivity (btu/hr/ft²/deg F/ft)
Silver (most conductive)	241
Copper	220
Gold	171
Aluminum (pure)	125
Aluminum, 63S	116
Magnesium	91
High-beryllia ceramics	38.7 to 88.7
Red brass	63.7
Yellow brass	54.6
Beryllium copper	47.8
Pure iron	43.2
Phosphor bronze	29.6
Soft steel	26.8
Monel	20.5
Lead	18.9
Hard steel	14.8
Steatite	13.6

Thermal contact resistance should be minimized by soldering, brazing or welding. If pressure joints are used, special care to insure tight fits is required. Also the conduction path should be kept as short as possible.

An example of heat removal by conduction is the method used to cool electron tubes. Metal tube shields placed around the tubes provide a conduction path from the tubes to the chassis. The chassis, in turn, conducts the heat to a structural member of the equipment from which it can be dissipated by conduction, convection, or radiation, or a combination of these. Conduction from equipment structural members to the airframe is generally unfeasible since it requires direct contact between highly conductive materials. In addition, it is difficult to use conduction if the equipment is shock mounted, unless a conductive material, or convection or radiation, is used to provide a path "around" the shock mounts.

Forced Convection/12/

Little or no reliance is placed on natural convection for removing heat from equipment. The high heat loads in confined spaces require the use of forced convection to keep equipment temperatures within acceptable limits. Forced convection transfers heat from an object at a much faster rate than possible with free or natural convection.

When a fluid moves along a solid surface, the drag caused by the surface makes the fluid velocity zero at the surface of the solid. With increasing distance from the surface, the velocity increases as a second power function of viscosity and distance until a free-stream velocity is reached, as shown in Fig. 5-6. In laminar or smooth flow, the fluid can be thought of as moving in layers, each moving faster than the one under it, and slipping on each other. Heat from the surface must pass by conduction through these layers of slowly moving fluid before it can be carried away by the rapidly moving fluid.

If the free stream velocity is increased, as by a blower, a critical velocity is reached at which the layers are broken up. The fluid particles then move in swirls and eddies, and the local velocity is irregular. This is called turbulent flow.

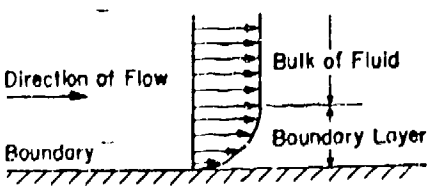


Fig. 5-6. Fluid velocity profile./12/

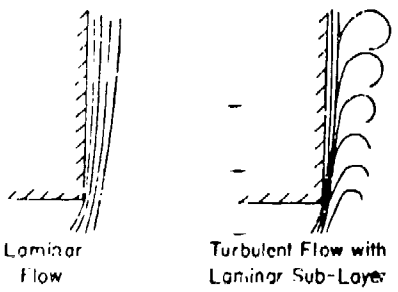


Fig. 5-7. Laminar and turbulent flow./12/

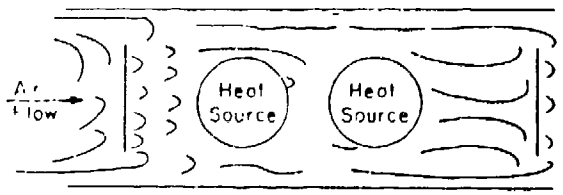


Fig. 5-8. Sharp-edged plate turbulator./11/

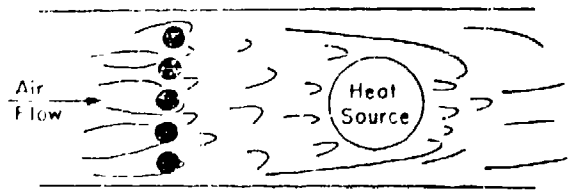


Fig. 5-9. Pod-type turbulator./11/

Since the fluid velocity at the boundary must be zero, there is still a thin layer of laminar flow under the turbulence.

The laminar sub-layer is greatly reduced in thickness when turbulent flow occurs, and it is believed that this reduction in thickness reduces the resistance offered to heat flow. As soon as it reaches the turbulent fluid, the heat is rapidly carried away by the mixing due to velocity fluctuations. Increasing the velocity increases the turbulence and reduces the sub-layer thickness. There is no actual discontinuity in the flow, but turbulence gradually increases and the boundary layer gradually decreases in thickness as the force applied to move the fluid increases.

Turbulators. Turbulent rather than laminar air flow is desirable because the turbulence results in a much thinner layer of air at the boundary through which the heat must flow by conduction. Designs of forced-convection cooled equipment should always assure turbulence near the surfaces of heat-producing parts. Air flow patterns can be observed by injecting smoke at several points along the flow path. If, at any point, low turbulence exists, it will be evident by a concentration of smoke at that point. When components of different size and shape are placed in series, the turbulence will vary and may become undesirably low in some places. If such spots are found, the turbulence may be increased by putting "turbulators" into the air stream. A sharp-edged plate set perpendicular to the stream is an effective turbulator, the action of which is shown in Fig. 5-8. Both upstream and downstream turbulators are shown. It is apparent that the turbulator throttles the air flow and increases the required blower power by increasing the number of obstacles in the flow path.

Another method for increasing turbulence is to use a row of small rods placed in front of a heat source as shown in Fig. 5-9. No definite design rules can be given for turbulators. If hot spots are found and a study of the air stream indicates low turbulence, various types and locations of turbulators should be tried until an effective arrangement is found.

In small spaces, air flow velocity cannot be increased beyond a certain amount no matter how much power is used. This limits the amount of heat that can be removed from an enclosure or subassembly. Proper placement of heat producing components is then very important. Two basic requirements in these cases are that one component does not shield another from the air flow; and that air already heated to capacity is not used for cooling another.

Fins. The effectiveness of forced convection can be increased by providing extended surfaces, or fins, over which the air is directed. Fins provide additional heat transfer by conducting heat outward from the object to which they are attached, thus increasing the surface area of the heat source. The additional heat transfer provided by the fins more than offsets the slight increase in resistance due to the metallic heat flow path of the fins.

The following general factors should be considered when using fins:

1. Fins should be made of a metal with a high thermal conductivity.

2. Fins should be either integral with the part or bonded to the part with a good metal-to-metal contact so that there is a minimum of contact resistance.

3. Short, rather thick fins are more effective than long thin ones. The temperature drop from the base to the tip of a long thin fin may be appreciable, and tends to make the fin less effective. /11/

Selection of Blowers/13/

Blowers used as a source of air motion for removing heat from equipment fall into two general categories: (1) internal devices in closed equipment (pressurized and/or sealed) producing circulating air flow over the components, and (2) devices supplying external air for the dissipation of heat by forced convection from the ultimate heat-transfer surfaces of the equipment. Internal devices of the first category are used to establish uniform thermal conditions within the equipment. They aid in the transfer of heat from components to case surfaces of the equipment or to other heat exchange surfaces, which are utilized for external heat dissipation. The devices of the second category are used with open or closed equipment. In the case of open equipment, they may produce air flow directly over the surface of components, or, for closed equipment, they may supply air to external heat dissipating surfaces, such as the case surface proper, or to extended surfaces forming a case envelope or separate heat exchanger.

In choosing a blower for internal air circulation in pressurized or closed vented equipment, the selection is affected principally by the pressure level within the equipment and the air flow requirement. With pressurized equipment, the basic problem of heat removal under variable operational conditions rests primarily upon the ability to provide adequate heat dissipation from the case surface. The requirements imposed on internal blowers of such equipment are constant for all operating conditions. Such blowers may operate at constant speeds, which will result in the same air circulation under all operating conditions, since the internal pressure level of the equipment will remain essentially fixed. With closed vented equipment, internal blowers having no means of control may be used, provided that at all operating conditions, the external heat dissipation from the equipment case is sufficient to prevent overheating of components within the equipment. Since the pressure level within the equipment is reduced as the altitude increases, the weight flow capacity of the internal blower and its ability to improve the heat distribution within the equipment are diminished. Under conditions where components tend to reach their temperature limits, the problem of inadequate air circulation within the equipment, resulting from the reduced pressure level, becomes important. Continued reduction in component temperature can be brought about under low pressure conditions by increasing the flow rate of the internal blower. In such a situation, a requirement may exist for control of the internal blower to provide an increased circulation rate. However, such usage is limited, since at low pressures, the blower power required to maintain a mass flow of air consistent with that at the higher pressures results in a significant temperature rise in the air as it passes through the blower, thus limiting the cooling capability of the air.

When blowers are used to supply air for direct dissipation of heat either by flowing over components or by blowing over the surface of the equipment, the demands placed on the operating characteristics are considerably more severe. It is possible that sufficient air flow may be unobtainable, for the reason stated in the preceding paragraph, if the units are to be cooled over a wide range of operating pressure levels. Careful evaluation of the equipment heat transfer and pressure drop is required as the basis of blower selection. Once the characteristics of the equipment are established, the performance of a blower of known characteristics can be predicted when operated with the equipment under specific conditions of air temperature and pressure. The blower should be selected on the basis of computed air requirements at the maximum altitude of operation. The characteristics of its drive unit will depend on the degree of temperature control desired at other altitudes. The control requirements are particularly severe if the desired range of operating altitude is wide.

Blower Types. /8/ Two general classes of fans or blowers cover all commercially available types. They are axial-flow types and centrifugal types. The centrifugal blower is best suited to produce constant surface temperature of the equipment. To meet other requirements, or to cope with critical space limitations, the axial fan may be a better choice.

Axial-Flow Fans. There are two broad variations of axial-flow fans: the propeller fan, and a more refined, somewhat more efficient design, using inlet and outlet vanes, known as the axial fan. In both types, the air enters the impeller in a direction parallel to the impeller rotor axis. In current applications, the axial-flow family of fan impellers functions widely in air-intake capacities and is well suited for flushing large volumes of air over equipment components. This type of fan impeller is available in a variety of sizes and capacity ratings.

Propeller Fans. Propeller fans are widely used for pushing air through chassis compartments and over heat-generating components. For its physical size and horsepower rating, this type of fan is capable of moving relatively large volumes of air. It is not recommended where air is to be moved through restricted areas that develop back pressures in excess of 0.15 to 0.25 inches of water. Higher pressures can be provided by special high-speed fans, but they generally produce more air noise. A typical propeller type fan is shown in Fig. 5-10.

Axial Fans. The axial fan represents a fan design of higher efficiency than the propeller type, from which it is derived. It features inlet and outlet vanes that cause a whirl in the air, which provides more static pressure than attained by the basic propeller-type fan. The vanes also keep the air delivery in an axial direction, establish more uniform flow, and maintain high efficiency with quiet operation. The range of air delivery ratings extends from 20 to 5000 cubic feet per minute, with static pressures up to 10 inches of water. A typical axial-type fan is shown in Fig. 5-11.

Centrifugal Blowers. The blades of a centrifugal blower are arranged to provide high efficiency by driving the air in a circular orbit within a scroll-type housing. Considerable centrifugal force is imparted to the air within the housing, and then the air is expelled through an outlet in a direction tangential to the circle described by the tip of the impeller blades. Centrifugal blowers are useful where high pressure and moderate-to-low-air-handling capacities are called for, and where air-ducting may be required. A typical centrifugal blower is shown in Fig. 5-12.

Direct Liquid Cooling/11/

Direct liquid cooling is an effective method of heat transfer for assemblies having high heat concentration or those that must operate in a high temperature environment with a small temperature gradient between them and the cooler surfaces. Equipment can be designed for several types of liquid cooling systems, any one of which may have cooling capacities greater than those of forced air convection systems. Sealed assemblies can be designed for direct immersion in the coolant, the assembly can be filled with a liquid such as silicone fluid, or the assembly can be designed with passages for a liquid coolant adjacent to the heat-producing component. Cooling of directly immersed equipment may be increased by forced circulation of the coolant. However, this increased cooling requires some power and the addition of a pump.

The weight of directly immersed equipment may be reduced somewhat by spraying the coolant over the heat producing components, collecting the heated coolant in the bottom of the container, and then pumping it through a heat exchanger and back to the spray nozzles. Such a cooling system represents a savings in the amount of coolant liquid required, but needs a higher pressure pump, and, consequently, more power to run the pump than does a completely immersed equipment. It should be noted that free or natural convection systems, as well as the spray system, will not operate under zero gravity conditions.

Direct Vaporizing Cooling

Vaporization cooling is the most effective heat removal method known. It has the advantages and disadvantages of direct liquid cooling, together with greatly decreased thermal resistance. Expendable systems are simple, but involve disposal of the vapor and replacement of the coolant. Nonexpendable, or continuous, systems are complex, expensive, and necessitate the use of a heat exchanger to condense the vapor back into a fluid. Vaporization cooling systems are particularly suited to installations with extremely high heat concentrations.

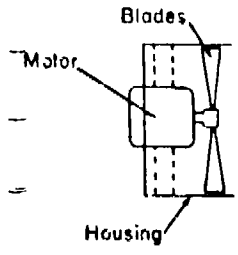


Fig. 5-10. Typical propeller-type fans.

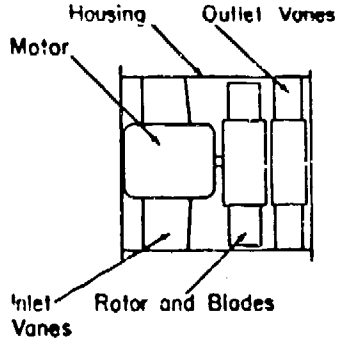


Fig. 5-11. Typical axial-type fan.

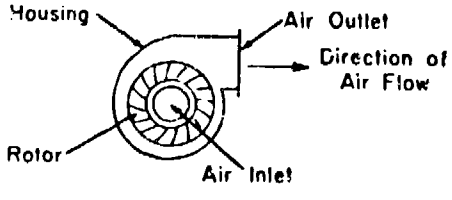


Fig. 5-12. Typical centrifugal blowers.

Radiation

Fundamentally, the amount of heat radiated by an object depends on the square of its absolute temperature and the properties and area of its radiating surface. In general, polished surfaces make poor radiators, while rough surfaces make good ones. A lampblack coating makes an excellent radiating surface and is used as a standard of comparison for other radiating surfaces. An increase in the surface area of an object will increase the amount of heat that the object radiates. There is a relationship between the rate at which a surface radiates heat and the rate at which the same surface, under similar conditions, absorbs heat. A good radiator of heat is also a good absorber of heat, and surfaces that radiate slowly also absorb slowly. The amount of radiant heat reflected by a surface is also dependent on the properties of the surface. Polished surfaces reflect best, and black or roughened surfaces reflect poorest.

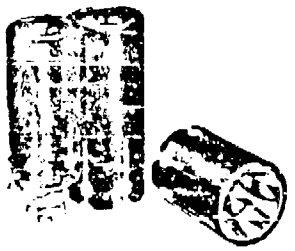


Fig. 5-13. Heat-dissipating tube shield for miniature tubes.

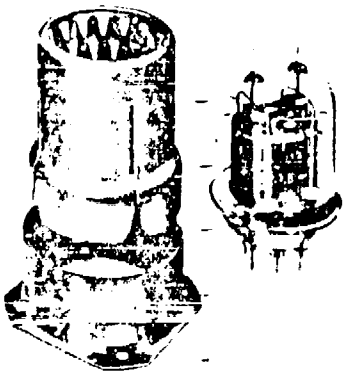


Fig. 5-14. Heat-dissipating shield for power tube.

Heat removal by radiation may be increased by: (1) using materials with high emissivity and absorbency; (2) increasing the temperature differential between the radiating and receiving objects; (3) choosing the geometrical shape of the radiating and receiving surfaces so that the receiving object accepts heat at a faster rate than the radiating source supplies it; and (4) proper placement of components, with special attention given to the location of components radiating considerable amounts of heat.

Tube shields are excellent examples of heat removal by radiation. Figures 5-13 and 5-14 show tube shields specifically designed to dissipate heat by radiation. The shields are black on the inside, to absorb heat from the tubes, and black on the outside, to radiate the heat as quickly as possible. Notice that these shields have inserts with numerous tabs punched inward to make physical contact with the bulb, so that conductive heat transfer is also used.

Comparison of Heat Removal Methods

Figure 5-15 shows a basic comparison of heat removal methods. The diagram, however, does

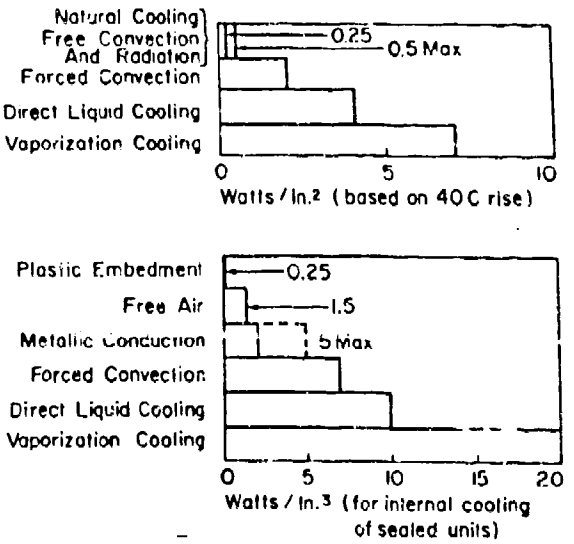


Fig. 5-15. Comparison of heat removal methods./11/

not take into consideration weight, cost, space or efficiency. In many locations, because of space and weight limitations, it may only be possible to use natural cooling means. In practice, several types of cooling methods will normally have to be used to produce an efficient as well as effective heat removal system.

HEAT EXCHANGER /11/

A heat exchanger is a device used to cool a liquid or gas by transferring heat to another liquid or gas. The exchanger is commonly a wall made of material of high thermal conductivity. Heat exchangers are normally classified according to their internal construction. A type of heat exchanger named for its operating principle rather than its construction is the "boiling" or change-in-state exchanger. In this type of exchanger, the ultimate fluid undergoes a change of phase during the process of absorbing heat, and the resulting vapor is then either expelled from the system or is condensed back into a fluid and recirculated in the system.

Conventional Shell-and-Tube Type Heat Exchangers

In this type of heat exchanger, one fluid flows inside the tubes and the other fluid flows across or along the outside of the tubes, depending on the construction. The classification of shell-and-tube type heat exchangers is further subdivided into parallel-flow heat exchangers, counterflow heat exchangers, reversed-flow heat exchangers, and cross-flow heat exchangers, based upon the direction of flow of the shell-side fluid relative

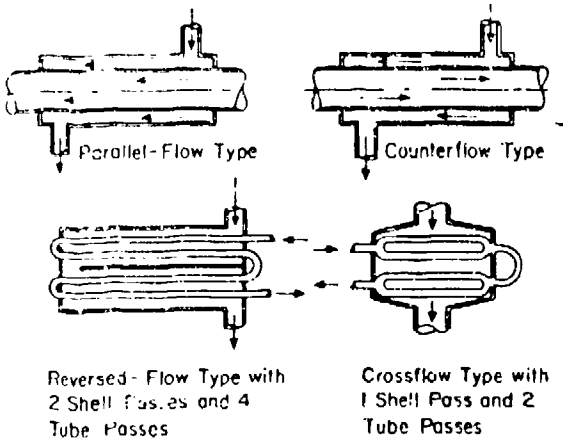


Fig. 5-16. Shell-and-tube type heat exchangers./11/

to the tube-side fluid. Figure 5-16 shows the four types of shell-and-tube type heat exchangers.

Extended Surface Heat Exchangers

For greater compactness, additional heat transfer surface can be obtained by the use of fins in good thermal contact with the primary heat transfer surface. There are many types of extended surfaces for heat exchangers. Figure 5-17 shows commonly used extended surfaces applicable to heat exchangers for equipment cooling. Finned-tube heat exchangers are particularly effective when the tube fluid is a liquid and the second fluid is a gas at ordinary pressure. They are, therefore, suited for the design of air-to-water (or other liquid) heat exchangers in forced-convection, air cooled equipment.

A relatively new modification of the extended surface heat exchanger is the "inner fin" surface. The longitudinal arrangement keeps the pressure drop at a low value. The inner fin provides a greater surface area, resulting in better transfer of heat.

Flat Panel Heat Exchangers

Cored heat exchangers are usually quite thick. The space normally available in equipment for heat exchangers is often limited in one dimension and does not always permit the use of wide compact heat exchangers. Flat heat exchanger panels (also called "tube-in-strip," "roll-bond," and "thermo-panels") are best suited for cooling equipment with a low heat concentration. Such exchangers have a high effectiveness, are low in weight, and because of their thinness, fit well along the walls of equipment enclosures.

There are two basic types of panel heat exchangers. One type (thermo-panels) consists of two plates with suitable embossings welded together to form the necessary flow channels. The other type (tube-in-strip and roll-bond) consists of a single sheet of metal, such as copper, brass, or aluminum, rolled from a casting or graphite coated sheet and then inflated to produce flow channels. Due to the method of fabrication, tube-in-strip panels or roll-bond panels can be patterned quite intricately to suit the needs of any particular heat removal system.

Comparative Features of Common Heat Exchangers

Shell-and-tube designs are well adapted to high pressure and can easily be designed so that the inside of the tubes can be cleaned by brushes or reamers. The outside of the tubes is difficult to clean; the shell should contain clean or non-scale-forming fluid. Expansion is easily allowed for by making one tube header floating and by placing an expansion joint in the shell. Shell-and-tube designs are heavier and bulkier than other types.

Figures 5-18 and 5-19 show the temperature gradients existing in tubular heat exchangers. With counterflow, the temperature difference is nearly constant, and the exit temperature of the cold fluid can be higher than the exit temperature of the hot fluid. All portions of the tube surface have about the same heat transfer effectiveness, and extreme temperature differences are not present. With parallel flow, the heat transfer rate is high over the first part of the tube length, and then decreases. Initial cooling or heating is therefore rapid. Parallel flow exchangers tend to be shorter than counterflow exchangers.

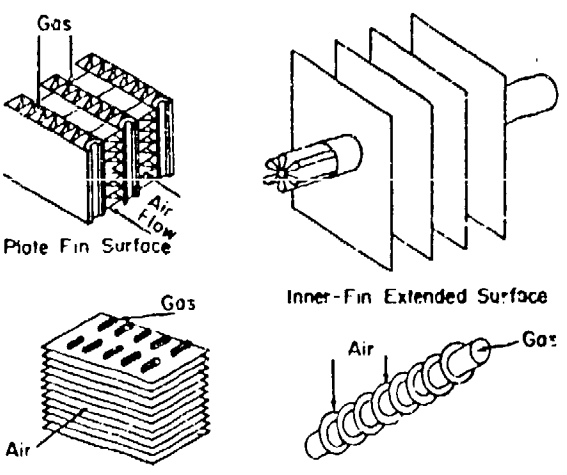


Fig. 5-17. Types of extended surfaces for heat exchangers./11/

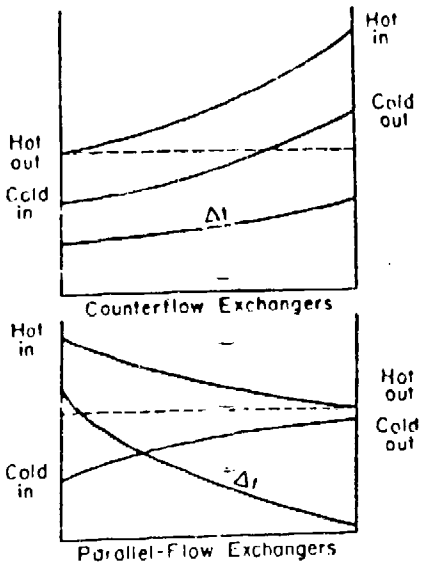


Fig. 5-18. Bulk temperature variation in heat exchangers./11/

In crossflow exchangers, the flow pattern is complex and very difficult to calculate, so that empirical formulas must be used. Turbulent flow in the shell side is easily developed. Crossflow exchangers tend to be "boxy," and roughly square in shape. Counterflow exchangers are long and of small diameter. Parallel flow exchangers are shorter and of larger diameter.

In crossflow, as in parallel flow designs, the highest temperature of the cold fluid is lower than the lowest temperature of the hot fluid, and the temperature difference varies widely from point to point on the core. Extended surface types can be made much lighter in weight (for low pressures) than shell-and-tube types, and the construction methods are frequently cheaper. Mechanical removal of scale is difficult or impossible, but dust and dirt accumulated on the gas side are easily removed.

HEAT SINKS

A heat sink is a body or medium to which the heat removed is rejected. For example, the chassis to which a heat conducting tube shield is attached is the heat sink for the shield. This example is a local or intermediate sink, as the heat must also be removed from the chassis otherwise it will attain the temperature of the heat source and heat transfer will stop. Heat must therefore be transferred from the intermediate sink to the ultimate sink.

Ultimate Sink

The ultimate sink is that body or medium into which the local and intermediate sinks transfer their heat for final dissipation. For most vehicles there are four ultimate sinks available: (1) the atmosphere surrounding the vehicle; (2) fuel supplied continuously o the power plant of the vehicle; (3) liquid carried for heat absorption only, and discharged as vapor; and (4) space receiving heat from radiation from the outer surface of the vehicle./13/

The method of transferring heat from an assembly or unit to the ultimate sink is dependent upon the method of heat removal from within the assembly or unit and the type of sink available, its location, and its temperature. The ultimate sink must be considered, since the temperature of local or intermediate sinks may increase when additional heat is added./11/

Natural Methods. If possible, equipment enclosures should be utilized to conduct heat from the equipment to the ultimate sink. In certain instances, the enclosures can be attached to structural members that are thermally connected to the ultimate sink.

Forced Convection. Forced convection is more applicable to this phase of cooling than natural methods, particularly if the ultimate sink is nearby air. The air should be properly directed and distributed over the equipment. Forced convection, at small flow rates, can readily provide thermal resistance about half of what is obtained with free convection and radiation. In general, thermal resistances on the order of 10 C per watt per square inch can be achieved with a reasonable air flow. Increased flow will, under certain conditions, lead to smaller gains, and the point of diminishing returns will be encountered.

"Indirect Liquid Cooling. Through the use of indirect liquid cooling, the heat sources can be

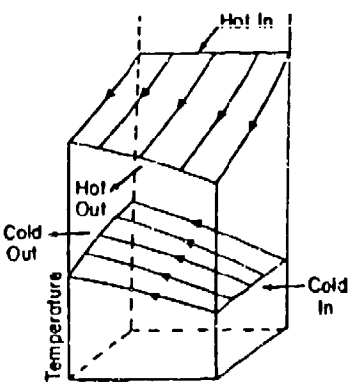


Fig. 5-19. Bulk temperature variation in crossflow exchanger./11/

arranged in the flow system independent of their physical locations, since the interconnecting pipe can be installed and routed almost as readily as electrical wiring. If carefully planned, this minimizes the flow rate and pumping power requirements and allows part placement for greater compactness. Because most of the heat transfer to the liquid is by conduction, the heat flow paths are well defined, and the interaction between parts is small.

One of the most important gains achieved by indirect liquid cooling is the resulting flexibility in the installation. The small space requirements of piping make the use of remote heat sinks feasible. For maximum compactness and flexibility, the equipment to be cooled need not have within itself the means for liquid circulation or ultimate heat exchange. These can be provided more efficiently and completely in a separate unit, or as part of an overall cooling system.

Even though parts may not be designed specifically for liquid cooling, suitable means can be provided for conducting their heat to liquid-cooled surfaces on which they are mounted. In this manner, the liquid may become the primary means of heat extraction from the equipment for transference to the ultimate sink.

FLIGHT VEHICLE HEAT REMOVAL SYSTEMS /14/

When the individual equipment heat-removal systems have been chosen, along with their sinks, they must then be integrated with the ultimate sink into an overall vehicle heat removal system. The heat removal systems used for this are ram air, expanded ram-air, bleed air, blower, fuel, expendable, and vapor cooling systems. The air systems are for both direct and indirect cooling of equipment items. The fuel, expendable and vapor systems are considered only as indirect systems.

The advantages and disadvantages of the various heat removal systems, together with a brief description of how they operate, are covered in the following paragraphs. A discussion of the considerations involved in selecting a heat removal system for a particular vehicle is also given. A more thorough analysis of heat removal systems is contained in reference/14/.

Ram Air Cooling System

Atmospheric air taken on board a flight vehicle may be used for cooling without prior conditioning as long as its total temperature is below the required temperature level of the equipment being served. When the atmospheric air is used as the ultimate fluid without any intermediate refrigeration equipment, and the source of pressure for overcoming flow resistance of the ultimate component is total pressure recovery during the intake process, the system is called a ram air system. The ram air system may be a direct or indirect cooling system. When air as the ultimate fluid is conveyed directly to and passes through the equipment, the system is classified as a direct system. When another fluid is used to transfer heat from the equipment to an intermediate component, which would be a heat exchanger, and the ram air cools the exchanger, the system is called an indirect cooling system.

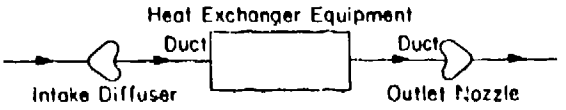


Fig. 5-20. Basic arrangement of a ram air system.

A block diagram of an indirect ram air system is shown in Fig. 5-20. Atmospheric air is taken on board the vehicle through an intake. At the exit of the intake, the first duct conveys the ram air to the heat exchanger. The air passing through the heat exchanger undergoes an increase in total temperature, because of heat received in producing a cooling effect, and the heated air is then conveyed by the second duct to the air outlet.

The weight and volume of direct ram air systems are defined by the weight and volume of the diffuser, nozzle and ducts connecting the heat exchanger with the diffuser and nozzle, since the equipment is not considered as a physical component proper of the heat removal system. Both the weight and volume of the system represent penalties on the flying vehicle. In addition to these penalties, the thrust generated during the escape of the ram air is generally not sufficient to completely cancel the drag resulting when the air is taken on board, so that a net drag is imposed on the vehicle.

Although indirect systems appear to increase the penalty on the vehicle because of (1) the added weight and volume of the intermediate heat exchanger and distribution fluid; and (2) the power required to circulate the fluid, and the somewhat larger weight, volume, and drag of the ultimate system, this is not always true. In the installation of complex electronic systems involving a large number of equipments with varying temperature requirements, the use of an indirect ram air system may save space (because of reduced ducting volume), reduce weight (because of reduced ducting weight), and increase reliability by reducing dust, maintaining better temperature control, and allowing simpler coolant duct connections. However, the temperature potential available for the ram air in indirect systems can never be quite as large as with direct systems for the same desired temperature level of the equipment.

The general advantages of ram air heat removal systems are:

1. Simplicity.

2. Low penalty in subsonic flight region.

3. Ease of control.

4. Possible freedom in location of ultimate system.

Disadvantages of the system include:

1. Relatively severe flight speed limitations.

2. Need of auxiliary equipment for ground cooling.

3. Large spatial requirements of ultimate system for high-altitude operation.

Expanded Ram-Air Cooling System

The temperature potential on which a cooling system operates is a direct function of the total temperature of the cooling fluid at the inlet to the equipment being cooled. Any reduction in this temperature can serve to lower the fluid flow rate required and to increase the temperature differential for heat transfer in any heat exchange device. Thus, should this temperature be reduced by some means, one may expect smaller heat exchangers and ducts, and lower external and momentum drags, because of the lower flow rates. However, there is a counteracting increase in the penalty from the physical devices introduced to increase the temperature potential of the system. Nevertheless, any means by which this temperature potential can be increased permits operation of the system at higher flight Mach numbers.

In general, lowering the total temperature of the fluid at inlet to the equipment requires the removal of heat energy. This is commonly accomplished by expanding the fluid in a mechanical device such as a turbine. The ram air system can be modified to permit reduction of this temperature by introducing a turbine after the ram air intake or diffusion process and ahead of the heat exchanger. The turbine must have a load, and so is directly coupled to a compressor located in the flow circuit after the heat exchanger. In this way, energy removed from the air during expansion in the turbine is delivered back to the air at a higher temperature level by the compressor. A system of this type using ram air to serve directly either the equipment or intermediate exchanger is called an expanded ram-air cooling system. A block diagram of an expanded ram-air system is shown in Fig. 5-21.

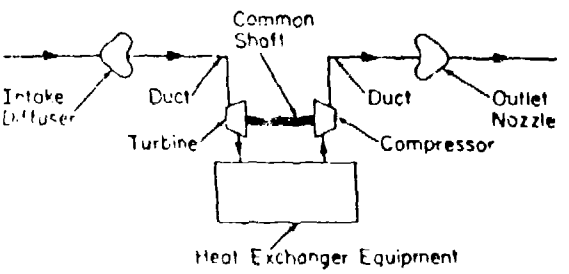


Fig. 5-21. Basic arrangement of an expanded ram-air system

Penalties on the flight vehicle resulting from the use of expanded ram-air systems are due to weight, volume, and drag, as with any other system. The weight and volume of the ultimate system are defined by the weight and volume of the inlet, outlet, ducts, turbine and compressor. With indirect systems, the weight and volume of the heat exchanger and distribution fluid must be included. Drag of the system arises from external and momentum drags associated with the ram air flow, and the equivalent drag of the increased fuel to a powerplant when shaft power is extracted for circulation of the transfer fluid through the system.

The primary advantage of the expanded ram-air system is the general possibility of using ram air for heat removal at higher flight Mach numbers. A second advantage of the system is that the ram air is conditioned without the system relying on any of the powerplants in the vehicle. This allows freedom of penalty directly imposed on the powerplant. Disadvantages of the system include the difficulty of using the system for ground cooling, the added complexity of controlling the turbine-compressor combination, low pressure levels in the heat exchanger of the ultimate system, and, in some instances, the fact that effective use of the system depends greatly on providing a very efficient intake diffusion process.

Bleed Air Cooling System

Like the expanded ram-air system, the bleed air system modifies the thermal state of the air used as the ultimate fluid before the air is delivered to the intermediate heat exchanger or equipment. However, in bleed air systems the availability of the air for cooling purposes is increased over that of the expanded ram-air systems, since for any flight speed it is possible for the temperature of the air at the exit of the turbine to be lower than the corresponding temperature in an expanded ram-air system. This means that bleed air systems may be used at higher flight Mach numbers than either the expanded ram-air or the straight ram-air cooling systems.

The general method by which the air availability is increased is by compressing the air by mechanical means, after it has been taken on board the vehicle. The air at the exit of the compressor has both a total pressure and a total temperature greater than its total pressure and

total temperature at the exit of the ram air intake. Then, by virtue of its higher total temperature, the compressed air may be cooled and have its total temperature lowered by ram air which does not pass through the compressor. The cooling process can take place in a conventional air-to-heat exchanger, where, by using the high air effectiveness of heat exchange on the high-pressure side of the exchanger, nearly all heat energy added to the air during passage through the compressor can be rejected to the ram air on the opposite side of the heat exchanger. Thus, at the exit of the heat exchanger the total pressure of the air that flowed through the compressor can be appreciably greater than the total pressure of the ram air, while its total temperature would be only slightly higher than the total temperature of the ram air. The air can then be expanded through a larger pressure ratio in a turbine, so that with an efficiency of energy in the turbine comparable with that of an expanded ram-air system, the total temperature of the air at the exit of the bleed-air turbine is lower, and the system cooling potential is greater. Using additional compression, a pre-cooling heat exchanger, and secondary ram air permits greater energy removal in the turbine than is possible in the expanded ram-air system. For systems of this type, the compressor or compressors of the vehicle powerplants are used to provide the additional compression. Air is extracted from the compressor and conveyed to the precooling heat exchanger. For this reason, the system is called a bleed-air system. A block diagram of the bleed-air system is shown in Fig. 5-22.

Penalties imposed on the vehicle by bleed-air systems are the result of the weight and volume, external and momentum drags, the equivalent drag due to air, and shaft power extraction from the powerplants in the vehicle. The weight and volume of the ultimate system are those of the ducts, precooler, turbine, compressor, air inlet and outlet, and system controls. The weight and volume for the distribution fluid and heat exchanger must be included with indirect systems. A major portion of the system's drag is represented by the equivalent drag of the increased fuel flow for maintaining constant propulsive thrust when air is extracted from the powerplants to serve as the ultimate fluid in the system.

The principal advantage of the bleed-air system is its ability to provide relatively high system temperature potentials at flight speeds in the range between Mach 1 and 2. This makes it possible to provide cooling of equipment items requiring temperature levels in the range from about 130 to 250 F (55 to 120 C) without the need of excessively high ram and bleed air flow rates. To provide this primary advantage, several additional parts must be included: namely a precooler and a secondary air flow circuit, each of which increases the weight and volume of the system and the penalty imposed on the flight performance of the vehicle. Another advantage of the system is that cooling of equipment during taxiing and

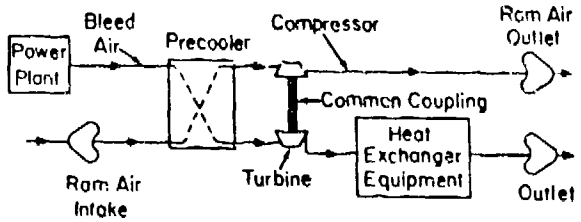


Fig. 5-22. Basic arrangement of bleed-air system for direct or indirect equipment cooling.

takeoff is possible without additional equipment. A possible disadvantage of the system is the fact that it relies on the use of a mechanical compressor, and this may restrict the flexibility in locating one or several of the units.

Blower Cooling Systems

When items to be cooled are located in compartments that have a natural throughflow of atmospheric air, external and momentum drags caused by a cooling system may be eliminated by providing a blower to overcome the flow resistance of any heat exchangers associated with the cooling system. The penalty of this type of cooling system results only from the blower and its power supply.

Blower systems, like ram-air systems, are severely limited in application by the flight speed and altitude. The limits imposed by flight speed are the same as discussed for ram air systems. The size of the blower at high altitudes is quite large. Also, control of blower systems over wide ranges of flight altitude and speed appears unduly complicated. Blower systems can only be used advantageously with small heat dissipation at subsonic flight speeds and moderate altitudes. Blowers designed for high-altitude operation usually can provide more than enough cooling on the ground.

Fuel Cooling Systems

The use of the vehicle's fuel as an ultimate fluid for cooling systems has often been proposed, since it represents an ultimate sink of considerable thermal capacity. Many arrangements and types of fuel cooling systems are possible, such as: (1) heat transfer to fuel flow to the powerplants, (2) steady-state operational conditions, (3) indirect systems, and (4) no change in phase of the fuel.

The temperature of the fuel at the inlet to the cooling system is assumed equal to the adiabatic skin temperature of the vehicle. This is the temperature considered most representative of the equilibrium fuel temperature for steady-state thermal conditions. Indirect systems are best, since it is not considered practical nor desirable to convey fuel away from the immediate vicinity

of the vehicle's fuel system. The heat exchanger is located close to a fuel line, and a distribution fluid transfers heat in the equipment to the exchanger. The fuel is considered to serve as an ultimate fluid without change in phase, so that the pressure level of the fuel in the heat exchanger is assumed sufficiently high to prevent boiling, and the heat absorbed is insufficient to cause carburetion difficulties.

A block diagram of a fuel cooling system is shown in Fig. 5-23. The system consists of the equipment, a distribution fluid, a heat exchanger and the ultimate fluid. A pump circulates the distribution fluid between the equipment and the heat exchanger. The distribution fluid is heated in the equipment and cooled in the exchanger by the fuel passing through the opposite side of the exchanger.

The principal advantage in using fuel as the ultimate sink is the relatively low penalty imposed on the vehicle by the cooling system, since weight and drag of the ultimate system is negligible. Furthermore, no air inlets or outlets are required, and operation and control of the system is relatively simple, because it provides the necessary fuel flow for cooling in a bypass arrangement with one or more main fuel lines. Without change in phase, the fuel is capable of receiving heat at the rate of about 850 Btu per minute for each 1000 pounds per hour of fuel flow. The available cooling capacity of the fuel is about 1.5 percent of the vehicle propulsive power at a flight Mach number of 0.9 for each 100 F temperature rise of the fuel; at Mach 1.5 the available cooling capacity for each 100 F temperature rise is on the order of 1 percent of the required propulsive power.

The primary disadvantage of fuel cooling systems for operation under conditions of thermal equilibrium is the relatively high temperature of the fuel in comparison with the desired temperature level of the equipment. Since the equilibrium temperature of the fuel may be assumed equal to the adiabatic skin temperature, flight speed limitations on fuel cooling systems

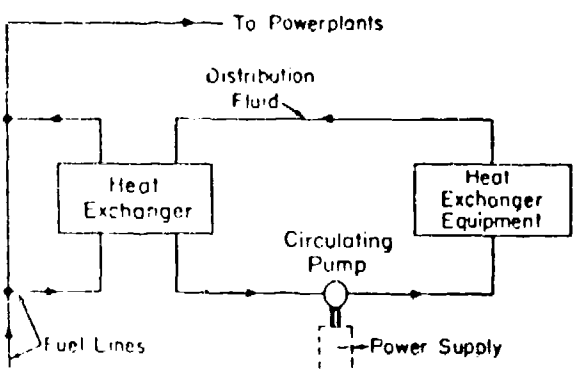


Fig. 5-23. Basic arrangement of a fuel cooling system.

are essentially the same as for ram air cooling systems. Thus, for cooling equipment in the temperature range of 130 to 250 F (55 to 120 C) under steady-state thermal conditions, fuel cooling systems are restricted to use at relatively low flight speeds. A method of alleviating this limitation is to use the fuel as a heat sink and connect a refrigeration system to it. The greatest availability of the fuel as an ultimate sink is for vehicle operation corresponding to the transient heating of the fuel system.

Factors, such as the effect of an increase in fuel temperature on the solubility of gases, fuel pumpability, volumetric expansion, fuel seals, and so forth, will introduce problems in the fuel supply system. The general problem of increased fuel system vulnerability could also affect the use of fuel as an ultimate sink for heat removal systems.

Expendable Cooling Systems

Often, relatively simple devices may be used based on the acceptance of low efficiency or a low coefficient of utilization. In principal, a cooling system of this type is one where the ultimate fluid is expended in absorbing heat. The use of expendable cooling systems appears more and more advantageous with increasing flight speeds because of the rapidly increasing penalty with flight speed of other types of cooling systems, and the decreasing flight endurance of vehicles with increasing flight speed. Therefore, a lower coefficient of utilization of the ultimate fluid can be justified with decreasing operational time, providing the weight and drag of the cooling system is minimized.

An expendable cooling system is one where the ultimate fluid is carried within the vehicle, undergoes a change in phase during the process of absorbing heat, and is then expelled from the vehicle. Liquid-to-vapor phase change for the expendable fluid is considered. A direct expendable system consists of the equipment as well as storage and flow control equipment. The ultimate fluid in direct systems is delivered to the equipment heat exchanger, where boiling of the fluid occurs. The resulting vapor is then exhausted from the vehicle.

An indirect expendable system consists of a heat exchanger and distribution fluid in addition to the other units. The expendable fluid is evaporated on the ultimate side of the heat exchanger and a distribution fluid is circulated between the equipment and exchanger. A block diagram of an indirect expendable heat removal system is shown in Fig. 5-24.

The penalty imposed on a vehicle by an expendable cooling system is principally due to the weight of ultimate fluid required. For steady-state thermal conditions, the weight required is in direct proportion to the operating

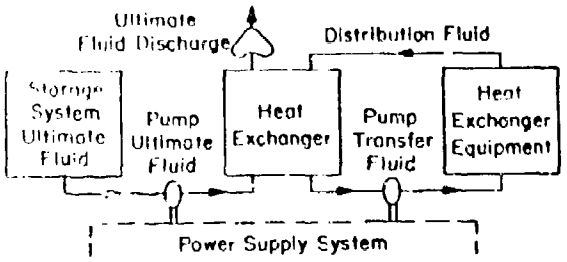


Fig. 5-24. Basic arrangement of an indirect expendable cooling system.

time of the cooling system, so that the "break-even" point of this system, in comparison with other types of systems, can be evaluated in terms of operating time for the cooling system. The break-even time increases with increasing flight speeds because of the general increase in penalty for other types of cooling systems with flight speed. In general, expendable systems, can be designed from conventional aircraft parts and are relatively simple in operation and control.

Vapor Cycle Refrigeration Systems

For the previously described cooling systems using air as the ultimate fluid, the system temperature potential is provided by limiting the vehicle flight speed or by creating an energy transfer by the use of turbines, compressors, and heat exchangers to modify the thermal state of the air before serving as a thermal sink. In addition to any method by which the thermal state of the ultimate air is modified, a heat pump can be used to lower the temperature level of the sink serving the equipment or distribution fluid, and to raise the temperature level of the source serving the ultimate fluid. In this way, the overall effective temperature potential of the system is increased. A cooling system of this type is in direct contrast to the philosophy of expendable cooling systems, since by introducing a heat pump, the temperature effectiveness, efficiency, or coefficient of utilization is improved by sacrificing simplicity of the system. The overall cooling system could be a ram air system, or an air system in which the thermal state of the ultimate air is modified prior to serving as a thermal sink for the heat pump. Fuel may also be used as the ultimate sink in a vapor cycle cooling system. The heat pump serves as a heat exchanger for the cooling system, so that the system is of the indirect type, regardless of whether or not the heat pump is in the vicinity of the equipment being cooled.

Cooling systems employing a heat pump can use a vapor cycle refrigeration machine for the exchanger and a ram air system as the ultimate sink. The evaporator in the vapor cycle machine furnishes the low temperature sink for the transfer fluid serving the equipment, and the condenser of the vapor cycle machine provides a high temperature source for the ram air serving as the ultimate sink. Shaft power for driving the compressor of the refrigeration machine is provided by the power supply system. A block diagram of such a system is shown in Fig. 5-25.

The primary advantage of a cooling system using a heat pump is its ability to provide cooling at high flight speeds. Theoretically, a cooling system of this type has no flight speed limitations. However, from a practical viewpoint, it is limited by its complexity, weight, power requirements, and availability of suitable refrigerants. The reason for this is that with increasing flight speed, it becomes desirable to increase the temperature differential created by the heat pump, and to consider units capable of modifying the thermal state of the ultimate sink. A detailed evaluation of vapor cycle refrigeration systems for use in flight vehicles is contained in reference /14/.

Consideration in Selecting a Cooling System

In the design of a cooling system to provide adequate and practical protection for flight vehicles and their equipment, consideration must be given to many variables, such as:

1. Cooling capacity.
2. Temperature level.
3. Weight.
4. Size.
5. Performance penalties.

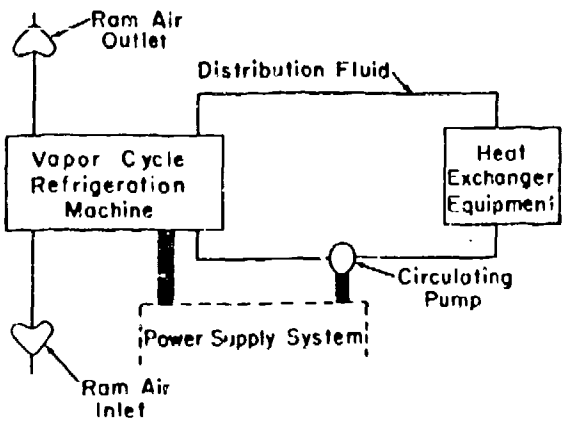


Fig. 5-25. Basic arrangement of a vapor cycle cooling system.

In addition, the type of vehicle must be considered. For example, a cooling system that would be satisfactory for a subsonic aircraft might be entirely inadequate for supersonic flight. Likewise, some cooling systems used effectively in atmospheric vehicles are unsatisfactory for use in space vehicles.

Probably the most important factor to consider in arriving at a cooling system configuration is how the cooling system can be integrated with other systems in the vehicle. An example of this is the combined air cycle cooling system and cabin pressurization system used in most gas-turbine propelled aircraft. In general, the use of more efficiently integrated systems results in a reduction of the performance penalties to the vehicle.

LOW-TEMPERATURE PROTECTION

Because in-flight compartment temperatures rarely stabilize at levels low enough to cause serious adverse effects on equipment operation, extensive coverage is not given in this handbook to low-temperature protection methods. Instead, a summary of important low-temperature protection techniques is presented in Table 5-11. A more detailed analysis of low-temperature effects and corresponding preventive measures is covered in reference/15/. It should be noted that the brief coverage does not mean that low-temperature protection can be neglected. On the contrary, factors such as the strategic importance of the Arctic and the advent of missiles and space vehicles have increased the need for reliable low-temperature equipment. One of the most extreme examples of this is the fuel system of many missiles. These vehicles store, pump and burn liquid fuels at temperatures as low as -320 to -425 F (-160 to -218 C). In addition to the extremely low temperatures, the materials used in these fuel systems must withstand high pressures and impact forces. One metal that might possibly be used in these applications is titanium, which increases in strength with decreasing temperature. Tests have shown that at -300 F (-148 C) the strength of titanium is twice as great as that at room temperature.

Table 5-11. Low-Temperature Protection Methods

Effect	Preventive measures
Differential contraction	Careful selection of materials
	Provision of proper clearance between moving parts;
	Use of spring tensioners and deeper pulleys for control cables;
	Use of heavier material for skins.
Lubrication stiffening	Proper choice of lubricants:
	Use greases compounded from silicones, diesters or silicone-diesters thickened with lithium stearate;
	Eliminate use of liquid lubricants wherever possible.
Leaks in hydraulic systems	Use of low-temperature sealing and packing compounds, such as silicone rubbers.
Stiffening of hydraulic systems	Use of proper low-temperature hydraulic fluids.
Ice damage caused by freezing of collected water	Elimination of moisture by:
	Provision of vents;
	Ample draining facilities;
	Eliminating moisture pockets;
	Suitable heating;
	Sealing;
	Desiccation of air.
Degradation of material properties and component reliability	Careful selection of materials and components with satisfactory low-temperature capabilities.

Methods of protecting the external surfaces of atmospheric flight vehicles from cold weather environmental effects such as icing and frosting are covered in later paragraphs.

SHOCK AND VIBRATION PROTECTION

There are two broad methods of protecting the vehicle and its equipment against shock and vibration. Where possible, design techniques and component parts should be chosen that will withstand the shock and vibration environments. Where the environments are too severe, judicious location of equipment and parts, or the use of isolation protective systems, is required.

Sources of Shock and Vibration

The airframe structure requires protection from shock, vibration, acceleration and acoustics occurring outside of and inside the structure. High speed flight may induce flutter that is sufficiently violent to cause almost instantaneous failure at a critical flutter speed, while flight through gusts results in high accelerations and stresses of the airframe. Certain maneuvers result in severe load factors being applied to the vehicle, and intense acoustic pressure loads usually damage the skin as a result of a large number of relatively small loads applied at a high rate. Imbalance in reciprocating power plants and noise from propellers and jet streams induce vibration. Inside the vehicle, rotating or moving equipment, such as pumps, compressors, turbines, actuators, etc., generate vibrations of many frequencies and amplitudes, which further complicate the problem.

Shock and Vibration Protection at the Vehicle Level

Basic structural design techniques, such as using suitable materials and frame design, will protect the flight vehicle against most of the environmental stress levels. This, however, is more a part of aeronautical engineering and is not covered in this handbook. The part of environmental engineering that deals with stresses at the vehicle level is concerned mostly with fatigue, which is the tendency for a metal to break under conditions of cyclic stressing considerably below its ultimate tensile strength.

Fatigue Damage. Fatigue damage occurs to airframe structures that are exposed to intense vibration and acoustic pressure loads. Damage to the vehicle skin can be minimized by (1) using the proper skin material and configuration and (2) controlling the vibration and acoustic stresses that are applied to the skin. It should be noted that the fatigue problem is not limited to the vehicle skin but affects every part of the vehicle, from the structure to the smallest component.

Skin Material and Configuration. Induced stresses in the vehicle skin material must be avoided during manufacture and processing of the material, as well as by proper design techniques. These induced stresses include stress raisers, which are factors such as sharp changes in contour or surface defects that concentrate stresses locally; internal stresses that take place during heat treating, forming, machining, etc.; and built-in stresses that result from improper assembly and design.

The effects on a vehicle's fatigue life of various methods of mounting the skin to the structural members of the airframe are shown in Fig. 5-26. When mounted as shown in (A), failures in the skin occur first near the bolt heads. Mounting (B) is the same as (A), except that a layer of bonding material is placed between the skin and the structure. With this method, the skin first peels away from the bonding, and then failure occurs near the bolt heads. This mounting tends to last about 50 percent longer than mounting (A). To eliminate peeling, both sides of the skin should be bonded and clamped between two rigid surfaces, as shown in (C). Failure then occurs at the edge, and the skin lasts twice as long as it would with the (A) method. Method (D) shows the skin rolled to an 8-foot radius and fastened to a curved rigid frame. Skin failure now starts near the bolt heads as it did with methods (A) and (B), but, curving the skin increases the average life 15 times over that shown in (A), even though the stress cycles increase about 50 percent. A further increase of fatigue life is obtained by leaving the edges of the frame sharp, instead of round. This causes the failures to occur at the edge of the frame instead of at the bolt head, but the fatigue life is doubled as indicated by the bar of dashed lines. Mounting (E) is the same as (D), except that a pressure differential of 6 pounds per square inch is put across the skin. This high differential pressure causes the skin frequency to nearly triple, and life is greatly increased. When the skin thickness is doubled from 0.032-inch to 0.064-inch gage and mounted with method (A), fatigue life increases about twenty times. /16/

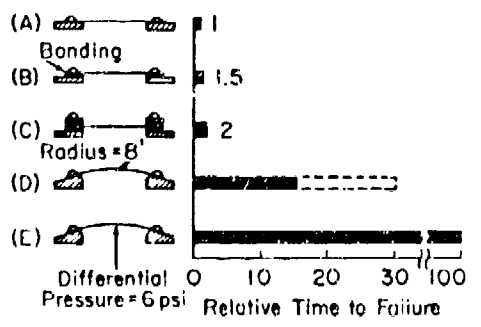


Fig. 5-26. Relative skin fatigue life. Skin gage is 0.032 inch; linear dimensions are constant./16/

Controlling Skin Stresses. There is little that can be done to reduce the stresses caused by the external environment; but fortunately, the internally generated stresses cause the most trouble and can be controlled to some extent. The vibration and acoustic levels that reach the skin can be kept down by using equipment and methods that generate less vibration and noise. For example, propeller noise may be reduced by increasing the number of blades, using wider blades, and removing the tips from the blades. Also, acoustic loading from jet engines can be minimized by placing the engines as far as possible from vulnerable areas.

Vibration and noise-generating equipment can be isolated by using special mounts to minimize the transmission of stresses to the skin. This is covered later in this section.

Flutter and Vibration. /17 Flutter and excessive vibration can be minimized by:

1. Using high torsional rigidity of fixed and movable surfaces.

2. Proper static balance of control surfaces.

3. Dynamic balance of control surfaces and tabs.

4. Inherent mass balancing by favorable location of structural weight.

5. Uniform spanwise distribution of weight along the span of the surface.

6. Irreversible tab mechanisms located as close to the tab or control surfaces as possible.

Panel flutter can usually be prevented by the use of sufficiently stiff structural panels. If thick panels are undesirable, a possible alternative solution is the use of internally pressurized compartments so that the outer skin is kept at constant tension. Control surface buzz can be prevented by sufficient rigidity of the actuating system and the control surfaces, or by using hydraulic damping about the hinge axis. Buffeting can generally be prevented by placing lift surfaces so that they lie outside the wake of other parts from which the air flow may separate as a result of either flight attitude or a high Mach number.

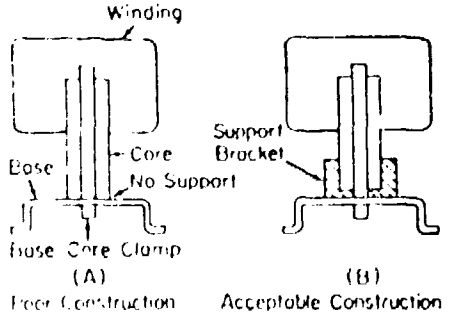


Fig. 5-27. Transformer design to resist shock and vibration.

Selection of Electronic Components

Whenever possible, components should be selected that can withstand the anticipated shock and vibration forces. In many cases, no components are available that have been specifically designed for operation in the expected environments. Then, the only recourse the designer has is to apply the available components in a manner that minimizes the environmental effects, or to use components that are available, and by judicious design, control the environment.

Studies have been made, such as reference /18/, concerning what happens to components subjected to shock and vibration, but little information is available as to how to select a component for use in this environment. For the most part, the information given in the following paragraphs is of a general nature. It is intended as a guide to aid the designer in selecting and using components.

Relays. The effects of shock and vibration can be decreased by using relays with contacts that are mounted on short, thick supports. /8/ Wiping, or follow-through contacts, such as used in a stepping relay, should be used whenever possible. This contact arrangement will not bounce open when subjected to shock and vibration. Relays should be used in the energized position, if possible, as the holding force is greater, and there is less danger of inadvertent opening. Adequate current should be supplied to the coil to obtain the most armature attraction.

Transformers. Certain types of transformer assemblies have definite points or areas that are susceptible to shock and vibration. The transformer shown in Fig. 5-27 illustrates this point. /19/ As attached to the base in (A), the transformer is vulnerable to lateral excitation. Adding a support bracket between the base and the core, as in (B), raises the natural frequency of the transformer and distributes the strain. Short leads should be used in a transformer to reduce the forces imposed on the terminals. Also, transformers should have the mounting bolts go through the core, instead of being welded to the shell. The transformers shown in Fig. 5-28 are examples of good design for shock and vibration environments.

Capacitors. Capacitor elements should be firmly held in their containers to prevent damage to the dielectric, the foil, and the leads to the terminals. A loose internal assembly may also cause intermittent open and short circuits during exposure to shock and vibration. In paper capacitors, the extended foil construction is best able to withstand the excitation forces.

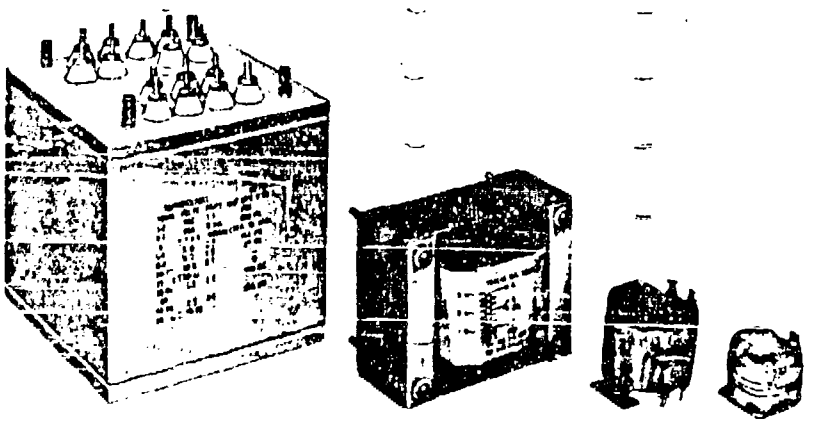


Fig. 5-28. Transformers designed to withstand shock and vibration. (Courtesy of Bell Telephone Laboratories, Inc.)

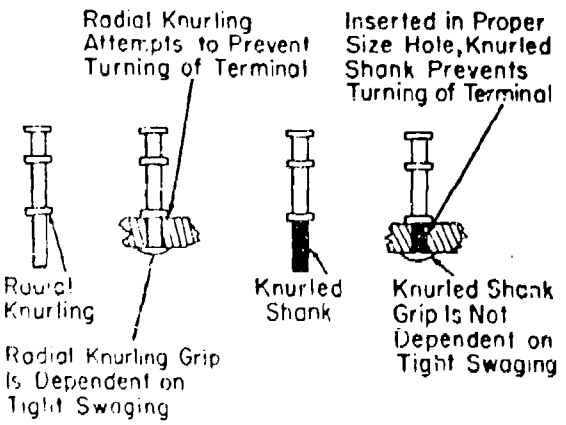


Fig. 5-29. Knurled terminal posts.

Resistors. Very little information can be offered on selecting fixed resistors to withstand shock and vibration. However, as to shaft operating variable resistors, the following should be considered. The slider spring tension should be sufficient to prevent the slider from breaking contact with the resistance element as a result of shock and vibration; adequate shaft torque should be used to prevent creepage from shock and vibration; the shaft should be reduced to the minimum permissible length; and the lightest knob should be used. /18/

Terminals. The rigidity of a terminal in its mounting hole determines, to some extent, the ability of the attached lead to withstand mechanical excitation. If the terminal becomes loose and vibrates, the lead becomes susceptible to vibration forces. By vibrating and bumping the edges of its mounting hole, a loose terminal causes wear around the edge of the hole and becomes looser. The terminal board must be of a composition that will not readily wear or crack around the mounting hole, and the terminal must be made of such material that the terminal shank will not crack excessively when it is swaged. A knurled terminal grips the board better and resists turning in the hole. Terminals with knurled shanks are more resistant to turning than those with radial knurling. Figure 5-29 shows a radial and a knurled shank terminal post.

Wiring and Cabling. /19/ Stranded wire and cable have a relatively high degree of damping and are preferable to solid conductor wiring in a shock and vibration environment. In addition to the internal damping offered by the insulation, internal friction between multiconductor cable components or between individual strands of stranded conductors provides damping that reduces the vibration amplitude at resonance.

Selection of Fasteners /8/

In many cases, even though the equipment is properly designed and isolated so that it will not be directly damaged by shock and vibration forces, the repetitive nature of the forces tends to cause fastened devices to come loose after a period of time. Fasteners, then, should be

chosen to resist vibration and acoustic forces. Many specialized fasteners have been developed for particular purposes, and these fasteners are used in large quantities in military equipment. Some commonly used fasteners are described in the following paragraphs.

Self-Locking Nuts. Self-locking nuts of the thread interference type provide torque in the nut to resist vibration or other forces that tend to separate the joint. Locking is accomplished in any one of several ways. The nut may have an insert made of a relatively soft material, such as fiber, nylon, or lead, as shown in Fig. 5-30. The screw impresses its own thread in the insert, and the resiliency of the insert material exerts a force on the screw thread to prevent it from loosening.

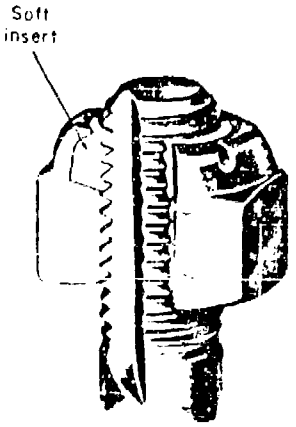


Fig. 5-30. Self-locking nut with relatively soft insert that grips threads to prevent loosening. (Courtesy of Elastic Stop Nut Corp.)

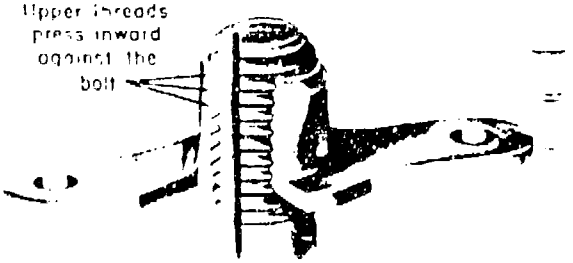


Fig. 5-31. Self-locking nut with thread slightly deformed inwardly to grip screw thread tightly. (Courtesy of Elastic Stop Nut Corp.)

In another type of self-locking nut, several of the threads are deformed to an elliptical shape or inwardly, as shown in Fig. 5-31. The deformed thread then grips the screw thread over a portion of its periphery and the nut does not loosen readily. Still another self-locking nut is made in two parts, as shown in Fig. 5-32, with the top of the bottom portion slotted so that it can compress when the upper portion of the nut is threaded on it.

Self-locking nuts are available in a variety of forms: plain; clinch, for fastening the nut into a plate or structure; anchor, for fastening to a plate or structure by riveting, eyeleting, welding, or a similar method; and floating, which is similar to anchor, except that the nut has freedom of movement for a short distance in two directions to allow for tolerances in fitted parts. Some examples of clinch-type nuts are shown in Fig. 5-33.

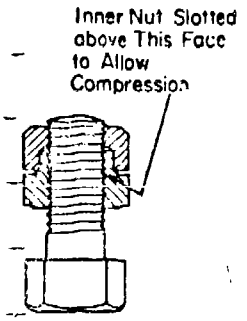


Fig. 5-32. Two-part self-locking nut. Top nut compresses slotted portion of bottom nut against screw thread.

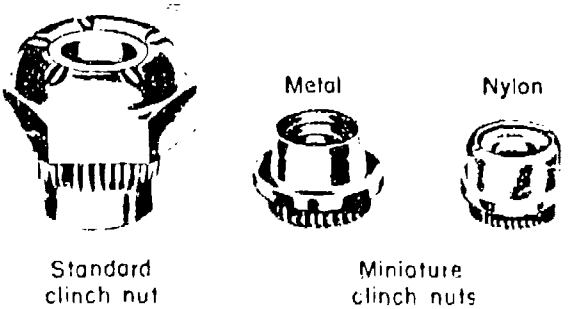


Fig. 5-33. Self-locking nuts that may be clinched into panel and anchored by riveting or welding. (Courtesy of Elastic Stop Nut Corp.)

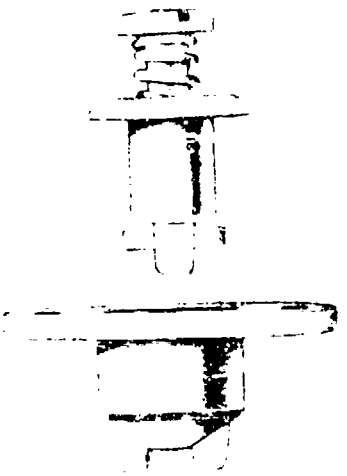


Fig. 5-34. Quarter-turn fastener that locks or releases with quarter-turn of rotating element. (Courtesy of Camloc Fastener Corp.)

Fig. 5-35. Quarter-turn fastener installed to hold two parts together.

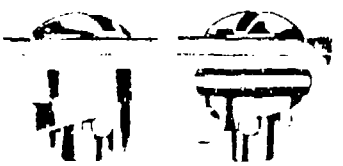


Fig. 5-36. Half-turn fastener using cam receptacle and rubber sleeve. (Courtesy of General Tire and Rubber Co.)

Fractional-Turn Fasteners. Fractional-turn fasteners are widely used in airborne applications. They operate, to fasten or release, with a quarter or half turn of the rotating member. They are useful in attaching panels to racks, fastening replaceable subassemblies to chassis, closing access and inspection doors in airframes, etc. Choice of a suitable fractional-turn fastener depends on such factors as space available, weight of the objects fastened together, kind of tools available for operation, vibration and shock forces, whether sealing is required, and need for retaining the fastener in objects during separation.

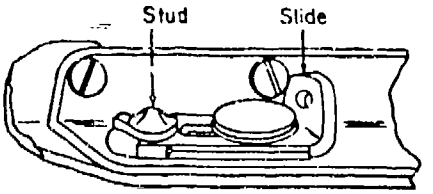


Fig. 5-37. Snap-slid fastener operated by small movement of sliding section. (Courtesy of Aircraft Radio Corporation)

Many quarter-turn fasteners consist of two parts, and others consist of one piece. Both kinds have various types of heads for operation with screwdrivers, a coin or the fingers. Some fasteners have detents or other devices to lock them against inadvertent loosening; and in others, care has to be taken to avoid turning them too far so that they release inadvertently. Most of these fasteners need specially shaped holes in both parts to be fastened, but several use plain round holes.

Figure 5-34 shows a fastener that consists of a stud assembly and a cam-type receptacle. The same fastener installed to hold two panels together is shown in Fig. 5-35. The stud assembly may be installed so that it is self-retaining, or so that it may be removed as the fastener is opened. The receptacle is attached to its parts by riveting or welding. Two sizes of this fastener have rated tensile and shear strengths of 200 and 700 pounds, and ultimate tensile and shear strengths of 300 and 1050 pounds.

A fractional-turn fastener using a rubber sleeve that expands in a radial direction to squeeze against the sides of the holes in the panel and the frame is shown in Fig. 5-36. The fastener has the cam device in the stud portion, and as it is turned, the spring wire rides in the cam and pulls the fastener tight.

Snap Slides. The snap-slide fastener, shown in Fig. 5-37, is useful in fastening panels, covers, and assemblies to chassis or other structures. The fasteners are designed to permit removal and replacement of equipment and other parts in a few seconds. At the same time they are strong enough to carry airborne equipment under severe stress. The open end of the slide

is so designed that it must be forced open slightly before the stud is engaged. This prevents the slide from coming loose.

Fastening Clamps. Fastening clamps for securing equipment to the airframe or racks must be capable of staying tight under constant vibration. It is standard practice with ordinary nut and bolt fastening to use a safety wire to prevent the bolt from becoming loose. However, the safety wire tends to slow down removal and replacement of equipment. Self-locking fastening clamps are available that do not require safety wires. A typical one is shown in Fig. 5-38. The clamp consists of three principal parts: an inner nut to secure the equipment to the rack; an outer nut; and a serrated locking nut to lock the inner nut in place. The outer nut is spring loaded so that it applies constant pressure on the inner nut to prevent it from loosening. The serrated locking nut couples the inner and outer nuts, and normally is seated in the nut recesses. The outer nut can be screwed up or down to the best locking position, and then can be pulled up slightly from its locking position without screwing. An internal spring pulls the outer nut back down to its locking position when it is released. With the outer nut pulled up, the inner nut can be unscrewed to release the equipment. The entire clamp assembly is usually attached to the rack with a hinge, so that the clamp can be swung down to facilitate removal and replacement.

Application of Components

Three basic considerations are involved in protecting parts from the effects of shock and vibration. The first consideration is the location of a part with respect to the linear dimensions of the structure or chassis on which it is mounted; in other words, whether a part is put on the edge, the corner, or in the center of the structure. The second consideration is the orientation of a part with respect to the direction of shock and vibration excitation. And the third consideration is the manner of mounting the part.

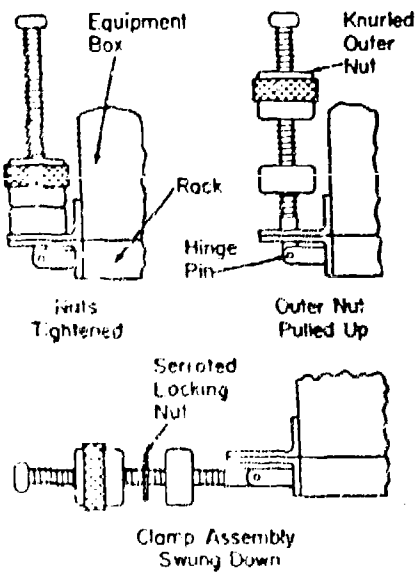


Fig. 5-38. Self-locking fastening clamp.

The ability of a part to withstand shock and vibration depends on the response of the part to the encountered excitation, and on its ability to withstand that response without malfunction or failure. The size and shape of a part, the way in which it is mounted, and such material properties as density and elastic modulus effect its natural frequencies.

Parts Location

Some degree of shock and vibration protection is obtained by properly locating parts on the supporting structure or chassis, since the location can affect the natural frequency of the structure and the amount of shock protection provided. Such placement takes into account both the weights of the parts and their motions in response to excitation. In most cases, calculating the best arrangement of parts is impractical, since the time spent in making the calculations is greater than the time necessary to test and modify an arrangement arrived at by empirical methods.

The following is a list of parts-location techniques and considerations for designing equipment to be used in a shock and vibration environment:

1. Maximum support should be given to parts of maximum weight.

2. Sufficient space should be provided for movement of parts under excitation.

3. Centers of gravity of parts and equipment should be kept close to the plane of mounts.

4. Heavy parts should be located at the corners or sides of a chassis, and lighter items should be centrally located.

5. Parts should be distributed about the mounting structure so that the chances of their striking one another are minimized.

6. The total mass of parts remote from the plane of mounts should be kept as small as possible.

7. Heavy parts should be located low in equipment and placed as close to mounts as possible.

8. There is reason to believe that an irregular arrangement of parts on the mounting structure is of value, since such an arrangement prevents all the parts from resonating at the same frequency and in the same direction.

9. The natural frequencies of the portions of the mounting structure on which sensitive parts are located should be far removed from the natural frequencies of the sensitive parts. A frequency ratio of 2 to 3 is desirable.

Parts Orientation

An indication of the importance of parts orientation as a protective measure against shock and vibration can be gotten from the following discussion of relays.

Relay Orientation. The relay ranks with the electron tube as one of the major sources of malfunction in airborne equipment. The operation of a relay under conditions of shock and vibration is generally unpredictable. Typical shock and vibration failures are: contact chattering, armature binding, armature jarring from position, and mechanical warping and breakage. When cantilever mounted and vertically oriented, relays with long body dimensions often amplify the mechanical excitation appearing at their mounting base. This undesirable combination is shown in Fig. 5-39. From the 10-g motion of the base, successive amplifications occur until a 30-g level is reached at the armature.

Clapper-Type Relay. The clapper-type relay, shown in Fig. 5-40, fails fastest when subjected to shock and vibration along axis 1. At low vibration frequencies along this axis, some contact chatter occurs but the degree of chatter varies depending on the contact-tip pressure for the particular relay design. Severe chatter occurs at or close to the resonant frequencies of the relay's contact support members. Contact chatter also occurs as a result of shock forces. Axis 2 of the clapper-type relay appears least sensitive to shock and vibration. Unless specialized clapper types are used, there is assurance of optimum relay performance if the relay is oriented so that acceleration forces are directed parallel to this axis. Along axis 3, the average clapper-type relay is not considered susceptible to effects of vibration accelerations. Shock accelerations of 30 to 50 g, however, cause considerable contact chatter.

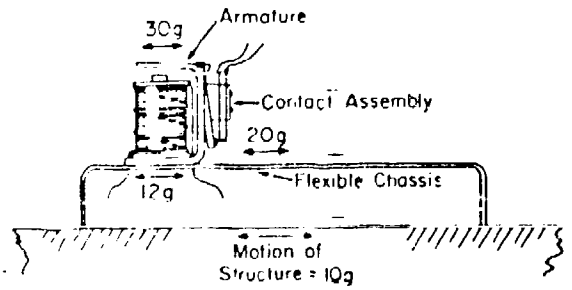


Fig. 5-39. Shock amplification throughout long-body relay fastened on flexible chassis./19/

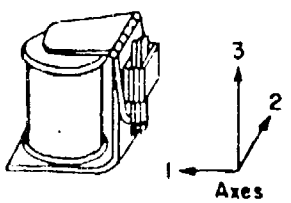


Fig. 5-40. Clapper-type relay and axes.

Rotary-Type Relay. The rotary type relay, shown in Fig. 5-41, is normally not affected by linear vibration. It is sensitive only to rotational vibration in a plane perpendicular to its axis.

Summary of Relay Orientation. Experience shows that relays are usually oriented according to available space or convenience of attachment. Certain optimum orientations of relays, however, exist for various types of environments. The dynamic forces in conventional aircraft and helicopters are primarily along the vertical axis, but in helicopters, forces nearly as great appear along the transverse axis. Missiles launched from the ground often experience large dynamic forces along the longitudinal axis. The effect of these forces on the relay depends mainly on the particular relay and its orientation in relation to the dynamic force encountered. Figure 5-42 shows orientations for three types of relays. These orientations assume that the support is rigid, and that motion occurs along or about one axis only. When rigid supports are unavailable, sufficient rigidity must be designed into the supporting

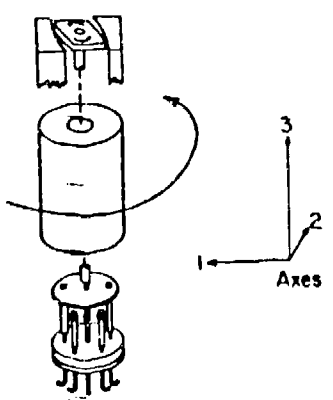


Fig. 5-41. Rotary-type relay and axes.

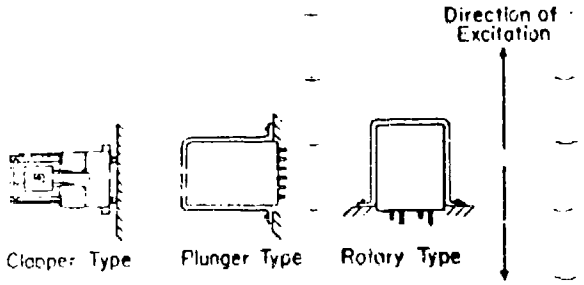


Fig. 5-42. Best orientation for three popular type relays./19/

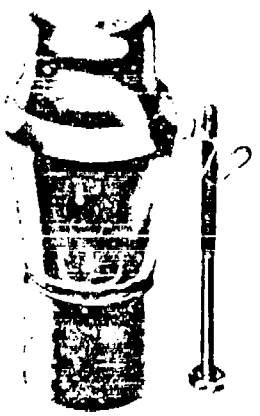


Fig. 5-43. Hat and post device for holding tube in socket. (Courtesy of Times Facsimile Corp.)

structure to increase the natural frequency of the assembly beyond the environmental exciting frequencies.

Parts Mounting

The resonant frequencies and behavior of any part, after considering its shape, mass distribution, and elasticity, are determined largely by the mounting method used. The mounting arrangement is the one aspect of design over which the designer has the greatest control. Mounting methods for several common electronic parts are described in this section to show the wide latitude the designer has in selecting a mounting arrangement. Fasteners for use in mounting have been covered previously in this chapter.

Electron Tube Mounting. Except for the special case of individually isolated tubes, the best that

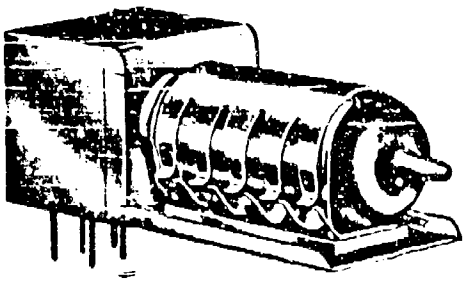


Fig. 5-44. Cradle-type tube shield for miniature tube./8/

can be accomplished in tube mounting is to subject the entire tube to the vibration existing in the chassis. The mounting must not only restrict the tube's motion under shock, but should also attenuate the shock, if possible. The simplest way to mount a tube is to push its pins into a socket that is fastened to the chassis. While this method of mounting is satisfactory in mild environments, it does not provide good support for the tube. Tubes that are pin mounted may, under shock or vibration, pop out of their sockets, strike other parts, or amplify the base motion and subject the interior of the tube to high accelerations.

One method used for securing tubes with bases is to clamp the tube by its base, with the clamp secured to the chassis. However, base-gripping clamps are usually more rigid than other types and tend to transmit full shock forces directly to the tube. Also, although the base-gripping clamp holds the base of the tube securely, the envelope containing the tube elements is still a cantilever, and under severe shock and vibration the cement that holds the envelope in the base often fails. When this happens, the leads will soon fail.

Clamps that grip the envelope are preferable to the base-gripping type. There are two general types of envelope-gripping tube clamps: the "hat and post" type and the shield type. The hat and post type is available in many varieties. The one shown in Fig. 5-43 is for a regular size glass envelope. Tube shields, in addition to providing electrical shielding and temperature control, give the tube mechanical protection and help hold it in its socket. Many varieties of tube shields are available; a cradle-type of miniature tubes is shown in Fig. 5-44.

Transistor Mounting. Although inherently resistant to shock and vibration, transistors can fail because of improper mounting. Figure 5-45 shows five types of transistors that are mounted in various ways. The transistor shown in (A) is screwed to the chassis. The type shown in (B) has a threaded stud that screws into a

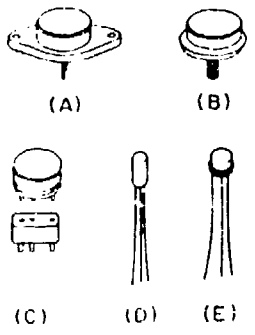


Fig. 5-45. Five types of transistors.

heat sink. From a shock and vibration standpoint, these two types are desirable because they fasten securely. Transistors (C), (D), and (E) do not fasten as securely as the other two, and other means must be used to insure their resistance to shock and vibration. Type (C) mounts in a socket like an electron tube, and for airborne applications it must be mounted with some form of retainer. The retainer may consist of a strip of metal extending across a row of plug-in transistors and securely bolted to the chassis. Rubber grommets are used at the points of contact between the strip and the transistors.

Transistors (D) and (E) are supported by their leads, which makes them vulnerable to shock and vibration. The long type, (D), is usually mounted on printed-wiring boards with the long side flat against the board, and should be held to the board by spring clips or wire straps. The flat, button type, (E), may be used without retainers, if mounted on a printed-wiring board with the leads holding the base tight against the board. Both of these types are less susceptible to failure if a coating is used to make the board and other parts rigid. The coating also makes the transistor adhere to the board.

Transformer Mounting. In many cases, a transformer is the heaviest part on a chassis. The transformer should have strong brackets and be securely mounted with large bolts. Frequently, the transformer is mounted on a relatively flimsy chassis, which lowers the chassis' resonant frequency to a point where it is in the shock and vibration spectrum. Thus, input accelerations are amplified by the chassis, the bolts, or on the chassis itself. Careful attention to mounting will prevent the transformer from breaking loose.

Capacitor and Resistor Mounting. Mounting capacitors and resistors by their leads is a simple and economical installation. Components mounted by their leads are masses supported by complex resilient beams with little damping. Should such an assembly be excited at its resonant frequency, the stress on the leads can easily become great enough to cause them to break. Lead-mounted capacitors and resistors fail more quickly when excited at resonance than when excited at other frequencies, and their life may be increased by increasing their natural frequencies. Figure 5-46 shows the results of tests on a particular resistor size and type and illustrates the increased life that can be obtained by increasing the natural frequency through shortening the lead lengths.

The method of mounting capacitors and resistors by using short leads as their supports may be acceptable in conventional aircraft, where the high-frequency excitation is of low value. But, when this method of mounting is used in a guided missile, where chassis vibrations of appreciable magnitude may exist for long periods at frequencies coinciding with the natural frequency of the lead-mounted part, it may be necessary to clamp or cement the capacitor or resistor to the chassis.

Proper mounting techniques for both fastened and lead-mounted capacitors and resistors incorporate many minor but important considerations. For example, as shown in Fig. 5-47, the lead should be handled carefully with proper tools to prevent nicking or scratching, and the lead should be given a slight bend to allow for temperature contractions of the wire between the component and the terminal.

Proper design of equipment structure can minimize the effects of shock and vibration, and control the transmission of shock and vibration excitation. The mounting structure generally takes the form of a rack and chassis. Structurally, the rack may vary from a simple mounting base to a complex construction that integrates many equipments; the chassis may vary from a sheet metal box to a complex casting. No matter what form the rack or chassis may take, the design of these structures is essentially a matter of providing the best strength and flexibility. A rack or chassis that is too

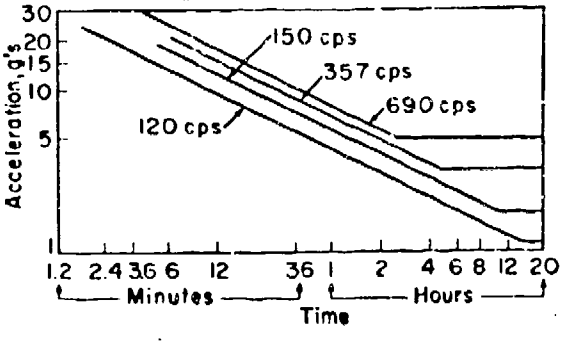


Fig. 5-46. Fatigue life vs natural frequency of lead-mounted resistor./19/

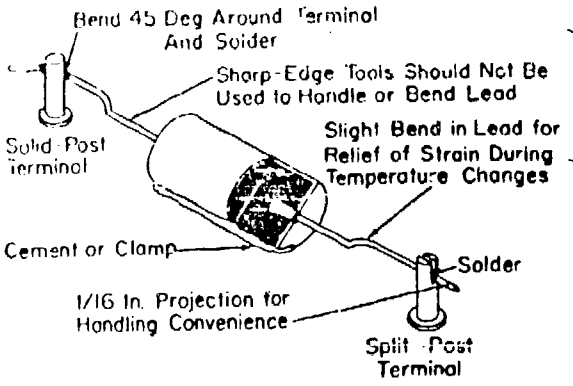


Fig. 5-47. Proper mounting technique for lead-mounted capacitor or resistor./19/

flexible may amplify vibration excitation; one that is too rigid may transmit an unnecessary amount of shock excitation.

Design Considerations./19/

Structures are designed to withstand shock and vibration forces by: (1) controlling the response of the structures to the environments, (2) giving the structures the proper stress characteristics, and (3) isolating the structures from the forces. A proper combination of these is generally used.

The response of a structure to shock and vibration excitation is determined largely by the excitation frequency and resonance characteristics of the structure. The stress characteristics of the structure depend on the choice of materials, type of structure used, and stress distributions resulting from manufacturing. Only stress distribution is covered here, since material and structure characteristics are part of mechanical engineering. Isolation of the structure requires the use of an auxiliary protective system; this is covered later in a separate section.

Resonance affects the magnitude of the load applied to a structure and its transmission characteristics. Any shock or vibration at the resonant frequency is amplified in force, causing an increased chance for damage and coupling to other parts. The ratio of the output vibration amplitude to the applied vibration amplitude is known as transmissibility. Transmissibility can be considered a magnification factor, and is greatest at resonance. It decreases down to unity below resonance, and can become less than unity above resonance. Therefore, structural parts chosen should be tested and/or analyzed to determine their natural frequencies. Since natural frequencies are fixed for a specific material configuration, the magnitude of the excitation reaching the parts at those frequencies must be of a low value. The excitation is a function of the environment existing at the mounting and the flexibility of the structure.

The anticipated environment is the determining factor in designing for natural frequencies of the mounting system and equipment. For setting the natural frequencies of the racks and chassis, the following rule-of-thumb is useful: the natural frequencies should be no less than two times, and preferably three to four times, the highest frequency of the excitation source. This source will be either the isolators or the airframe, depending on whether flexible or rigid mounting is used. Often, especially in missiles, the excitation frequencies are so high that it is impossible to design the rack and chassis of a rigidly mounted equipment so that the natural frequencies are above the excitation frequencies. In this case, the chassis and rack natural frequencies should be in a range where the acceleration levels are low, and the chassis and rack should be damped to limit resonance response. Damping is considered part of the protective system.

The number of structures in the mounting system should be minimized. Making the remaining structures as rigid as possible will further increase the resonant frequency. Solidly mounted equipment must be inherently rugged enough to withstand the shock and vibration environment without the cushioning of isolators. Ruggedization can be incorporated into the equipment by numerous conventional techniques, as well as by special methods such as embedment and miniaturization.

Rigidity Factors

Rigidity in a structure can be accomplished by designing the structure for an inherent stiffness and, where necessary, adding stiffeners to increase the rigidity.

Inherent Stiffness. The inherent stiffness of a structure depends on the modulus of elasticity of the material and its cross-sectional area and shape. The modulus of elasticity values, E, for several materials are given in Table 5-12. Typical cross sections of structural shapes are shown in Fig. 5-48. These shapes are available

Table 5-12. Moduli of Elasticity, E, for Various Materials /19/

Material	E (lbs/in.^{2})
Aluminum	10.2×10^6
Magnesium	6.1×10^6
Steel	$28\text{-}31 \times 10^6$
Brass	13.4×10^6
Copper	14.5×10^6

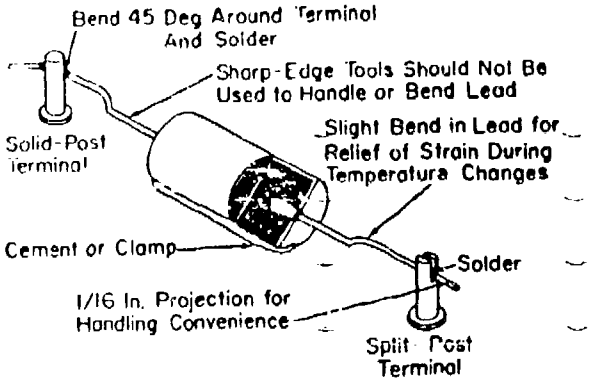


Fig. 5-47. Proper mounting technique for lead-mounted capacitor or resistor./19/

flexible may amplify vibration excitation; one that is too rigid may transmit an unnecessary amount of shock excitation.

Design Considerations./19/

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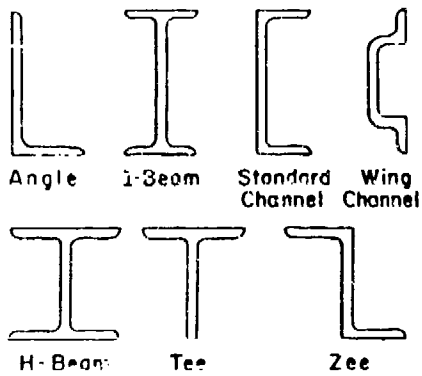


Fig. 5-48. Typical cross sections of structural shapes./19/

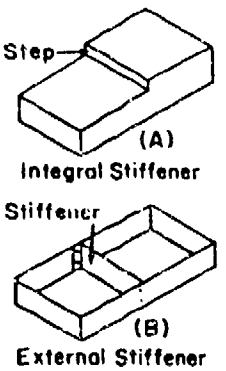


Fig. 5-49. Examples of chassis stiffeners./19/

in a complete range of sizes and materials. Their design is a result of specialized needs, generally to give the proper amount of stiffness in each direction of deflection at minimum weight.

If a beam is loaded three times as much vertically as it is horizontally, with equal deflections in each direction, then it should be three times as stiff in the vertical plane. This means that the moment of inertia in the vertical plane must be three times that in the horizontal plane. A square "H-beam fulfills these requirements. The other structural shapes satisfy other ratios of vertical-to-horizontal stiffness.

Structural sections should be oriented so that maximum stiffness occurs in the plane of maximum excitation. For example, since an ordinary chassis is, in section, similar to a channel, if the major excitation is in the vertical axis, the best chassis orientation is vertical.

Stiffeners. Stiffeners increase the natural frequency and strength of a structure. They can be both integral and external. Integral stiffeners are formed into the structure when it is made. The stepped chassis shown in Fig. 5-49(A) is an example of integral stiffening. The riser between the two steps is bent from the top plate of the chassis and acts as a stiffener across the width of the chassis. External stiffeners are beams fastened to a structure, as shown in Fig. 5-49(B). They are located where needed and may be added during later design and testing stages. The simplest stiffener is a beam placed across the width of the structure, on either the top or bottom, and attached to the structure along the length of the beam. The point of maximum static deflection for a uniformly loaded or centerloaded chassis is its center. A beam across the center of the chassis provides additional stiffness and reduces the static deflection.

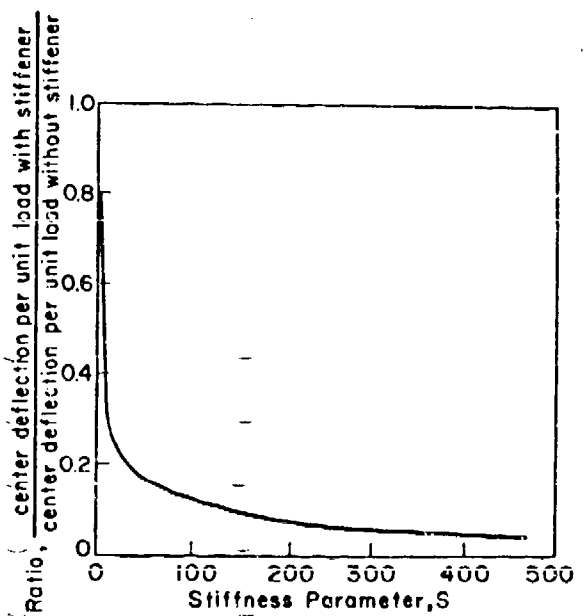


Fig. 5-50. Effect of cross-member stiffener on box-type chassis./19/

The amount of reduction in static deflection with the addition of a stiffener can be estimated by determining the stiffness parameter of the structure and stiffener, and referring this stiffness parameter to the chart shown in Fig. 5-50. This chart is a plot of stiffness parameter versus the ratio of deflection for the stiffened and unstiffened chassis. The curve in this chart was obtained by measuring the static deflection of chassis with and without a stiffener under a given load.

The stiffness parameter, S, is a dimensionless quantity and is determined by an empirically derived formula. The formula is:

$$S = \frac{E_s (I + Ae^2)}{Db}$$

where: S = stiffness parameter, dimensionless

E_s = modulus of elasticity of stiffener, lb/in.^{2}

I = moment of inertia of cross section of stiffener about axis through centroid (in.^{4}) parallel to top of chassis

A = cross-sectional area of stiffener, in.^{2}

e = distance from centroid of stiffener cross section to center of thickness of top of chassis, in.

b = width of chassis, in.

D = rigidity of top of chassis, lb/in.

$$D = \frac{E_c h^3}{12 (1 - \sigma^2)}$$

where E_c = modulus of elasticity of chassis, lb/in.^{2}

h = thickness of top of chassis, in.

σ = Poisson's ratio for the chassis material, dimensionless

It should be noted that stiffening a structure to raise its natural frequency is not a cure-all for unwanted resonance. In some cases, stiffening may lower the equipment's resistance to shock excitation, so that a compromise may be necessary between stiffening and some other means of shock and vibration protection, such as damping.

Stress Distributions

The stress distributions within structural materials have a decided effect on how much shock and vibration the structures can take. In a plate that has no bends, cutouts, or sudden changes in cross section, the stress is distributed along many lines parallel to the direction of stress. If the plate is bent, perforated, or drawn when being formed, these stress distribution lines have to pass through or around the deformation. This results in stress concentrations, which tend to increase the deleterious effects of shock and vibration forces.

Stress concentrations can be minimized by (1) making sheet metal bends generous and properly formed, (2) providing bend-relief at corners, (3) filleting at all changes in cross section, (4) avoiding sharp cornered cutouts and notches, and (5) planning hole shape and location with a view toward their effects on flexibility and strength.

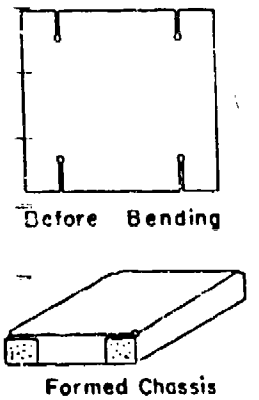


Fig. 5-51. Enlargement of slot ends to reduce stress concentrations at corners./19/

Sheet Metal Bends. Large bend radii reduce the likelihood of stress concentrations and of surface cracks due to forming. Because of practical reasons, bends cannot always be made large, but they should be greater than certain minimum values. A safe rule-of-thumb for common sheet stock, such as aluminum and steel, is to make the bend radius about four to six times the thickness of the material. The minimum safe radii for specific materials are given in tables of sheet metal bend radii in standard handbooks on metals.

Enlargement of the ends of slots prior to bending sheet metal into a structural shape such as a chassis, reduces stress concentrations at the bent corners. This also lessens the chances of cracking at the corners, especially where two bends are made close to each other. This is shown in Fig. 5-51.

Forming Techniques. If sheet metal is formed on a brake, the method of gripping the metal determines the strain produced by bending. When the sheet is bent, stretching occurs mainly along the surface indicated in Fig. 5-52(A). An alternative vise shape, shown in Fig. 5-52(B), uses inserts to restrain but not to grip the sheet. The same radius is obtained on bending, but stretching is distributed over a greater length, thus reducing the chance of cracking at the outside surface of the bend. Another good method of shaping structures from sheet metal is by hydroforming. Pressure behind a diaphragm forces the sheet stock onto a die. The hydraulic method gives equal pressure at all points, distributing stresses uniformly over the sheet.

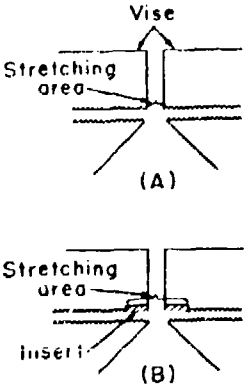


Fig. 5-52. Vise insert distributes bending stresses over greater surface./19/

Cutouts. Cutouts for parts will not weaken a structure very much if only a small portion of the metal is removed. The holes should not be aligned in such a way as to "hinge" the material, thus making it more flexible, nor to perforate it so that it tears readily.

Protective Isolation System/19/

In many cases, shock and vibration forces are so severe that it is not practical, from a size and weight standpoint, or even possible to design an equipment structure to withstand the environment. In such cases, an isolation system must be used to bring the environmental forces within tolerable limits. The isolation system should be used at the shock and vibration source to minimize the environmental problem for other equipments, and at the susceptible equipment to bring the forces to within levels that can be withstood.

Equipment is usually insulated from shock and vibration by shock and vibration isolators. Damping is often used to reduce the peak amplifications, and special stabilizers are used in instances where unstable configurations are involved.

Damping

Damping is used to reduce shock and vibration amplitudes by dissipating some of the energy in the form of heat. In addition, damping reduces resonant tendencies of structural members. Four types of damping are used: viscous, hysteresis, friction and air. Viscous damping results from the displacement of fluids. Hysteresis damping is caused by energy losses in a cyclically stressed material. Friction damping is the result of the sliding resistance of two contacting surfaces. Air damping is caused by the displacement of air, and is a form of viscous damping.

Viscous Damping. Viscous damping results from the opposing force that a fluid generates to resist a change in motion. All fluids have an internal friction that resists relative motion between particles. As a fluid flows over a surface, such as the walls of a tube, the fluid particles in contact with the surface tend to remain at rest, and the velocity of flow increases with the distance from the surface. Considering the fluid to consist of layers, there is an apparent friction between adjacent layers. Viscosity is the term used in designating the amount of this internal friction. In a viscous fluid, the rate of velocity with the distance is proportional to the force per unit area parallel to the direction of flow. This may be expressed as follows:

$$\mu = \frac{Fd}{Av}$$

where: $\frac{F}{A}$ = shearing stress on fluid

v = relative velocity between layers

μ = proportionality constant (coefficient of viscosity)

The viscosities of several liquids are given in Table 5-13. The severe changes in viscosity produced by a moderate increase in temperature should be noted. For flight vehicle use, fluids that undergo a minimum change in viscosity with temperature changes, such as the silicone fluids, should be selected.

The type of device that uses viscous absorption of shock and vibration is similar to that described later for air damping.

Hysteresis Damping. Hysteresis damping is the result of the gradual dissipation of energy

Table 5-13. Coefficients of Viscosity for Various Liquids /19/

Liquid	Temperature F (C)	Coefficient of viscosity (dyne-sec/cm^2)
Water	68 (20)	0.01
Light machine oil	60 (16) 100 (39)	1.14 0.34
Heavy machine oil	60 (16) 100 (39)	6.61 1.27
Motor oil, SAE 30	60 (16) 100 (39)	3.62 0.69
Glycerine	68 (20)	8.50
Castor oil	68 (20)	9.86

that occurs within a flexing body due to imperfections in the elastic properties of materials. In a perfectly elastic material, strain is proportional to stress, and the strain energy is recovered fully at each removal of stress. In a material that is not perfectly elastic, the strain energy is not recovered fully at each removal of stress. The energy lost is due to hysteresis and is dissipated in the form of heat.

The damping capacity of a material is the ratio of the hysteresis energy loss per cycle of stress to the full strain energy at the maximum stress of the cycle. The energy loss per cycle due to damping is given by the difference in amplitude between immediately successive cycles of oscillation. The amount of damping afforded by hysteresis is small, and it is common to express it in terms of an equivalent viscous damping ratio. If the transmissibility at resonance is known, the equivalent damping ratio can be obtained from Fig. 5-53 from the approximate formula:

$$\frac{c}{c_c} \approx \frac{1}{2T}$$

where: $\frac{c}{c_c}$ = damping ratio

T = transmissibility

While it is common to express hysteresis damping in terms of equivalent viscous damping, the viscous damping formulas are good approximations for hysteresis damping only with small damping values. The more exact expressions for transmissibility at resonance, T_{max}, and logarithmic decrement, Δ, are:

$$T_{max} = \frac{1 + h^2}{h}$$

$$\Delta = \frac{2h}{1 - h^2}$$

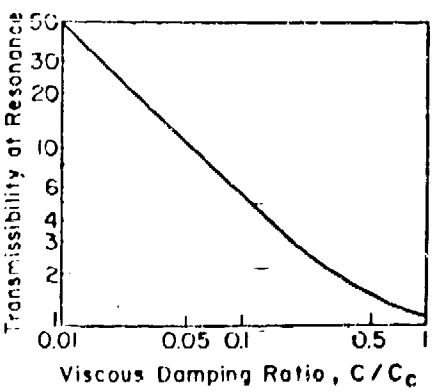


Fig. 5-53. Transmissibility at resonance as function of damping ratio./19/

Table 5-14. Approximate Hysteresis Values for Various Materials /19/

Material	Hysteresis coefficient (h)	Equivalent viscous damping ratio
Steel	0.01	0.0005
Rubber, 30 durometer	0.04	0.02
Rubber, 60 durometer	0.16	0.08
Neoprene	0.12	0.06
Buna	0.40	0.20
Silicone rubber	0.23	0.11
Cork	0.13	0.064

where h is a hysteresis damping coefficient, and for small values $h \approx 2\frac{c}{c_c}$.

Table 5-14 gives approximate hysteresis values for various materials. Rubber, especially synthetic, is a commonly used material in isolation mounts because of its relatively high damping coefficient. Although cork is a good damping agent, it is seldom used in airborne applications, since it is subject to a wide variety of physical properties, depending on its use and age. For isolator uses, sufficient damping is provided by the damping characteristics of the material. Extra damping, such as friction damping, is required in many other instances to dissipate adequately the energy passed into the mounting system.

Friction Damping. Friction is the force which acts between the contacting surfaces of two objects and tends to resist their sliding motion. If the resistance to sliding prevents motion of one object relative to the other, it is called static friction. If the resistance opposes the motion of two moving objects, it is called kinetic friction. The force required to overcome static friction is given in the equation for the coefficient of static friction:

$$F_s = C_s F_c$$

where: F_s = the force, applied in the direction of motion, just sufficient to start the object moving

C_s = the coefficient of static friction, which is a constant for a given pair of substances under given conditions

F_c = the force pressing the friction surfaces together

Similarly, a force F_k, required to move an object with uniform speed against friction, is defined by the equation:

$$F_k = C_k F_c$$

where: C_k is the coefficient of kinetic friction. If C_s is equal to C_k, the frictional force is defined as coulomb friction. Normally friction materials do not provide a constant friction force since the static friction does not equal the kinetic friction. However, in the usual mathematical treatment of friction damping, it is assumed that the frictional force is constant, regardless of the position or velocity of the vibrating mass.

With coulomb damping, the reduction in amplitude in successive cycles is a constant quantity and is given by the equation:

$$\Delta X = 4F/k$$

where: ΔX = the reduction in amplitude per cycle

F = the friction force

k = the spring constant

Since the damping force is constant, this type of damping should not be used in a system that is excited at resonance, unless the driving force is known to be less than the frictional force. If the reverse situation exists, the amplitude will increase in successive cycles, theoretically, to infinity.

The amount of necessary damping can be determined using Fig. 5-54, and plotting the maximum permissible transmissibility desired against the spring constant. For example, if the equipment weighs 20 pounds and causes the isolator on which it is mounted to deflect 1/2 inch, the spring constant, k, is 40 pounds per inch. If the maximum transmissibility is to be 2, the ratio of damping force to spring constant must lie between 0.00875 and 0.01275. To provide this ratio, the damping force must be between 0.35 and 0.51 pound. Friction dampers are available that provide a damping force of from 0.20 to 10.0 pounds.

Air Damping. Air damping results from the direct transfer of energy from a vibrating system to air. In reality, air damping is a form of viscous damping. At room temperature, air has about 1/50th the viscosity of water and the damping obtained is small compared to other forms of viscous damping; therefore, air dampers are preferred over friction or viscous dampers only for isolating lightweight components.

A vibrating object surrounded by air has forces imposed on it by the air and these forces are in a direction opposed to the velocity of the object. For free vibration, air damping produces a logarithmic decrement, as do hysteresis and viscous damping. For forced vibration, the damping force is proportional to the square of the velocity of the support. Air damping is usually stated, for convenience, in terms of an equivalent viscous damping value. Computing the equivalent damping of an air damper is extremely difficult due to the number of variables involved. The equivalent damping value is obtained by measuring the maximum transmissibility at resonance of a vibratory system containing the damper. The greater the damping force, the lower the maximum transmissibility. If the transmissibility value is known, the equivalent damping value can be obtained from Fig. 5-53.

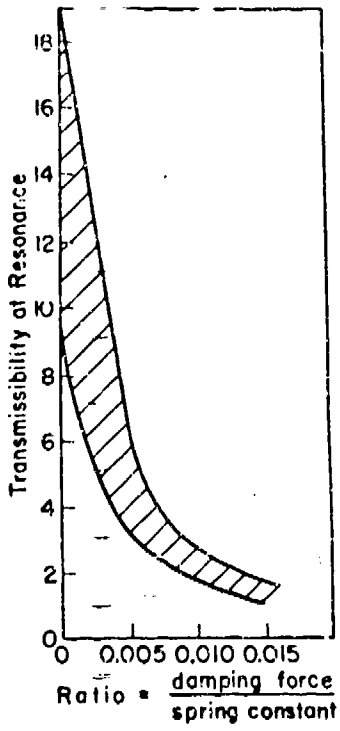


Fig. 5-54. Ratio of damping force to spring constant plotted against transmissibility./19/

A useful type of air damping system is the orificed dashpot. This type of air damping system does not depend on air viscosity alone, since adiabatic characteristics and turbulence enter into its operation and make it far superior to free air damping. Such an air damping system is shown in Fig. 5-55. The damper is composed of a piston that fits tightly against the walls of a cylinder that has two holes in its head. When moved by vibration, the piston causes pressure changes within the chamber that force air through the holes.

Air damping is incorporated into isolation mounts by means of a bellows that forces air

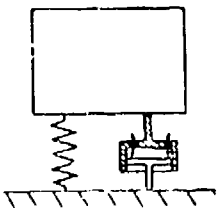


Fig. 5-55. Basic air damping system./19/

through a hole as the bellows is distorted by the relative motion between the support and the mounted equipment. The force required to move the air through the hole is lost by the system and limits the amplitude at resonance. A rubber bellows, sealed except for a hole, is effective for motion in both vertical and lateral directions. As the mass on the damper moves down or as the support moves up, the bellows flattens and its volume decreases. This increases the pressure inside the damper, and air is forced out through the hole. As the mounted object moves up, the volume of the bellows increases and air is pulled in through the hole. With lateral movement of the mounted object, the bellows is distorted, also resulting in pressure differentials and the movement of air in and out of the bellows.

The volume and the wall thickness of the bellows are critical in the design of an air damper. If the walls of the bellows are thin, they will stretch when there is a pressure buildup. The amount that the bellows will distend determines the ability of the damper to absorb shock. The thicker the walls, the higher the shock-transmission factor.

It should be realized that air damping normally has altitude limitations and cannot be used at extremely high altitudes or in outer space, unless it is employed within pressurized compartments.

Vibration Isolators

Isolators used for airborne equipment may be categorized according to the construction and material used in the resilient element. The resilient element can be rubber, a coil spring, woven metal mesh, or a combination of coil spring and woven metal mesh. The construction of the isolator will result in a certain spring rate that will largely determine its performance.

Rubber Isolators. Rubber has long been used in isolators, and, until World War II, practically all vibration isolators were made of natural rubber. The scarcity of natural rubber during the war resulted in the use of synthetics. The synthetics possessed qualities that for special applications were superior to natural rubbers. For example, Buna N and Neoprene maintain their elasticity and tensile strength at higher temperatures than does natural rubber, and are less likely to deteriorate when exposed to oil.

The deflection of a rubber isolator increases with time under continuous loading, especially at high temperatures. The slow distortion is known as drift or plastic flow. In an airborne environment where motion space is limited, drifting can eventually result in "bottoming" of the isolators during high amplitude vibration. For a well designed rubber mount, the loading should be conservative enough to eliminate this danger.

There are two general types of construction for rubber isolators: open and cup types. The open type consists of a molded rubber form bonded to a metal mounting flange and a core. The core, which is a cylinder in the center of the isolator, also is metal and attaches to the equipment.

The cup-type isolator has the rubber resilient element enclosed in, and bonded to, the cup, which acts as a housing. The core also is bonded to the rubber. This isolator has an advantage over the open type in that, even with complete failure of the resilient element, the cup and core will hold the equipment captive.

Metal-Spring Isolators. Metal-spring isolators have both advantages and disadvantages compared to rubber isolators. Metal springs do not drift, are least affected by temperatures found in flight vehicle environments, and their service life is relatively long. Metal-spring isolators require auxiliary damping devices, which may consist of vented air sacks, friction elements, or metal mesh. Metal mesh is a nonlinear spring of knitted wire damped by the friction between the interlocking wire loops. In some applications, mesh is used simply as a friction element and bears no load. In others, it acts as the main resilient element, bearing the major portion of the load in addition to providing damping.

Metal-spring isolators are also available in open and cup types. The open type uses metal mesh as the resilient element to include damping action in the isolator performance. Since there is no cup, it is difficult to provide damping by other methods. The cup types use either coil springs or metal mesh, or a combination of the two, as the resilient element. Figure 5-56 shows an example of an all-metal, cup-type isolator that uses metal mesh as the friction damping element. A hollow, finger-shaped metal mesh rubs against the inside surface of the core and against the coils of the load-bearing spring during movement of the core. The metal mesh bears no load and functions strictly as a friction element. Top and bottom snubbing are provided by a metal-mesh pad fixed on the flange of the core.

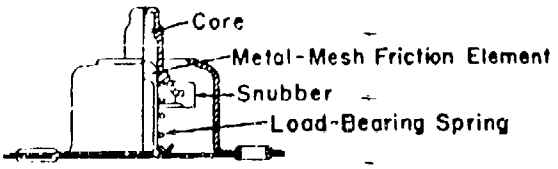


Fig. 5-56. All-metal, cup-type vibration isolator with metal mesh as friction element./19/

Shock Isolators

Shock isolators have stiffer springs than vibration isolators, and, therefore, have a higher natural frequency. The resilient elements of shock isolators are always nonlinear, while some vibration isolators use linear springs. Table 5-15 compares some of the characteristics of shock isolators and vibration isolators. Shock isolators are used to mount equipment when the anticipated environment is such that vibration fatigue is less a hazard to the equipment than is shock.

Shock isolators, as described in Table 5-15, are not used in protecting equipment in manned flight vehicles. Under high-amplitude, low-frequency vibration, the use of shock isolators can be more detrimental to the equipment than rigid mounting. Where severe shock is expected in conventional aircraft, devices that are primarily vibration isolators are modified for protection against shock. Some shock protective features of vibration isolators are stiffer linear springs, nonlinear springs and damping.

Shock Isolators vs Vibration Isolators. /20/ Vibration isolators are ineffective against shock, while shock isolators do not protect equipment from vibration frequencies below $\sqrt{2}$ times the isolator's fundamental, which is normally the higher frequencies. Consequently, the selection of the proper isolator depends on the frequency and magnitude of the mechanical excitation and frequently requires a compromise that will best satisfy the conflicting requirements. Neither shock nor vibration isolators are effective against accustic noise excitation.

Typical curves for the vibration amplitude of isolation-mounted equipment when subjected to an external forcing frequency are shown in Fig. 5-57. Curve A shows the response of equipment on soft vibration isolators having a natural frequency of 8 cps, and curve B shows equipment mounted on stiff shock isolators with a natural frequency of 25 cps. Isolator A, with a natural frequency of 8 cps, begins to isolate at about 12 cycles; whereas isolator B, with a natural frequency of 25 cps, begins isolation at about 35 cps. Therefore, to protect against frequencies below 35 cps a soft isolator of the A type is required.

Table 5-15. Characteristics of Shock Isolators Compared to Vibration Isolators /19/

Shock Isolators	Vibration Isolators
20-40 cps natural frequency.	7-25 cps natural frequency.
Resilient elements are highly nonlinear.	Resilient elements are linear or nonlinear.
Natural frequency changes with high amplitude vibration.	Natural frequency changes little or not at all with high amplitude vibration.
Very little provision for equipment movement.	Provision for equipment movement.

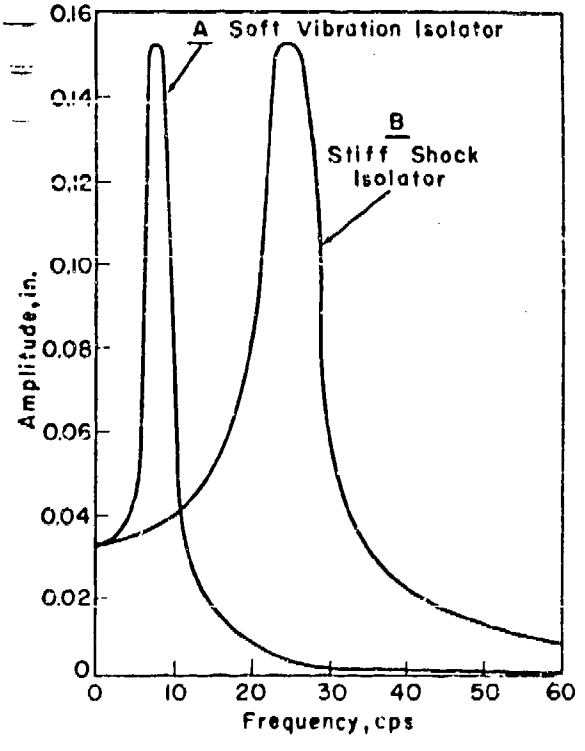


Fig. 5-57. Response curves for two types of isolators./20/

The nature of shock can be visualized by considering that the support to which the equipment is attached suddenly acquires a high velocity. The mounted equipment must move with the support at substantially the same velocity and displacement. By interposing resilient shock isolators between the support and the equipment, a longer period is allowed for the accelerations, and forces on the equipment are reduced. Energy is transferred to the equipment

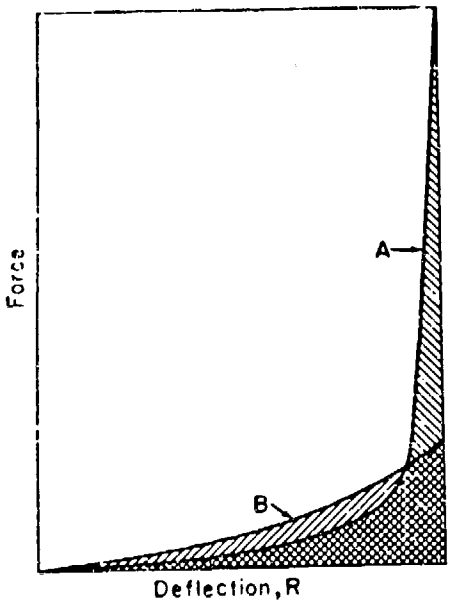


Fig. 5-58. Force-deflection curves for same isolators as in Fig. 5-57./20/

to bring its velocity up to the velocity of the support. This energy is transferred through the isolator, which stores the energy for a short time, and then transmits it to the equipment. The amount of energy transferred depends upon the weight of the equipment and the nature of the shock; it is virtually independent of the characteristics of the isolator.

Curves A and B in Fig. 5-58 represent the force deflection curves of the same isolators as in Fig. 5-57. If the distance R represents the amount the isolator can deflect under a shock force, the area under the force-deflection curve to the deflection R represents the energy stored by the isolator. If the same equipment is subjected to identical shocks when mounted on isolators of two different types, A and B, then the weight of the equipment and shock of the support in both cases are the same, and the area under curves A and B are the same. For an equivalent area, the curve for isolator A must reach a greater peak force than the curve for isolator B. Therefore, greater shock is transmitted through the isolator to the equipment. The gradual increase of force that is characteristic of isolator B makes it possible to attain the same area without reaching as great a maximum force. To achieve the lesser force of curve B, this isolator has a higher initial stiffness than isolator A, and can only isolate the relatively higher frequencies of vibration.

Selection of Isolators /19/

Isolators are selected on the basis of the weight they will support, the type of mounting system used, the critical frequencies of the equipment, and the shock and vibration excitation they are required to isolate and be able to withstand. The weight of the equipment and the desired natural frequency determine the spring rate of the isolator. Figure 5-59 is a graph from which the spring rate for a linear isolator can be selected that gives a system natural frequency for a given equipment weight.

The spring constant of each isolator in a mounting system can be equal or not, depending upon the configuration of the equipment and whether decoupling of vibratory modes is desired. If the center of gravity is such that the load on each isolator is equal, then all spring constants are equal. When the center of gravity results in an unequal distribution of weight to the isolators, then adjustments can be made in the spring constants so that decoupling is obtained within the mounting system.

Mounting System. The type of mounting system used influences the isolator horizontal-to-vertical stiffness ratio. For example, in underneath- and inclined-isolator mounting systems, the horizontal-to-vertical stiffnesses are different for maximum system effectiveness. In the center-of-gravity and double-side mounting systems, equal stiffnesses are used in the horizontal and vertical directions. Mounting systems are discussed in a later paragraph.

Fragility Level or Critical Frequencies of an Equipment. Isolators reduce the vibration excitation to a level that can be reliably tolerated by the equipment. The fragility level of an

Fig. 5-59. Natural frequency as function of spring rate for mass supported by linear springs./19/

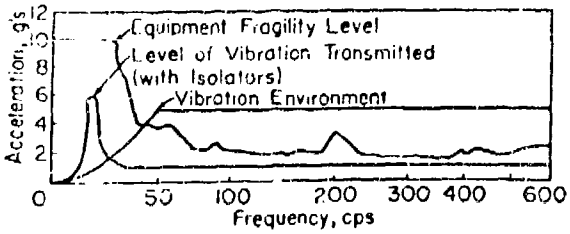


Fig. 5-60. Use of equipment fragility curve for selecting isolators to modify vibration environment./19/

equipment, that is, the maximum levels of vibration at discrete frequencies that the equipment can withstand, must be kept sufficiently above the level of the vibration environment. Figure 5-60 shows how vibration isolators accomplish this objective. The three levels shown are the fragility level, the level of vibration excitation, and the level of vibration reaching the equipment through the isolators.

The equipment fragility level is high, that is, less apt to fail, at frequencies below 40 cps. Vibration is normally at a low level below 50 cps, and at this point failure is possible. Failure is also possible at all the higher frequencies. Mounting the equipment on isolators gives the system a natural frequency of about 20 cps. This raises considerably the level of vibration transmitted to the equipment in the area below 30 cps; however, this is where the fragility level of the equipment is highest. At all points above 30 cps the transmitted vibration frequency is below the natural frequency, and also below the fragility level of the equipment. The equipment, therefore, should perform satisfactorily.

Flight Conditions. Depending on the type of flight vehicle, flight conditions vary and so become a factor in the selection of isolators. Among the different classifications of flight vehicles are fighter, bomber, cargo, trainer, helicopter and missile. There are important differences in the design of these vehicles, so the flexibility of wings, tail surfaces, and fuselage varies. Each type of flight vehicle has a different response to excitations from the power plant, gunfire, maneuvers, wind buffeting and landing shock. Further complications are introduced by the type of power plant used. Different excitations are provided by reciprocating engines, turbo jets, turbo props, ram jets and rockets.

While isolators are selected mainly for protection against vibration, shock environments must be given consideration too. The most severe shock occurs during landing and booster-assisted or catapult-assisted takeoffs. The direction of the shock is as important as the intensity. Shock in a downward direction does not compress the load-bearing spring of a single-acting isolator, and the shock is transmitted directly through the top snubbers. Shock in a lateral direction also causes snubber contact if horizontal stiffness of the isolator is low, as it may be for bottom-mounted equipment.

Fighters and guided missiles spend considerable time in maneuvers such as sustained, near-vertical climbs and uncoordinated, slow rolls and slow loops. Because of this, the attitudes a flight vehicle can assume with respect to the Earth should be considered when selecting isolators. The effects of these maneuvers on single-acting vibration isolators are shown in Fig. 5-61. In level flight (A) the isolators function perfectly; during a near-vertical climb or dive (B), gravity acts to unload the equipment from the top isolator and load the bottom isolator; and at the top of a slow roll or slow loop (C), the equipment is hanging from the mounts. As shown in (B) and (C), there is solid contact at the top of the snubbers, and the isolators are not protecting the equipment.

Static acceleration due to maneuvering results in similar effects on vibration isolators. When nosing down, static acceleration acts to pull the equipment away from the points of connection. In a dive pull-out, the equipment is forced toward the points of connection. Double-acting isolators are necessary if isolation is to be maintained regardless of the flight vehicle attitude.

Stabilizers

While not strictly isolators, stabilizers perform an important function in the protective system. Under resonant or shock conditions, tall equipment that is bottom mounted may sway considerably. The top of the equipment can swing far enough to strike structural members or other equipment. A stabilizer prevents this from happening. While performing this function, the stabilizer does not affect the efficiency of the mounting system. The construction and mounting of a stabilizer is shown in Fig. 5-62. The stabilizer effectively has no stiffness in the

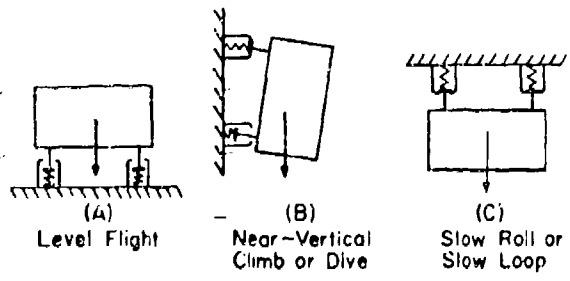


Fig. 5-61. Effect of flight vehicle attitude on single-acting vibration isolators./19/

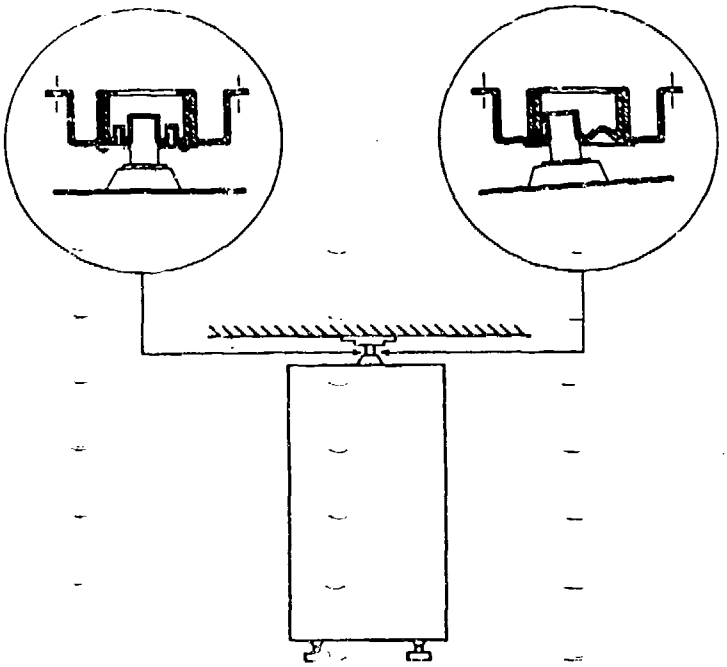


Fig. 5-62. Stabilizer under static and horizontal shock conditions./19/

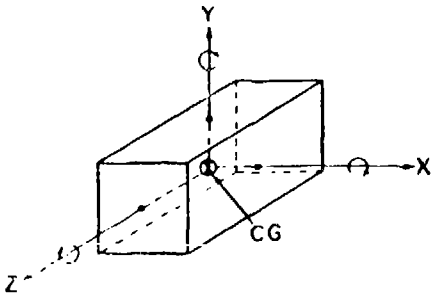


Fig. 5-63. Six degrees of freedom.

vertical direction throughout its operating range. Horizontal stiffness is provided by a resilient element, of predetermined stiffness, that buckles under a light horizontal load. It buckles again under increasing horizontal loads, and then stiffens slowly in compression under severe horizontal loads. The stabilizer is placed between the equipment and a rigid overhead supporting structure, as shown in Fig. 5-62.

Isolator Mounting Systems

The choice of isolators and the isolation mounting system is dependent mainly on the space available for both the isolation system and the expected sway of the equipment. For example, if the space dictates that an equipment be higher than it is wide, resulting in a high center of gravity, a bottom-mounting system should not be used without stabilizers. The shock and vibration environment, including the excitation frequencies, the stiffness of the supporting structure, and required stability of the equipment are other factors that should be considered.

Equipment in a flight vehicle is subjected to shock and vibration in all directions, so it must be free to move in all directions for total isolation. This requires a six-degree-of-freedom system. The equipment is free to move translationally in vertical, longitudinal, and lateral directions, and rotationally about the vertical, longitudinal, and lateral axes. The required degrees of freedom are shown in Fig. 5-63. The system has a natural frequency in each of these natural modes, and all must be considered when designing the isolation system.

When isolators of equal stiffness are located unsymetrically about the center of gravity of an equipment, certain of the rotational and translational modes will couple. When coupled, vibration cannot exist in one mode without existing in its coupled mode, or modes. Thus, a horizontal force through the center of gravity

will not only displace the equipment horizontally, but also will cause it to rotate. Each coupled mode has its own frequency and must be considered in the design.

Isolators may be arranged in many ways, but all arrangements are variations of basic systems. These systems are known as the underneath mounting system, the center-of-gravity mounting system, the double-side mounting system, the over-and-under mounting system, and the inclined-isolator mounting system. Each system has its advantages and limitations. In general, to prevent the supporting structure from disturbing the performance of the isolation system, the natural frequency of the supporting structure should be at least three times the natural frequency of the equipment on its isolators. In the discussion that follows, a rigid supporting structure is assumed for the mounting system.

Underneath Mounting System. /13/ The underneath mounting system is the most widely used, since most chassis configurations are suitable for this application and there are less limiting requirements. This system is used in applications where the distance from the base to the center of gravity of the supported equipment does not exceed isolator spacing by a ratio greater than 0.25. This relationship is necessary to maintain required stability and isolation. Fig. 5-64 illustrates critical dimensions for equipment having a uniform density.

The center of gravity height to isolator spacing ratio limits the use of the underneath system for narrow axis equipment. However, in most applications the height of the center of gravity seldom exceeds 0.36 of the overall height of the equipment. This permits equipment having ratios of equipment height to isolator spacing up to 0.7 to be mounted in this manner. A basic underneath mounting system is shown in Fig. 5-65.

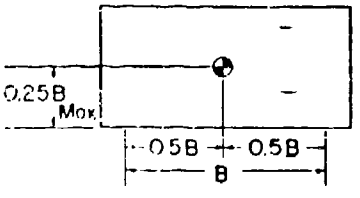


Fig. 5-64. Critical dimensions for underneath mounting./13/

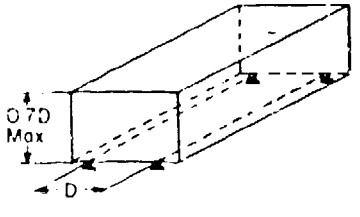


Fig. 5-65. Basic underneath mounting system./13/

Choosing the proper isolators for an underneath-mounted rectangular object is relatively simple. The total weight is divided by four, then the appropriate isolator is selected according to specification MIL-C-172 and Military Standards MS91418, MS91526, and MS91527, and placed at the four corners. However, if the center of gravity of the equipment is located unsymmetrically in the horizontal direction, the isolators at each corner will be different. The load on each isolator can be calculated using the following formulas and Fig. 5-66. /19/

$$\text{Load on isolator 1} = W\left(\frac{A1}{A1 + A2}\right)\left(\frac{B2}{B1 + B2}\right)$$

$$\text{Load on isolator 2} = W\left(\frac{A2}{A1 + A2}\right)\left(\frac{B2}{B1 + B2}\right)$$

$$\text{Load on isolator 3} = W\left(\frac{A1}{A1 + A2}\right)\left(\frac{B1}{B1 + B2}\right)$$

$$\text{Load on isolator 4} = W\left(\frac{A2}{A1 + A2}\right)\left(\frac{B1}{B1 + B2}\right)$$

W is the weight of the equipment with connectors and cables attached. The loads calculated with the above formulas can then be used with Fig. 5-59 to determine the spring constants of the isolators.

Center-of-Gravity Mounting Systems./19/ In center-of-gravity mounting systems, the isolators are located in a plane that passes through the center of gravity of the mounted equipment, as shown in Fig. 5-67. It is a refinement of the underneath mounting system in that while coupling of certain rotational and horizontal modes in the underneath system is unavoidable because of the unsymmetrical placing of the isolators relative to the horizontal plane through the center of gravity, these same modes are always decoupled in center-of-gravity systems. With coupled modes, the spread between natural frequencies of a system is greater, reducing iso-

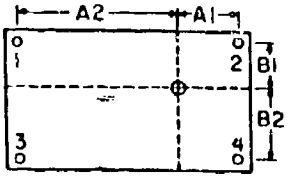


Fig. 5-66. Determining load on each isolator when center of gravity is located unsymmetrically in horizontal direction./19/

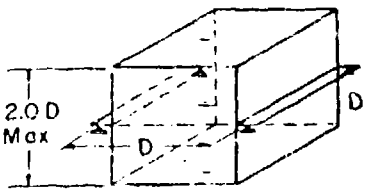


Fig. 5-67. Basic center-of-gravity mounting system./19/

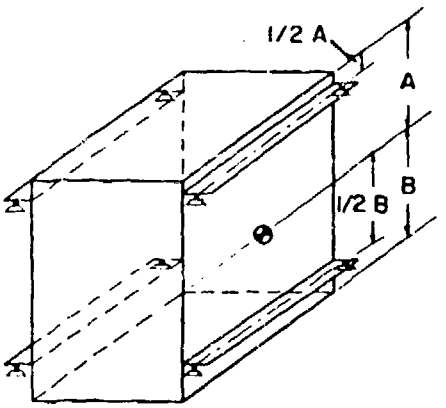


Fig. 5-68. Basic double-side mounting system./13/

lation efficiency. If the highest natural frequency of the mounting system is set well below the forcing frequency, it may put the lowest frequency at a level that introduces instability in the system.

Double-Side Mounting Systems./13,19/ Double-side mounting systems, also called double-level side mounting, are normally used on equipments that have a height-to-width ratio greater than two and a tendency for excessive flexing. Eight isolators are used, with four each placed symmetrically on opposing sides of the equipment so that the figure formed by the isolators is a cuboid. The double-side mounting system is shown in Fig. 5-68. The extra isolators provide additional support points that distribute the load more equally to the chassis. In addition to being used for equipment with a height-to-width ratio greater than two, the double-side mounting system should be used for very heavy equipment from a safety standpoint. With attachment points near the top and bottom of the equipment, it is more secure than the other systems. In fact, satisfactory results have been obtained with equipment having a height-to-width ratio up to five. The maximum limit of this system is reached when the structural rigidity of the equipment allows excessive bending to take place.

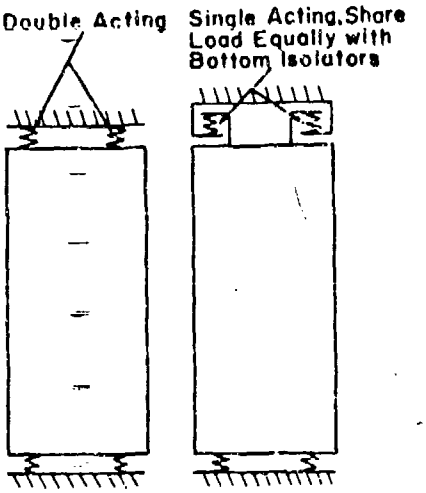


Fig. 5-69. Basic over-and-under mounting system./13/

Over-and-Under Mounting Systems./13/ In an over-and-under mounting system, eight isolators are used, but instead of being mounted at the sides of the equipment as in a double-side mounting system, the mounts are placed at the top and bottom of the equipment. This system is used when the space for the equipment provides an overhead support to which the isolators can be fastened. This system is also useful when the height-to-width ratio of the equipment exceeds one and a half, so that a bottom-mounted installation would tend to be unstable. Most of the discussion about the double-side mounting system applies to this system, since the isolators still form a cuboid. In the over-and-under mounting system, the mounts located at the top of the equipment carry an equal share of the load with the bottom mounts. To do this, double-acting mounts are used, or, the isolators are mounted so that they support the equipment as do the bottom mounts. Figure 5-69 shows the over-and-under mounting system, with two ways of mounting the top isolators.

Inclined-Isolator Mounting System. When four isolators are used and they cannot be located in a plane through the center of gravity, decoupling can be accomplished by inclining the isolators, as shown in Fig. 5-70. When equipment is bottom mounted, coupling occurs between translational modes because of the unsymmetrical position of the isolators relative to a horizontal plane through the center of gravity. This dissymmetry causes external forces, from the isolator horizontal stiffness, to apply a turning moment to the equipment when the equipment is displaced sideways. However, if the isolators are inclined instead of being placed vertically.

motion along either of the principal axes results in deflection of the isolators in both the radial and axial directions. Because the isolators are inclined, the usual reference of horizontal and vertical is changed to radial and axial. In this system, a translational motion results in external forces from both the radial and axial isolator stiffness.

Figure 5-70 also shows that the torque about an arbitrarily selected point, P, resulting from the axial isolator stiffnesses, opposes the torque caused by the radial isolator stiffnesses. There is a point P where the combination of the angles of isolator inclination and the radial-to-axial stiffness ratio makes the opposing torques equal in magnitude, and the resultant torque about P is zero. If this point P coincides with the center of gravity, the vibrational modes will be decoupled, since a horizontal motion of the equipment does not result in a turning moment being applied to the equipment by the isolators.

The angle of isolator inclination and the isolator horizontal and vertical stiffnesses are quite critical in this mounting system. It is a special purpose application of isolators and requires detailed analysis to operate successfully.

Additional Design Considerations. Each of the mounting systems discussed requires a prediction of natural frequencies, coupling modes, and decoupling modes before proper choice of isolators can be made. The methods for performing necessary calculations are contained in reference/19/.

EQUIPMENT LOCATION

Many equipments are highly sensitive to shock and vibration forces, and it may be impractical to rely on the isolation system alone to bring the forces within tolerable limits. This is especially true at locations within the vehicles that have a very high shock and vibration level. Because of this, it might be best, in some cases, to consider changing the location of the equipment to a point that puts less of a requirement on equipment. This, of course, requires that a complete shock and vibration analysis be made to determine the levels that exist at every vehicle station. Examples of these are given in Chapter 3.

It should be noted, however, that equipment locations in a flight vehicle cannot be selected solely on the basis of shock and vibration considerations, since to do so might impair vehicle characteristics, such as causing an unacceptable center of gravity.

MOISTURE PROTECTION

The principal harmful effects of moisture are corrosion and the development of fungi. Essentially, there are three methods of protecting against these harmful by-products. The first

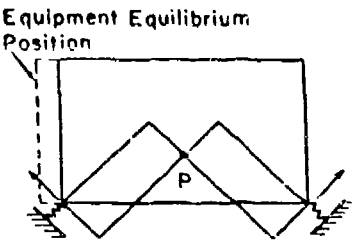


Fig. 5-70. Basic inclined-isolator mounting system./19/

method is to choose fungus- and corrosion-resistant materials that also meet strength, weight, environmental and mechanical requirements. This method is always desirable, but not always attainable. A second method of protection is by applying fungicidal treatments, or coating the material or component with a seal that is impervious to moisture. This method is an aid rather than a complete solution, and may also have undesirable side-effects. A third method is to seal the component hermetically. This method, while very effective in keeping out the moisture, is often limited in application. The best solution to the moisture protection problem is to combine all three protection methods as outlined in the following checklist./21/

1. Choose materials with low moisture absorption qualities whenever possible.

2. Use hermetic sealing whenever possible. Make sure the sealing area is kept to a minimum to reduce danger of leakage.

3. Where hermetic sealing is not possible, consider the use of gaskets and other sealing devices to keep out moisture. Make sure the sealing devices do not contribute to fungal activity, and detect and eliminate any "breathing" that may admit moisture.

4. Consider impregnating or encapsulating materials with fungus-resistant hydrocarbon waxes and varnishes.

5. Do not place corrodable metal parts in contact with treated materials. Glass and metal parts might support fungal growth and deposit corrosive waste products on the treated materials.

6. When treated materials are used, make sure they do not contribute to corrosion or alter electrical or physical properties.

Additional information on moisture protection can be supplied by The Prevention of Deterioration Center, National Research Council, 2101 Constitution Avenue, Washington 25, D. C. The center maintains a complete catalog of fungus- and corrosion-resistant materials. Other excellent guides are the "Engineering Handbook

Series for Aircraft Repair, "AN 01-1A-10; "Handbook of Instructions for Aircraft Designers," ARDCM 80-1; and "Handbook of Instructions for Ground Equipment Designers," ARDCM 80-5. The three handbooks list basic protective and cleaning materials, as well as general protective requirements for various materials.

Fungus-Resistant Materials

Most synthetic textiles, with the exception of some rayons, have acceptable resistance to fungal growth. The following pure plastics have good resistance: acrylics, phenol formaldehydes, nylon, polyester, polyethylene, Teflon, vinyls and silicones. Natural and synthetic rubbers are subject to fungus attack; their susceptibility, however, depends on the predominating elastomer, the compounding materials, and the method of processing. Tables 5-16 and 5-17 indicate the susceptibility of various types of natural and synthetic rubbers to microorganisms; however, conflicting data exist. The conflict is due to the differences in test methods and interpretation, and the presence of various nutrients for microorganisms./22,23/

Table 5-16. Resistance of Natural Rubbers to Microorganisms /22/

Material	Resistance	References
Pure natural rubber - caoutchouc	Attacked	24, 25, 26, 27
Highly purified natural rubber, 99%, not vulcanized	Attacked	27, 28
Natural rubber vulcanizate	Attacked Resistant	24, 29 30
Hevea latex	Attacked	27
Guayule latex	Attacked	27
Crude sheet	Attacked	27, 31
Crepe rubber	Attacked	27
Pale crepe, not compounded	Attacked	24, 32
Pale crepe, compounded	Resistant Attacked	32 24
Plantation crepe	Attacked	27
Smoked sheet, not compounded	Attacked	24, 32
Smoked sheet, compounded	Resistant Attacked	32 24
Reclaimed rubber	Attacked	33
Gutta-percha	Some attack but less than natural rubber	24
Chlorinated rubber	Resistant	27

From Deterioration of Materials -- Causes and Preventive Techniques, by Glenn A. Greathouse and Carl J. Wessel, courtesy of Reinhold Publishing Corporation, Book Division.

As discussed previously, fungus-resistant materials should always be used. The types of materials listed in Table 5-18 are generally considered fungus-inert and should be used in preference to the fungus-nutrient materials listed in Table 5-19. However, this does not exclude the use of the fungus-nutrient materials in hermetically sealed assemblies and other accepted and proven products such as paper capacitors and treated transformers. If it is necessary to use fungus-nutrient materials in other than hermetically sealed assemblies, fungicides and preservatives should be used as specified in MIL-T-152./55/

Fungicides/23/

Fungus rotting can be virtually eliminated by incorporation of a fungicide in the material. Protective coatings that are fungus-proof can be applied to a wide range of materials. Many types of fungicides are available, but there is no perfect fungicide for all materials and all purposes. The selection of a chemical usually represents a compromise between ease of application, safeness to handle, lack of objectionable odor and color, and its chemical and dielectric properties. The most commonly used government-approved fungicides are:

1. Copper 8-guinolinolate -- used for textiles, hemp and jute.

2. Paraphenyl phenolformadiehyde with salicylanilide -- used primarily for plastics and electronic equipment.

3. Paranitropheno -- used for leather products.

4. Dihydroxyl dichlorodiphenylmethane -- used mainly in textiles.

Aside from the four fungicides listed, there are several other fungicides used for different materials:

Textile -- copper naphthenate, 2,2'methylenebis (4-chlorophenol).

Paper -- chlorinated phenols (pentachlorophenol).

Rubber -- nitrophenol, zinc salicylate (1%), zinc benzonate (1%).

Paints, varnishes, enamels and lacquers -- chlorinated phenols, salicylanilide.

Table 5-17. Resistance of Synthetic Rubbers to Microorganisms /22/

Material	Resistance	References
Neoprene-polychloroprene, not compounded	Resistant Attacked	29, 32 26, 27
Neoprene, compounded*	Resistant Attacked	24, 28, 29, 31, 32 25
GR-S, butadiene-styrene, not compounded	Resistant Attacked	24, 25 32
GR-S, butadiene-styrene, compounded	Resistant Attacked	28**, 32 24, 28
GR-S, butadiene-styrene, compounded, acetone extracted	Resistant –	25
Buna-S, butadiene-styrene, uncured	Attacked –	27
"Hycar OR," butadiene-acrylonitrile, not compounded	Attacked –	26, 27, 31 32
"Hycar OR," butadiene-acrylonitrile, compounded	Resistant Attacked	32 31
Buna N, butadiene-acrylonitrile, compounded	Attacked	29
GR-I (butyl), isobutylene-isoprene, uncured	Resistant Attacked	24, 25 26, 27, 32
GR-I (butyl), isobutylene-isoprene, compounded	Resistant Attacked	28, 32 24
"Thiokol," organic polysulfide, uncured	Attacked	26, 27
"Thiokol," organic polysulfide, vulcanized	Resistant	27, 31
"Thiokol," organic polysulfide, sheets for gasoline tank linings	Attacked	34
Silicon rubber	Resistant	28
Experimental elastomers from:		
Butadiene	Attacked	26
Isoprene	Attacked	26
Isobutylene	Attacked	26
Acrylonitrile	Attacked	26
Styrene	Attacked	26

* Neoprene containing nutrients may be attacked, but the hydrocarbon itself is not attacked. /25/

** This sample produced by improved processing to give fungal resistance. /28/

From Deterioration of Materials -- Causes and Preventive Techniques, by Glenn A. Greathouse and Carl J. Wessel, courtesy of Reinhold Publishing Corporation, Book Division.

Table 5-18. Fungus-Inert Materials /35/

Metals	Cellulose acetate
Ceramics (steatite, glass, glass bonded mica, etc.)	Nylon
Mica	Polyvinyl chloride
Plastics with glass, mica or asbestos filler	Rubber (natural or synthetic)
Tetrafluoroethylene (such as Teflon or equivalent)	Silicone
Chlorotrifluoroethylene (such as Kel-F or equivalent)	Polyethylene
	Polystyrene

Table 5-19. Fungus-Nutrient Materials /35/

Cotton	Leather
Linen	Paper and cardboard
Cellulose nitrate	Cork
Regenerated cellulose	Hair and felts
Wood	Plastic materials with cotton, or wood flour filler

Wood preservatives -- coal-tar creosote compounds, carbolineums, wood-tar creosotes, pentacholorophenol, copper naphthenates, zinc naphthenates, chromated zinc chloride, chemonite, "Wolman" salt tanolith, zinc chloride, zinc meta-cresenite, and copper chromated zinc chloride.

Corrosion-Resistant Materials

It is difficult to make definite comparisons of the corrosion resistant properties of metals, since their resistance varies with the chemical environments. However, in vehicle design, the metals most commonly used for their corrosion-resistant properties are:/23/

1. Titanium.
2. Stainless steel.
3. Molybdenum alloys.
4. Pure aluminum.
5. Cadmium.
6. Chromium.
7. Zinc.
8. Nickel.
9. Tin.
10. Copper alloys.

The aluminum and magnesium alloys are seriously degraded by corrosion and should be avoided. Dissimilar metals far apart in the galvanic series (Chapter 3) should not be joined directly together. If they must be used together, their joining surfaces should be separated by an insulating material, except if both surfaces are covered with the same protective coating./36/

Protective Coatings

Corrosion of materials, particularly metals, can be prevented by the use of metallic coatings or by using organic coatings such as paints or varnishes. Metal coatings may be applied by a number of methods, such as electroplating, metal spraying, dipping, adhesion through a metallic powder technique, and metallurgical bonding through rolling.

Electroplating is the most common method and is used with such plating materials as cadmium, zinc, chromium, silver, nickel, tin and lead. Zinc and aluminum are frequently sprayed on materials, and pure aluminum is rolled on aluminum alloys and other less corrosion-resistant metals to form a "clad" material.

Surface treatment involves a chemical reaction on a base metal, forming a surface oxide or other coating that is resistant to corrosion. Anodizing and alodizing are the two processes frequently used in the aircraft industry. These processes also serve as a suitable base for paint.

MIL-S-5002, "Surface Treatments for Metal and Metal Parts in Aircraft," specifies that, with exceptions, all aluminum alloys and clad aluminum alloy parts used in military aircraft should be anodized, and all carbon- and low-alloy steel, brass, bronze, cooper and nickel alloy parts should be cadmium or zinc plated. Some good protective finishes for various metals are given in Table 5-20.

Table 5-20. Finish Application Table (Courtesy of Product Engineering)

Material	Finish	Remarks
Aluminum alloy	Anodizing	An electrochemical-oxidation surface treatment for improving corrosion resistance; not an electroplating process. For riveted or welded assemblies, specify chromic-acid anodizing. Do not anodize parts with nonaluminum inserts.
	"Alrok"	Chemical-dip oxide treatment. Cheap. Inferior in abrasion and corrosion resistance to the anodizing process, but applicable to assemblies of aluminum and nonaluminum materials.
Copper and zinc alloys	Bright acid dip	Immersion of parts in acid solution. Clear lacquer applied to prevent tarnish.
Brass, bronze, zinc diecasting alloys	Brass, chrome, nickel, tin	As discussed under steel.
Magnesium alloy	Dichromate treatment	Corrosion-preventive dichromate dip. Yellow color.
Stainless steel	Passivating treatment	Nitric-acid immunizing dip.
Steel	Cadmium	Electroplate; dull white color, good corrosion resistance, easily scratched, good thread antiseize. Poor wear and galling resistance.
	Chromium	Electroplate; excellent corrosion resistance and lustrous appearance. Relatively expensive. Specify hard chrome plate for exceptionally hard abrasion-resistant surface. Has low coefficient of friction. Used to some extent on nonferrous metals, particularly when die-cast. Chrome-plated objects usually receive a base electroplate of copper, then nickel, followed by chromium. Used for build-up of parts that are undersized. Do not use on parts with deep recesses.

Table 5-20. Finish Application Table (Courtesy of Product Engineering) (continued)

Material	Finish	Remarks
Steel (continued)	Blueing	Immersion of cleaned and polished steel into heated saltpeter or carbonaceous material. Part then rubbed with linseed oil. Cheap. Poor corrosion resistance.
	Silver plate	Electroplate; frosted appearance, buff to brighten. Tarnishes readily. Good bearing lining. For electrical contacts, reflectors.
	Zinc plate	Dip in molten zinc (galvanizing) or electroplate of low-carbon or low-alloy steels. Low cost. Generally inferior to cadmium plate. Poor appearance and wear resistance. Electroplate has better adherence to base metal than hot-dip coating. For improving corrosion resistance, zinc-plated parts are given special inhibiting treatments.
	Nickel plate	Electroplate; dull white. Does not protect steel from galvanic corrosion. If plating is broken, corrosion of base metal will be hastened. Finishes in dull white, polished, or black. Do not use on parts with deep recesses.
	Black oxide dip	Nonmetallic chemical black oxidizing treatment for steel, cast iron and wrought iron. Inferior to electroplate. No buildup. Suitable for parts with close dimensional requirements, such as gears, worms and guides. Poor abrasion resistance.
	Phosphate treatment	Nonmetallic chemical treatment for steel and iron products. Suitable for protection of internal surfaces of hollow parts. Small amount of surface buildup. Inferior to metallic electroplate. Poor abrasion resistance. Good paint base.
	Tin plate	Hot dip or electroplate. Excellent corrosion resistance, but if broken will not protect steel from galvanic corrosion. Also used for copper, brass and bronze parts that must be soldered after plating. Tin-plated parts can be severely worked and deformed without rupture of plating.
	Brass plate	Electroplate of copper and zinc. Applied to brass and steel parts where uniform appearance is desired. Applied to steel parts when bonding to rubber is desired.
	Copper plate	Electroplate applied preliminary to nickel or chrome plates. Also for parts to be brazed or protected against carburization. Tarnishes readily.

Organic coatings are the most versatile means for protecting metals against corrosion, since an organic coating can be applied to all surfaces. The major protection derived from such coatings as paints and varnishes is due to their ability to act as a barrier, and thus prevent moisture from reaching the metal surface. Acceptable organic coatings come in a wide variety of paints, varnishes, greases, rubbers and waxes.

Component Protection/8,13,37/

Antennas, Lightning Arrestors. Antennas should be streamlined and recessed, and should be located within plastic domes or covers to avoid the breathing effect. Slot and cavity antennas may be hermetically sealed.

Base, Chassis, Cabinets and Relay Racks. Cabinets should be designed to prevent water from being led in on wires or from other external or protruding parts. Moisture traps or wells should be eliminated, either in the design or by use of drainage holes. If possible, the assemblies or equipments should be hermetically sealed.

Batteries. "Shelf life" of dry batteries is increased by encapsulation in plastic films or by packaging in water-tight metal cases. Batteries should be stored in cool places.

Cables. Precautions should be taken to protect the insulation at the ends of cables from moisture. Moistureproof jacketing, which will withstand the required temperature range and mechanical abuse, should be used.

Capacitors. Mica and paper capacitors in molded plastic cases have good moisture resistance, but metal-cased capacitors are better. Tuning capacitors should be hermetically sealed.

Coils. Coil wires should be kept dry and protected with chemically inert, impervious materials with good electrical insulating properties, such as silicones. The material should not vaporize at high temperatures, since the products of vaporization may be deposited and cause trouble in such parts as relays and switches. Hermetically-sealed units should be used wherever practical.

Connectors and Couplings. All parts and mating surfaces of connectors should be coated with a silicone compound such as DC-4 (Dow Corning). Metal parts of all MF, VHF and UHF connectors should be silver plated inside and out. Connectors should be designed with improved couplings and longer creepage paths. Whenever possible, superior insulating materials, corrosionproof platings and moistureproof connectors should be used. Cables to connectors should be looped to allow moisture runoff. When moistureproof connectors cannot be used, the connector case should contain a drain hole. Do not mount connectors vertically.

Cords (Tie Cords) and Lacings. Avoid the use of cords containing unprotected susceptible material. Glass, vinyl, nylon or dacron material is recommended. If linen or cotton cord is used, it should be treated with a fungicide that will not reduce flexibility.

Crystals (Quartz). Present phenolic and metal crystalholders are moistureproof. The better holder is made of metal, and is solder-sealed with the leads brought out through glass beads. The crystal faces should be plated with gold and silver to improve tolerances and permit direct attachment of leads.

Electron Tubes. Resin-filled tube bases should be avoided wherever possible. Care must be exercised in the packaging, handling and storing of tubes.

Fuse and Fuse Holders. Whenever practicable, coat the fuse, including the contact surfaces, and the interior of the fuse holder with a silicone compound such as DC-4. The exterior of the fuse holder, except contact surfaces, should be coated with fungicidal varnish. If possible, sealed fuse should be used.

Headsets. Earphones should be covered with chamois, treated with a nontoxic fungicide. Metal adapter rings should be used instead of phenolic rings.

Hydraulic, Pneumatic, etc, Systems. Lines should be routed to eliminate all moisture traps. Systems should be completely drainable and have ample self-locking drains at low points.

Instruments. Hermetically-sealed and rugged instruments, which will operate from -67 to +392 F (-55 to +200 C), should be used. When instruments are repaired, precautions should be taken to prevent moisture and dust from entering the case. Avoid handling meter parts with bare hands.

Lubricants. Use silicone or other water-repellant greases.

Magnetic Materials. Magnetic materials with high corrosion-resistance should be used. If this is not possible, the materials should be treated with a silicone compound such as DC-4 or a fungicidal varnish. Where close clearances are necessary, a thin coat of lacquer is recommended.

Mechanisms, Relays, Gears, etc. Provide sufficient ventilation, heating and drainage to prevent accumulation of water. Design equipment to withstand stresses produced by freezing of surface moisture.

Microphones. Use high-grade nickel steel for the diaphragm and magnet to provide good electrical contact and corrosion resistance. The microphone should be protected from moisture by covering it with either a lightweight coat of nylon or fine screens. Whenever possible, throat microphones, which are not affected by the moisture of human breath, should be used.

Motors, Blowers and Dynamotors. All parts, except the commutators and brushes, should be given MFP (Moisture Fungus-Proofing) treatment. Provision should be made for brushes to be periodically cleaned, and a means of positive lubrication should be provided. Whenever possible, hermetically sealed units should be used.

Plugs (Telephone), Jacks, Dial Lamp Sockets, etc. All surfaces, except contacts, should be given MFP treatment, and a silicone coating such as DC-4 should be used on metal parts. Fungus- and corrosion-resistant materials should be used.

Power Plants. Use waterproof spark plugs to avoid spark plug fouling caused by moisture condensation. Use metal rotors. Where wood is absolutely necessary, pre-dry the wood and coat with moistureproof varnish.

Radomes. Use fiberglass laminates or other moistureproof materials. Erosion coatings will largely eliminate moisture absorption.

Rectifiers. Rectifiers should be treated with fungicidal varnish. However, care should be taken to avoid using mercurial fungicides on equipment having selenium rectifiers. Silicone coatings such as DC-4 may also be used. A fungicidal varnish should also be applied to the terminals after connections are made. Hermetically sealed units should be used whenever possible.

Resistors. Hermetically sealed fixed resistors of the metallic resin or deposited carbon-film type are preferred. A good seal should be used for the rotating shaft of a variable resistor.

Semiconductors. All semiconductor devices should be hermetically sealed.

Solders. For operation at high and low ambient temperatures, lead-silver solders should be used. Only resin, or resin and alcohol should be used as a flux on electronic equipment.

Speakers. Paper speaker cones are susceptible to moisture absorption and fungus growth and should be treated with moisture- and fungus-resistant compounds. Whenever possible, aluminum cones should be used.

Switches. Use of a hermetically sealed switch will prevent corrosion of metal parts and warping of plastic bodies and wafers due to moisture absorption. However, in cases where this is not practicable from the standpoint of size and availability, surfaces should be treated with fungicidal varnish. By means of accessories, such as toggle boots, O-strings, or diaphragms placed over the switch opening, the entry of moisture can be retarded.

Transformers. Adequate terminal spacing, high-temperature wire coverings and tapes, as well as proper case finishing should be used. Corrosion of transformer cases can be retarded by plating the cases with such corrosion-resistant metals as chromium, cadmium, nickel or zinc. Corrosion of windings in open-type constructions can also be retarded by the use of high-purity metals. Chlorides, sulfides and other soluble salts should be avoided. Where temperature permits, the use of a highly resistant material such as Mylar is recommended. A coating with a moisture-resistant fungicidal varnish will also be beneficial. Vacuum impregnating with a good grade of insulating varnish is necessary whenever paper or other fibrous material is used.

Hermetic Sealing./8,13/

Where practical, hermetic sealing is the most reliable method of controlling moisture; it also protects against sand and dust. A true hermetic seal can be constructed only out of metal, glass, or non-porous ceramic materials, since these are the only materials that are essentially moistureproof. In general, organic material cannot be used for a true hermetic seal. However, some organic materials do have a low vapor transmission rate, and so can be considered a hermetic seal. Fused metal joints, soldered glass bushings, or metal bellows arrangements are some types of hermetic seals. These types of seals are meant to be permanent. They should not be broken and resealed frequently in order to have access to internal parts. The use of O-rings, gaskets and lapped disk seals are not hermetic seals. These are waterproof seals and give poor sealing against vapor.

In applying hermetic sealing, care must be taken to ensure that the seal is absolute and permanent for all conditions to which the unit will be exposed. A partial seal on a unit that contains some free space will be susceptible to breathing, and moisture will condense and accumulate in the air space. If the space is small, it may be possible to prevent breathing by filling it with a good casting resin.

Cost, maintenance and other factors should be taken into account when considering the relative merits of overall equipment hermetic sealing as opposed to subassembly hermetic sealing. Overall package sealing simplifies the problem of adequate hermetic sealing to the extent that there is only one large seal to be made, and all parts are protected by it. On the negative side, overall sealing makes servicing difficult by requiring the entire equipment to be opened. Once the seal is opened, there is a loss of inert gases and possible entrance of moisture. Subassembly sealing, on the other hand, has the primary advantage of allowing case replacement of the sealed units, particularly if they are plug-in type subassemblies. However, an equipment consisting of individually sealed subassemblies will tend to be heavier and more expensive than an overall sealed package. A general rule that should be followed is to limit sealing to expendable individual components or relatively small subassemblies that may easily be replaced.

Sealing Methods

When hermetic sealing is used, various characteristics of the method employed must be taken into consideration. The sealing technique must offer proper mechanical rigidity, resist temperature extremes, have good heat transfer characteristics, and be easy to apply. In addition, for electronic equipment, the dielectric constant, high frequency losses and magnetic shielding qualities of the sealing material must be considered. Generally, hermetic sealing can be accomplished by (1) embedment, (2) gas filling, and (3) liquid filling. A comparison of the merits of some of these hermetic sealing techniques is given in Table 5-21. Tables 5-22 and 5-23 list the detailed characteristics of many embedment compounds and silicone fluid fillers.

The decision to use an embedment, gas or liquid-filler type of hermetic seal depends on the specific application. Each method has many advantages and disadvantages, some of which may be important in some applications but not in others. The following is a list of the advantages and disadvantages of each method:

Embedment -- Advantages

1. Provides a resilient mechanical support and so also helps in shock and vibration protection.

2. Eliminates the need, in many cases, for detail mounting hardware.

3. Allows the use of less expensive unprotected components.

4. Allows compact construction and efficient space utilization.

5. Allows critical parts to be protected against unauthorized tampering in the field.

6. Provides support for any shielding on cover that may be used.

7. Is relatively inexpensive.

Embedment -- Disadvantages

1. Adds losses to high-frequency electronic equipment.

2. Multiplies stray capacitances by approximately the dielectric constant of the material.

3. In general, will not withstand high temperatures.

4. Will not, in general, withstand low temperatures, particularly when irregularly shaped objects are embedded.

5. Provides poor heat removal.

6. Makes embedded units expendable.

7. Requires a time-consuming procedure in production.

8. Adds weight to the assembly.

9. Some embedment compounds show evidence of long term shrinkage (over a few years), which leads to cracking.

Gas-Filling -- Advantages

1. Adds no electrical losses to the equipment.

2. Does not increase circuit capacitances.

3. Can withstand both high and low temperatures.

4. Allows moving parts to be sealed.

Table 5-21. Relative Merits of Some Hermetic Sealing Techniques /13/

Technique	Mechanical rigidity	Heat transfer	Temperature resistance		Effective dielectric constant *	Losses at high frequency	Humidity protection	Ease of use
			High	Low				
Resin embedment	E	P	P	P to F	2.5 to 4.0	F to G	E	P
Foam embedment	G	P	P	F	1.03 to 1.2	G	G	P
Ceramic embedment	E	F	E	E	10	F to G	E	F
Plastic coating	P to F	P to F	P	F	1.0	G to E	F to G	F to G
Silicone film	P to F	P to F	G	G	1.0	G to E	P	G
Silicone fluid filling	P	F to G	G	F to G	2.5 to 3.5	G to E	E	F
Gas filling	P	F	E	E	1.0	E	G to E	F to G

* Circuit stray capacitances are increased by approximately this factor.

E = Excellent, G = Good, F = Fair, P = Poor.

5. Prevents oxidation of lubricants, commutators, switch contacts, etc.

6. Reduces arcing tendencies.

7. Permits sealed parts to be replaced and serviced.

8. Provides convection cooling of sealed parts (cooling is better than with embedment).

Gas-Filling -- Disadvantages

1. Provides no support for sealed parts.

2. Requires a strong container to withstand internal gas pressures, particularly at high altitudes.

3. Requires special maintenance equipment.

4. Provides less heat removal than liquid filled units.

5. Leakage is difficult to detect.

Liquid-Filling -- Advantages

1. Provides the best heat removal.

2. Reduces arcing tendencies.

3. Allows the use of unprotected, uncased components.

Liquid-Filling -- Disadvantages

1. Increases weight.

2. Provides no mechanical support for the sealed components.

3. Requires the use of a pressure relief system.

4. A leak can disable the unit and cause trouble in other assemblies.

5. Makes maintenance difficult.

6. Heat removal varies with temperature, which changes the viscosity of the fluid.

7. Some fluids are solvents for some dielectric materials.

8. Stray capacitances are multiplied by the dielectric constant of the fluid.

9. Causes losses in electronic equipment.

Design Considerations/13/

In equipments where sealing is not used and moisture tends to develop, positive steps should be taken to insure against the accumulation of moisture. Care should be given to the mounting of component parts so that moisture traps are not present. Vertical surfaces should be used wherever practical to hold component parts. Drain holes or other means of free drainage should be provided, sometimes even to the extent of filling possible well areas with filleting compounds.

Insulating materials should be limited to those having less than 1.1 percent water absorption. Overall equipment spraying with varnish must be avoided. Spacings between terminals and between uninsulated parts or components should be kept as large as possible in order to prevent mold bridging.

Condensation Control

Condensation control can be accomplished through dehumidification and good temperature control. Dehumidifiers using absorption by silica gel should be placed in areas where moisture would present the most problems. If silica gel is used, indicator materials must be included to show when replacement is necessary. Cooling systems can be used to prevent the temperature gradients that cause condensation; and the cooling system should employ moisture removal methods. Cooling is covered elsewhere in this chapter.

INTERFERENCE PROTECTION/13,38/

Interference can be either man-made or natural. Generally, not much can be done about natural interference; however, the interference from atmospheric electricity, known most commonly as precipitation static, can be minimized by dissipating the atmospheric charge. This is covered elsewhere in this chapter under "Atmospheric Electricity Protection."

For man-made interference, there are three areas in which interference suppression techniques can be applied: (1) at the source of the interference; (2) at the interference transmission medium; and (3) at the interference-susceptible equipment. Electronic interference should be controlled in the basic design of all units of the equipment. The equipment should also be designed to minimize susceptibility to interference from external sources.

The best place to apply interference suppression is at the source, not at the transmission medium, and then at the susceptible equipment. Most often it has to be used in all three areas to bring about satisfactory performance. However, when interference generation is kept to a minimum, interference suppression in the other two areas becomes much easier to accomplish. It must also be remembered that many pieces of equipment, especially electronic equipment, can be both a source of interference as well as a susceptible equipment.

Table 5-22. Embedment Compound Characteristics
(as supplied by the listed companies) /13/

Item	Specific gravity	Heat distortion point (C)	Dielectric strength (volts/mil)	Dielectric constant vs frequency (25 C unless noted)	Moisture absorption (% volume unless noted)
Ariss Laboratory ARI-TEMP 201	-	-	700	60 cps 3.6	0.10
Ciba Co., Inc. ARALDITE	1.1 to 2.2	100 to 120	890	50 cps 1 mc 22 C 3.7 3.6 50 C 3.9 -	1 to 0.14 (168 hr)
CIBA 505	-	-	500	60 cps 3.8	0.10
Dow Chemical Co., Inc. STYROFOAM	0.024 to 0.072	79	-	60 cps to 3000 mc 1.03	0.03 (80 to 90% rh, 15 days)
Dow Corning Corp. RTV5302/5303	-	-	-	-	-
E.I. du Pont Co. TEFLON	2.1 to 2.2	166 (useful at 25)	400 to 500 (80 mil sample) 1000 to 2000 (65 to 12 mil sample)	100 cps to 100 mc 2.0	0.005
Emerson and Cuming, Inc STYCAST 1PM	1.05	1.25	450	60 cps to 10,000 mc 2.36 to 2.38	0.5 (25 C, 24 hr)
STYCAST 2850 GT	-	175	455	100 cps to 10,000 mc 4.7	0.1 (7 days)
STYCAST 55	1.05	85	600 (100 mil sample)	60 cps - 2.596 1 kc - 2.596 1 mc - 2.582 1000 mc - 2.584	0.2 (25 C, 24 hr)
LCCO W 28G Impregnating resin	1.22	approx. 200	412 (1 mil sample)	100 cps to 10,000 mc approx. 3.4	0.1 (7 days)
STYCAST 5050 CM	1.7	170	500 (100 mil sample)	100 cps to 1 mc 4.3	0.10 (25 C, 24 hr)

Power factor vs frequency (25 C unless noted)	Linear thermal expansion (parts per deg C)	Shrinkage on polymerization %	Low temp. limit (C)	Volume resistivity (ohm/cm^3)	Remarks
-	7.2×10^{-5}	5	-65	-	For electron tube amplifiers. Cures at 275 F.
50 cps 1 mc 25 C 0.007 0.027 100 C 0.005 0.027	2.5 to 6.0×10^{-5}	0.5 to 2.3	-60	10^{16} to 10^{17}	Thermal expansion reduced to 2.5×10^{-5} by addition of fillers. Adhesion to most metals is excellent.
-	$3/6 \times 10^{-5}$	1.5	-100	-	For high temperature transformers. Cures at 300 F.
1 kc to 3000 mc 0.0002	5.4 to 7.2×10^{-5}	-	lower than -234	-	Good for many applications up to 2.5×10^{4} mc. Very light, with high strength to weight ratio. Greater strength properties available in lighter density foams.
-	-	-	-60	-	Silicone rubber.
100 cps to 100 mc 0.0005	5.5×10^{-5}	-	-268	10^{15}	Thermal conductivity 1.7 BTU/hr/sq ft/ deg F/in. No Solvents.
60 cps to 10,000 mc 0.0003	5.0×10^{-5}	7	-70	10^{13}	Low-loss, low dielectric constant casting resin. Usable over extremely wide temperature range with large inserts.
100 cps to 100 mc 0.01 100 mc to 10,000 mc 0.02	1.5×10^{-5}	1/2	-75	25 C: 5×10^{16} 150 C: 1×10^{13}	Good high temperature range. Excellent adhesion. Thermal coefficient of expansion similar to brass and aluminum.
60 cps - 0.00098 100 cps - 0.00062 1 mc - 0.00084 1000 mc - 0.00085	7.0×10^{-5}	10	-20	10^{14}	Excellent machinability.
100 cps to 10,000 mc 0.02	5.0×10^{-5}	4	-	2.3×10^{16}	Impregnant for transformers, coils, and capacitors. Can be used as casting resin.
100 cps - 0.015 1 to 10 kc - 0.040 100 kc - 0.030 1 mc - 0.019	5.5×10^{-5}	5	-65	10^{12}	Black, opaque material.

Table 5-22. Embedment Compound Characteristics
(as supplied by the listed companies) /13/ (continued)

Item	Specific gravity	Heat distortion point (C)	Dielectric strength (volts/mil)	Dielectric constant vs frequency (25 C unless noted)	Moisture absorption (% volume unless noted)
H. H. Robertson Company STYPOL 107E	1.253	56	(1/8 in. sheet) 365	60 cps - 3.86 1 kc - 3.59 1 mc - 3.35	0.27 (24 hr)
STYPOL 502E	1.540	-	336	60 cps - 5.53 1 kc - 5.10 1 mc - 4.23	0.30
STYPOL 507E	1.561 (solid resin at 25 C)	55	378	60 cps - 4.57 1 kc - 4.15 1 mc - 3.74	0.14
Koppers Co. DYLITE	-	-	-	-	-
Lockheed Aircraft Corp. Rigid Isocyanate LOCKFOAM NO. 2075	0.048 to 0.480	110 to 140	-	10 lb per cu ft density foam 50 kc - 1.22 500 kc - 1.24 1 mc - 1.17 9.3 mc - 1.19	0.3 to 0.5% by weight (100% rh, 24 hr)
M.W. Kellogg Co. KEL-F	2.1	approx. 200	530 (short time test on 1/8 in. sample) 5000 (step-by-step method, 5 mil sample)	1 kc - 2.8 1 mc - 2.5 100 mc - 2.5	does not absorb or transmit moisture in 5 mil films or greater
Melpar, Inc. MELPAK IV	1.275	170	450	4.7 at 8.4 mc	(24 hr) 0.034
MELPAK V	1.292	200	500	3.6 at 1 mc	0.30
MELPAK VI	1.480	300	475	3.4 at 80 to 120 mc	0.27
Minnesota Mining and Mfg. Co. EC 1120-PC	-	-	-	-	-
National Bureau of Standards, Diamond Ordnance Laboratories NBS RESIN	1.22	68 to 70	610 to 660	100 cps - 2.44 10 kc - 2.43 1 mc - 2.42 100 mc - 2.5	(24 hr) 0.01
EN-2.5 CASTING RESIN	1.06	51	-	100 cps to 1 mc 2.61 100 mc - 2.60	0.02

Power factor vs frequency (25 C unless noted)	Linear thermal expansion (parts per deg C)	Shrinkage on polymerization %	Low temp. limit (C)	Volume resistivity (ohm/cm^3)	Remarks
60 cps - 0.013 1 kc - 0.0079 1 mc - 0.024	-	8.7	-	-	For impregnating transformers.
60 cps - 0.069 1 kc - 0.072 1 mc - 0.049	-	8.4	-55	-	Inorganic filler provides increased resistance to cracking - higher thermal conductivity.
60 cps - 0.022 1 kc - 0.013 1 mc - 0.025	-	8.9	-	-	Harder, more rigid than 502E. Also has inorganic filler.
-	-	-	-	-	Polystyrene foam.
9300 mc 5×10^{-5}	3×10^{-5}	negligible	unaffected at -73.5	-	Density may be controlled from 1 to 40 lb per cu ft. Can be poured and formed in place at 21.1 C to 26.7 C.
1 kc - 0.025 1 mc - 0.006 100 mc - 0.006 (power factor lower at 200 C than at 25 C)	-80 to +20 4.5×10^{-5} 20 to 150 7×10^{-5}	0.005 to 0.010 per in.	-201	1.2×10^{18} (50% rh, 25 C)	Chemically inert, high impact, high-temperature material. Excellent electrical properties over wide temperature range. Can be injection extrusion, transfer, or compression molded.
0.62 at 34 mc	2.5×10^{-5}	6 to 8	-65	10^{15}	Hot spot temperature. Should be 170 C or less. Can be cured at room temperature, but higher temperature preferable.
0.015 at 1 mc	3.0×10^{-5}	2 to 3	-65	10^{17}	-
0.016 at 60 cps	2.5×10^{-5}	4 to 5	-65	10^{15}	-
-	-	-	-65	-	Polysulfide elastomer.
100 mc 0.0004 to 0.0008	11×10^{-5}	7.5	-55 (cracks at this temp.)	10^{17}	Specialized resin for UHF high impedance circuits. Quite expensive to manufacture.
100 cps - 0.0016 10 kc - 0.0010 1 mc - 0.0009 100 mc - 0.0010	-	9.8	-	10^{17}	A copolymer of styrene and fumaronitrile. Uses similar to NBS CASTING RESIN; less expensive but some sacrifice in dissipation factor at elevated temperatures.

Table 5-22. Embedment Compound Characteristics
(as supplied by the listed companies) /13/ (continued)

Item	Specific gravity	Heat distortion point (C)	Dielectric strength (volts/mil)	Dielectric constant vs frequency (25 C unless noted)	Moisture absorption (% volume unless noted)
Nopco Chemical Company LOCKFOAM Series A	-	-	-	-	-
Pittsburgh Plate Glass Co. SELECTRON 5000-5199	1.2 to 1.4	45 to 200	400 to 600 (short time test, 1/8 in. specimen)	(1/8 in. specimen) 60 cps - 3.30 to 3.70 1 kc - 3.10 to 3.30 1 mc - 3.00 to 3.25	(24 hr) 0.05 to 0.5
SELECTRON 5003	1.22	90	480	60 cps - 3.55 1 kc - 3.15 1 mc - 3.08	0.3
SELECTRON 5200	1.5	-	300 to 500	60 cps - 6.00 to 6.40 1 kc - 5.10 to 5.50 1 mc - 3.60 to 5.00	0.5 to 1.0
Products Research Co. PR-1201C	-	-	-	-	-
Rohm & Haas Co. PARAPLEX P-13	1.122 (at 25 C)	-	345 (100 mil casting at 25 C)	60 cps to 1 kc - 4.2 1 mc - 4.0 10 mc - 3.7 30 mc - 3.4	(% wt, 24 hr, 25 C) 0.6 (% wt, 24 hr, 25 C) 2.0
PARAPLEX P-43	.235	75 to 85 (2 C per min at 264 psi)	500	60 cps - 3.3 1 kc to 10 mc - 3.2 30 mc - 3.1 10,000 mc - 2.6	(% wt, 24 hr, 25 C) 0.3 (% wt, 24 hr, 100 C) 3.0
Topper Mfg Co. COLPLAST	-	-	500	3.9 at 60 cps	0.10
U. S. Navy Electronics Laboratories N.E.L. 177	1.235 - - -	85 (passes spec 16 E 4)	700 (30 mil sample, 60% rh, 22.2 C)	100 cps - 3.20 100 kc - 3.26 60 mc - 3.09 (62% rh, 23.3 C) - -	0.23

Power factor vs frequency (25 C unless noted)	Linear thermal expansion (parts per deg C)	Shrinkage on polymerization %	Low temp. limit (C)	Volume resistivity (ohm/cm^3)	Remarks
-	-	-	-	-	Isocyanate foam.
(1/8 in. specimen) 60 cps - 0.016 to 0.02 1 kc - 0.003 to 0.01 1 mc - 0.008 to 0.015	-	6 to 9	-55	-	Rigid resins with widely varying properties.
60 cps - 0.017 1 kc - 0.0036 1 mc - 0.013	8 to 10 x 10^{-5}	7.5	-55	-	General purpose casting resin.
60 cps - 0.13 to 0.15 1 kc - 0.04 to 0.06 1 mc - 0.015 to 0.05	-	6 to 9	-	-	Flexible resins that may be blended with resins.
-	-	-	-65	-	Polysulfide elastomer.
60 cps - 0.005 1 kc - 0.011 1 mc - 0.052 10 mc - 080 30 mc - 0.105	-	9.0	-	-	Flexible polymer. Can be mixed to obtain intermediate properties.
60 cps to 1 kc - 0.006 1 mc - 0.017 10 mc - 0.022 30 mc - 0.034 10,000 mc - 0.043	-	7.0	-	-	Rigid polymer. Can be mixed to obtain intermediate properties.
-	9.0 x 10^{-5}	3.0	-80	-	For use with semiconductors. Cures at room temperature.
100 cps - 0.0175 100 kc - 0.0156 60 mc - 0.0234 (62% rh, 23.3 C)	6.01 x 10^{-5}	-	-54	9 x 10^{12} (60% rh, 24.4 C)	Preliminary data only.

Table 5-23. Properties of Some Silicone Fluids* /13/
(Courtesy of Dow Corning Corp.)

Silicone fluids	Specific gravity	Flash point (C)	Dielectric strengths (volts/mil)	Dielectric constant (at 25 C)	Power factor	Heat transmission gram-cal/sec/cm2/deg C/cm	Remarks
200 fluid; 3 centistokes at 25 C	0.896	107	250 (0.1 in. sample)	100 cps - 2.412 1 mc - 2.405 100 mc - 2.39	100 cps - 0.0001 1 mc - 0.0002 100 mc - 0.0002	0.00027	Liquid methyl silicone. Volatile liquid. Useful to -55C.
200 fluid; 350 centistokes at 25 C	0.972	315	250 (0.1 in. sample)	100 cps - 2.74 1 mc - 2.72 100 mc - 2.70	100 cps - 0.0001 1 mc - 0.0002 100 mc - 0.0006	0.00039	Nonvolatile fluid. Useful from -40 C to + 200 C.
550 fluid; 100-150 centistokes at 25 C	1.08 (25 C)	315	350 (0.1 in. sample)	100 cps - 2.92 1 kc - 2.91 100 kc - 2.91	100 cps - 0.0001 1 kc - 0.0001 100 kc - 0.0001	----	Liquid phenyl-methyl silicone of exceptional heat stability. Useful from -40 C to +250 C.
200 fluid; 1000 centistokes at 25 C	0.973	315	300 (0.1 in. sample)	100 cps - 2.76 1 mc - 2.78 3000 mc - 2.74	100 cps - 0.0001 1 mc - 0.0003 3000 mc - 0.0096	0.0038	Nonvolatile fluid. Useful from -40 C to + 200 C.

* Dow Corning Corporation. Other silicone fluids are obtainable from other manufacturers, but because of different methods and conditions of measurements their data are not presented here. The figures given above are characteristic of the silicones as a group.

Interference suppression at the source and the susceptible points can be reduced by proper selection of components and equipments, and by the reduction of harmonic generation, arcing and corona. Since interference can be transmitted by conduction, coupling, or radiation, interference transmission can be reduced by filtering, shielding (in the case of noise, insulation is the accepted method of shielding) and judicious placement of equipment. Interference suppression must be used not only between equipments but also between sections within equipments.

Selection of Components

Whenever possible the designer should use interference-free components. For example, a blower equipped with an a-c induction motor should be used instead of a blower with a d-c commutator-type motor and a carbon pile regulator is better than the vibrating reed type. Additional information on component selection is contained in reference/39/.

Suppression Techniques

Shielding. Shields are used on small assemblies, such as chassis, as well as on equipments to isolate the effects of arcing, corona, and stray electromagnetic fields. The shield prevents the exit of interference at the source, or the entrance of it at the susceptible point.

The usefulness of shielding increases with the thickness of the shielding material, the square root of its conductivity, the square root of its permeability, and the square root of the interference frequency. Individual shields are also used within an overall shielded equipment to prevent coupling, contamination, and interaction within the equipment, and to reduce the overall problem of filtering. By isolating individual circuits with shields and lead filtering, normally noise-free leads will not require filtering prior to their exit from the overall shielded container, since contamination of these leads will probably not take place.

Shields made of ferrous materials should not be used for frequencies above 150 kc. Transparent conductive-coated face plates should be used over radar screens to reduce radiation interference. As an aid to determining shielding effectiveness, attenuation characteristics of various metals are given in Tables 5-24 and 5-25.

Meshed metallic wire may be used instead of solid metal shields where cooling is a problem, or where openings must be provided in a case. The openings should be as small as possible, preferably no larger than the holes in 22-mesh, 15-mil copper screening. If larger holes must be used, they should be covered with 16- to 20-mesh screening.

Table 5-24. Shield Thickness of Various Metals to Achieve 33 db Loss at 1 Mc /13/

Metal	Thickness (mils)
Aluminum	13
Brass	20
Copper	10
Magnesium	16.5
Silver	10
Steel	25 to 55
Tin	26
Zinc	18.5

Metallic shafts that tend to radiate interference should be grounded by serrated metallic fingers or a gasket. If, for design reasons, the shaft cannot be grounded, it should be made of an insulating material, and a wave-guide attenuator used around the shaft.

Mating Surfaces. Mating surfaces, especially where gaskets are used, have been a principal source of interference escape. A gasket must be conductive to prevent r-f leakage, and it must be pliable in order to conform to the joining surfaces and bring about large contact area. The gasket material should not be soluble in oil, gasoline or water, and it should be able to withstand temperatures from -67 to 365 F (-55 C to 185 C).

In general, the important requirements for mating surfaces is that a continuous electrical contact be maintained all along the joint. The best type of joint, from an interference protection standpoint, is a welded joint. If the joint is held closed by screws or bolts, a sufficient number should be used so that approximately equal pressure is exerted all along the joint. There are various methods of improving contact on mating surfaces. One method is to use tapered joints, as shown in Fig. 5-71. This arranges electrical contact along more than one line. Or, if thinner, structurally weak members are to be used, the "paint can" method shown in Fig. 5-72 can be used. To further increase the shielding effectiveness of a flanged joint, an annular ring, as shown in Fig. 5-73, can be used around the entire circumference of the joint. The serrated spring joint, shown in Fig. 5-74, also gives good continuous contact area.

Filtering. Complete shielding of an equipment, chassis or plug-in assembly is actually never possible because of the leads that must enter or leave the unit. These leads provide conductive paths for interference signals. To suppress this kind of interference transmission, all inter- and intra-wiring should be filtered.

Table 5-25. Shielding Effectiveness of Various Metals at 150 Kc /13/

Metal	Attenuation (db/mil)
Silver	1.32
Copper (annealed)	1.29
Copper (hard drawn)	1.26
Gold	1.08
Aluminum	1.01
Magnesium	0.79
Zinc	0.70
Brass	0.66
Cadmium	0.62
Nickel	0.58
Phosphor-bronze	0.55
Iron	16.9
Tin	0.50
Steel, SAE 1045	12.9
Beryllium	0.41
Lead	0.36
Hypernik	88.5
Monel	0.26
Mu-metal	63.2
Permalloy	63.2
Stainless steel	5.7

Harmonic Suppression Filters. Provided the frequency is fixed, or has less than a 2 to 1 tuning range, harmonic suppression filters may be used at the output of transmitters to prevent harmonics from reaching the transmission line and antenna. These filters are usually bandpass or low-pass filters, because only the frequencies above the fundamental are to be attenuated. High-pass filters may be required with equipments employing frequency multipliers. In designing bandpass or high-pass filters, use a cutoff frequency of 1.1 times the fundamental frequency. The filter should be placed to prevent the unwanted frequencies from leaving the transmitter. A Faraday screen between the output tank and the pickup coil will also aid in preventing harmonic coupling to the transmission line.

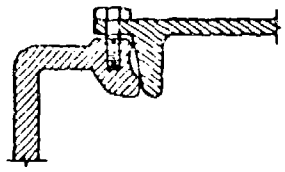


Fig. 5-71. Tapered joint.

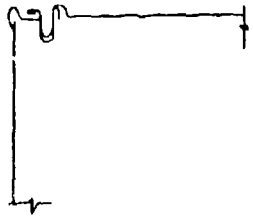


Fig. 5-72. "Paint can" joint.

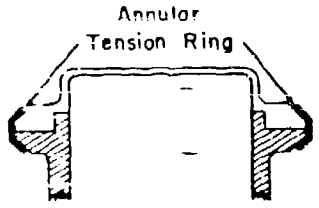


Fig. 5 73. Annular-ring type joint.

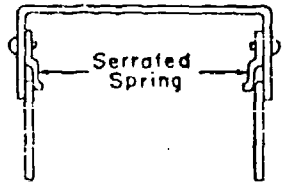


Fig. 5-74. Serrated spring joint.

Powerline Filters. In a vehicle electrical system, primary power wiring is common to many equipments and circuits, so that the power-line can serve as a common interference path between the equipments and circuits. Proper filtering should be used at necessary equipment exit and entrance points to suppress the transmission and reception of unwanted signals. Merely bypassing the leads to ground or the use of small inductors will help suppress r-f signals, but in many cases filter networks will have to be used. To be most useful, filters should be placed inside the equipment case or as close as possible to the exit or entrance point. Even a few inches of wire left unfiltered will radiate interference.

Bonding and Grounding. Bonding is a mechanical connection that provides a low-impedance path for interference currents and a-c and d-c power return paths. A good bond contains low d-c power resistance. This alone, however, does not insure a good bond, since a very low r-f impedance is also required. Bonding jumpers required to provide a conducting path around vibration isolators or other parts should be flat, unbraided beryllium-copper or phosphor-bronze, silver-plated metal strips.

Bonding is accomplished in two ways: directly and by means of jumpers. A direct bond is made by joining two metals, either permanently or semipermanently. Permanent bonds are preferred.

Bonding jumpers are used to connect electrically two physically separated surfaces. The jumpers are required, for example, with an equipment that is electrically separated from ground because the equipment is shock mounted. The jumper is used to bond the equipment electrically to ground without obstructing the action of the shock mount.

Bond impedance increases as the length of the strap is increased. Also, it is important to have a high ratio of jumper width to length. The length should not be greater than five times the width.

Arcing and Corona Suppression.

Arcing and corona should be minimized (refer to "Atmospheric Pressure Protection" in this chapter), or eliminated where practical. Where they cannot be entirely eliminated, their effects should be controlled by shielding the equipment generating them. All leads associated with the unit should be filtered, and located where they will have the least effect on other equipments and circuits.

SAND AND DUST PROTECTION/40/

Proper choice of abrasive-resistant materials for exposed surfaces will give protection against sand and dust. For example, stainless steel can be used to protect the thin rubber stripping on rubber propeller deicing boots, and protective covers may be provided for plastic surfaces, such as windshields and radomes. Materials chosen for use in protective devices should also be able to withstand other environments likely to be encountered./41,42/

The best way to protect the interior of a flight vehicle or equipment is to completely exclude the sand and dust. This can be done by hermetically sealing the various components. However, it is often more practical to do one of the following:

1. Provide suitable shields and covers for wearing surfaces, such as engine bearings.

2. Provide filters in the air intake systems of piston engines and other compartments.

3. Place delicate instruments and equipment in protected positions.

4. Recommend frequent greasing and cleaning of the equipment.

DEICING AND ANTI-ICING/43/

During flight, icing on wings, empennage, scoops, radomes and transparent areas can increase drag, cause control and power loss, and render air speed and other sensors inoperative. The icing problem on wings and empennage exists only for subsonic aircraft, or for supersonic aircraft when operating in the subsonic regime, particularly during takeoff, climbing and landing operations. The methods of protecting aircraft against icing may be divided into two classifications. First, there are mechanical systems in which ice is removed by a mechanical operation, such as the periodic inflation and deflation of a rubber boot, commonly known as a deicing boot. Second, there are thermal systems, in which the accumulation of ice is either prevented or removed by heating the vehicle surface. Thermal systems may be either continuous or cyclic. The continuous system (anti-icing) supplies sufficient steady heat to the vehicle surface to completely vaporize the impinging water, thereby preventing the formation of ice. The cyclic system (deicing) allows the ice to accumulate and then removes it. The ice is removed by adding sufficient heat to melt a thin film of ice adjacent to the skin. This breaks the bond between the ice and the skin, and the air stream sweeps away the accumulated ice./44/

The most widely used type of thermal anti-icing system provides spanwise air distribution and chordwise air flow through a "D" duct in the wing's leading edge, as shown in Fig. 5-75 and Fig. 5-76. There are also many arrangements of limited-type ice removal system that have potential application to supersonic aircraft. These include solid and liquid freezing-point depressants, chemical heat-release coatings, expendable leading edges, and detonating strips.

Anti-icing and defrosting of transparent areas, such as windshields, can be accomplished by various methods of heating (Fig. 5-77). Double pane construction with hot air

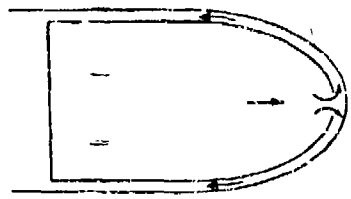


Fig. 5-75. "D" duct.

flowing through the panes is one method. The use of a transparent electrical conductive coating between plies of glass and monolythic plastic windshields is another efficient method. An external jet air blast on the windshields is still another method of anti-icing and defrosting, as well as an efficient, simple and reliable method of ram ice removal when sufficient quantities of compressed air are available. In the application of either anti-icing or deicing systems to flight vehicles, it is advisable to conduct an operational analysis (Chapter 4) to determine the effects of various anti-icing and deicing systems as well as various degrees of protection on the mission effectiveness of the flight vehicle. Anti-icing or deicing of engines that can be affected must always be provided./45,46,47/

ATMOSPHERIC PRESSURE PROTECTION/13/

Selection of Materials. Seals and gaskets should be made of materials that will not be easily distorted by reduced atmospheric pressures. Lubricants and other fluids that will not diffuse and leak at the expected pressures should be chosen. To minimize the wearing of commutator brushes in motors and generators at higher altitudes, cadmium iodide and lead chloride can be incorporated into the brush material. This will supplement the lubricating effects of water and oxygen, so that friction will be kept low at high altitudes./22,48/

Insulation that is made of unbonded or unsealed tape construction should not be used in an environment of extreme or rapidly changing pressures. Solid-type (extruded or molded) insulating material should be used. Insulating material that deteriorates rapidly under ionic bombardment should not be used in high voltage circuits at low pressures because it will be easily damaged by corona. Teflon, for example, has low resistance to ozone and should not be used when corona might be present.

Selection of components. /18/ Electronic components carrying high voltages and components using make-and-break contacts must be chosen carefully for the anticipated pressures. The insulation material should not be susceptible to arcing and corona at the low pressures, or the components should be hermetically sealed whenever possible. The terminals on parts such as transformers, inductors and

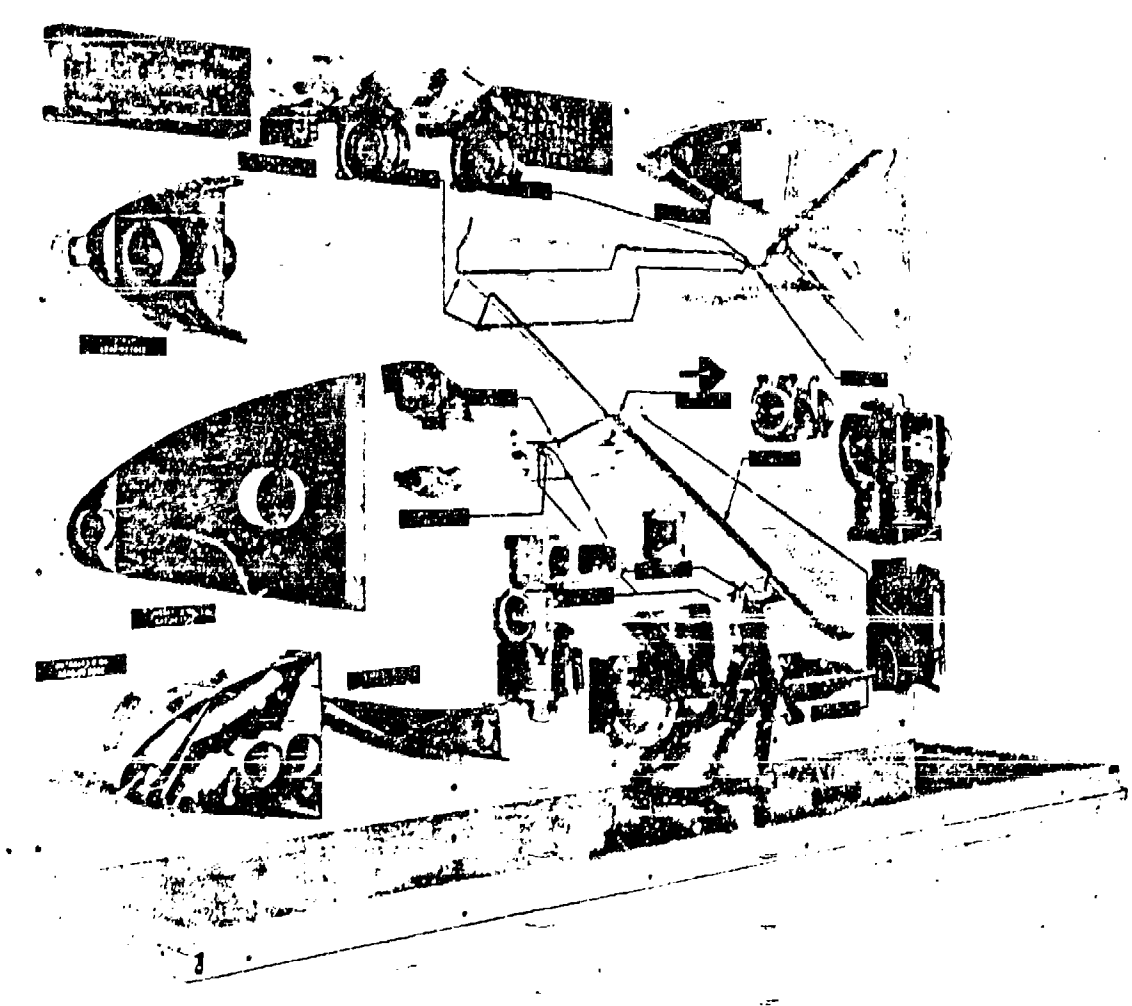


Fig. 5-76. Anti-icing system for wing, nacelle and empennage.

connectors should be spaced far enough apart to prevent arcover at the operated voltages. If such parts must be used below their atmospheric pressure ratings, they should be derated accordingly. Relays, switches and similar parts that use contacts should be chosen according to atmospheric pressures expected, or the parts should be sealed or derated. When choosing sealed units, such as metal-encased parts, the pressure gradient must be considered to prevent distortion or bursting of the container.

*Surface creepage distance is actual distance between electrodes along surface of insulation between them, including irregularities.

Arcover Prevention

The actual potential at which arcover takes place at various altitudes depends greatly on the distance between the parts and the configuration of the parts. The effective surface creepage distance* and actual air spacing between terminals or parts should not be less than that specified in Table 5-26 for the intended voltages. The configuration of the parts is important to prevent corona, which would ionize the air and cause arcover even at the specified safe air spacings. Sharp corners are most apt to cause corona, while rounded corners are least likely to do so. The degree of roundness, however, is also an important factor at the higher voltages. At sea level pressure, equipment that

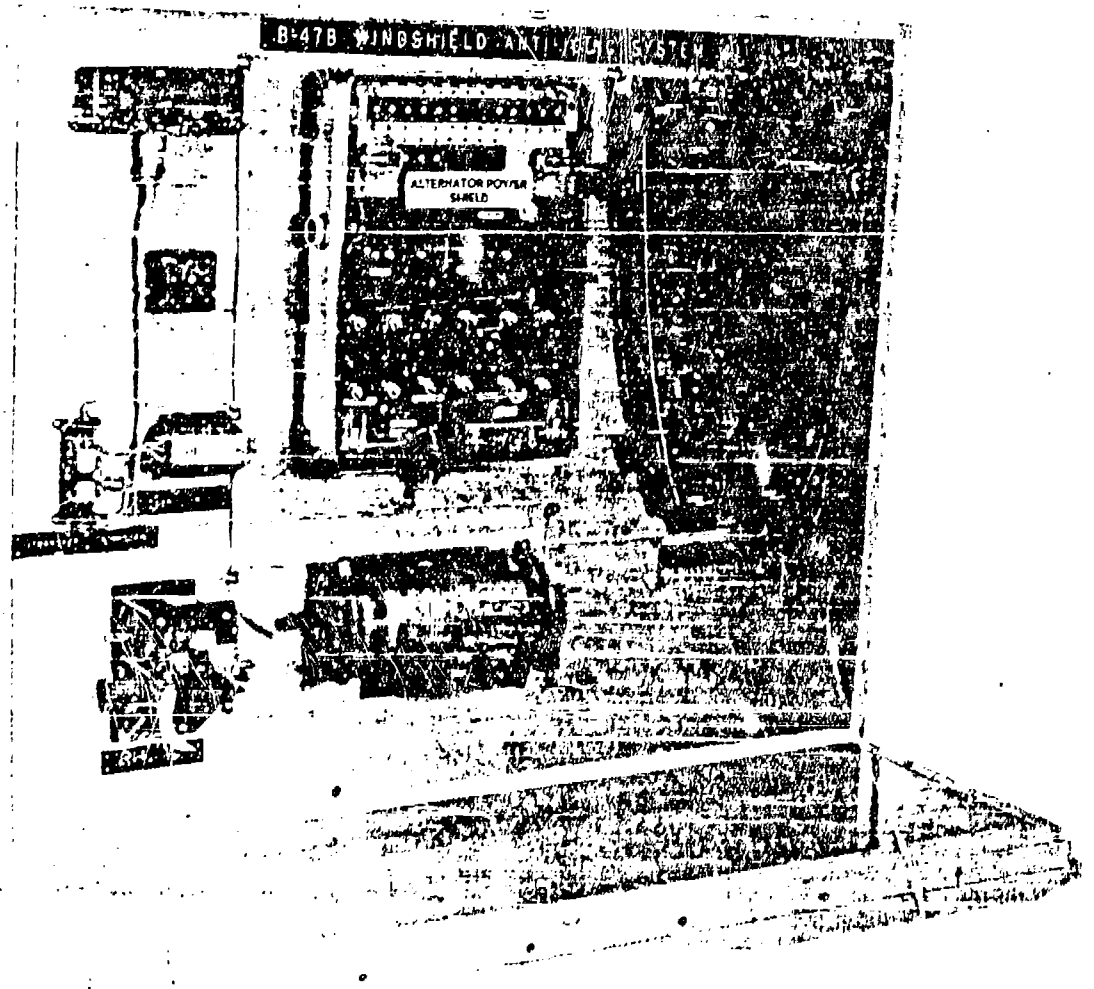


Fig. 5-77. Anti-icing system for windshield.

has exposed potentials of less than 1000 volts needs no special considerations; even square corners are permissible. From 1000 to 6000 volts, reasonably well-rounded corners are required. However, from 6000 to 20,000 volts, no set rules have been developed, and special tests should be conducted on the equipment to determine the proper configurations.

When it is not practical to modify exposed electrodes to rounded configurations and pressurization is not possible, a metal corona shield should be used. The shield should surround, though not necessarily completely, the poorly shaped electrodes in such a manner as to prevent any breakdown voltage gradient in the surrounding air. The corona shield must also be rounded. Maximum arcover and corona discharge occurs at pressures between 1 and 50 microns of Hg. Below a pressure of approximately 10^{-5} millimeters of H_g, the air density is too low to support a corona discharge.

Table 5-26. Contact Spacing vs. Working Voltages at Various Altitudes /13/

Maximum air space	Minimum creepage distance	Working voltage at 50,000 ft		Working voltage at 70,000 ft	
		dc	ac rms	dc	ac rms
-	3/64	100	75	70	50
1/32*	1/16	190	125	125	90
3/64	5/64	210	175	175	125
1/16	7/64	315	225	210	150
5/64	1/8	360	260	230	165
3/32	5/32	420	300	260	185
1/8	3/16	490	350	310	225
3/16	1/4	630	450	375	275
1/4	5/16	700	500	455	325
5/16	3/8	810	575	500	355

*Parts or terminals should be continuously insulated. There should be no open space existing between any part of the conductors having this mechanical spacing.

Pressurization

If, after careful selection of materials and components and the use of proper design techniques, low atmospheric pressures will still have detrimental effects on equipment, pressurization must be used. In a pressurized system, either the equipment or compartment is sealed, and accessory pumping equipment is used to maintain a predetermined pressure regardless of altitude. The pressurization equipment must maintain the pressure over extended periods, and pressure leakage should not be more than 8 cubic inches per minute when the pressurized enclosure is kept above 12 psia. Usually, pressurization within a sealed container is kept at the sea level equivalent.

When pressurization is used, the containers must be designed structurally to withstand the pressure gradients. Generally, spherical containers provide the most strength for a given weight, but a cylindrical shape is the best compromise from a space utilization standpoint (Fig. 5-78 and Fig. 5-79).

ATMOSPHERIC ELECTRICITY PROTECTION /49/

Generally, discharge wicks are used on the outer surfaces of flight vehicles to dissipate any electrical charge that may build up during flight. However, discharge wicks are not effective enough to prevent radio interference on the higher speed aircraft, which require a discharge current of several milliamperes to stay below the corona threshold. Other types of dischargers, such as biased resistive coatings on insulating strips at the trailing edge of a wing or fin, combination diverter dischargers, radioactive dischargers, and jet exhaust-gas dischargers, are being studied for more effective operation.

With jet aircraft, studies are being made using external wicks in or near the exhaust gases to increase the discharge rate of the tail pipe edges. Tungsten grids and a cavity discharger are also being considered.

Several protection systems have been proposed and applied to existing fuel tanks. One such system uses longitudinal ribs to divert electrical discharges from the tank wall and guide the discharges as they are swept rearward by the force of the windstream. Insulation is applied between the ribs to prevent discharges being swept off the ribs into the tank wall. This protection system is schematically illustrated in Fig. 5-80./50/

EXPLOSIONPROOFING

Standard measures for the prevention of igniting an explosive atmosphere include using sealed units to isolate the explosive atmosphere from a possible igniting arc, and using proper design to eliminate arcing. The most practical way of achieving this is to use hermetically sealed units, particularly for switches and relays, which have a natural tendency to arc. If sealing is not possible, then ignition sources, such as wafer switches and relays, should be isolated from accumulated explosive vapors./13, 40/

Explosionproof equipment should be constructed so that if explosions occur within a certain part of the equipment, they will not ignite any surrounding gas mixtures. The equipment should be in a metallic enclosure and be able to withstand specified explosions without bursting or loosening its joints. The joints should be made of metal and have close clearances; this will arrest the propagation of flame from the interior of the enclosure to the surrounding atmosphere.

Another method of minimizing the danger of explosive-atmosphere ignition is by the use of sintered metal screens instead of covers. Figure 5-81 shows a vented circuit breaker case with sintered metal ventilating panels replacing the customary covered openings. The sintered metal screens have successfully prevented explosions within the case from detonating a surrounding explosive mixture in an explosion test chamber. Additional information on explosion hazards and protection methods is contained in reference /51/.

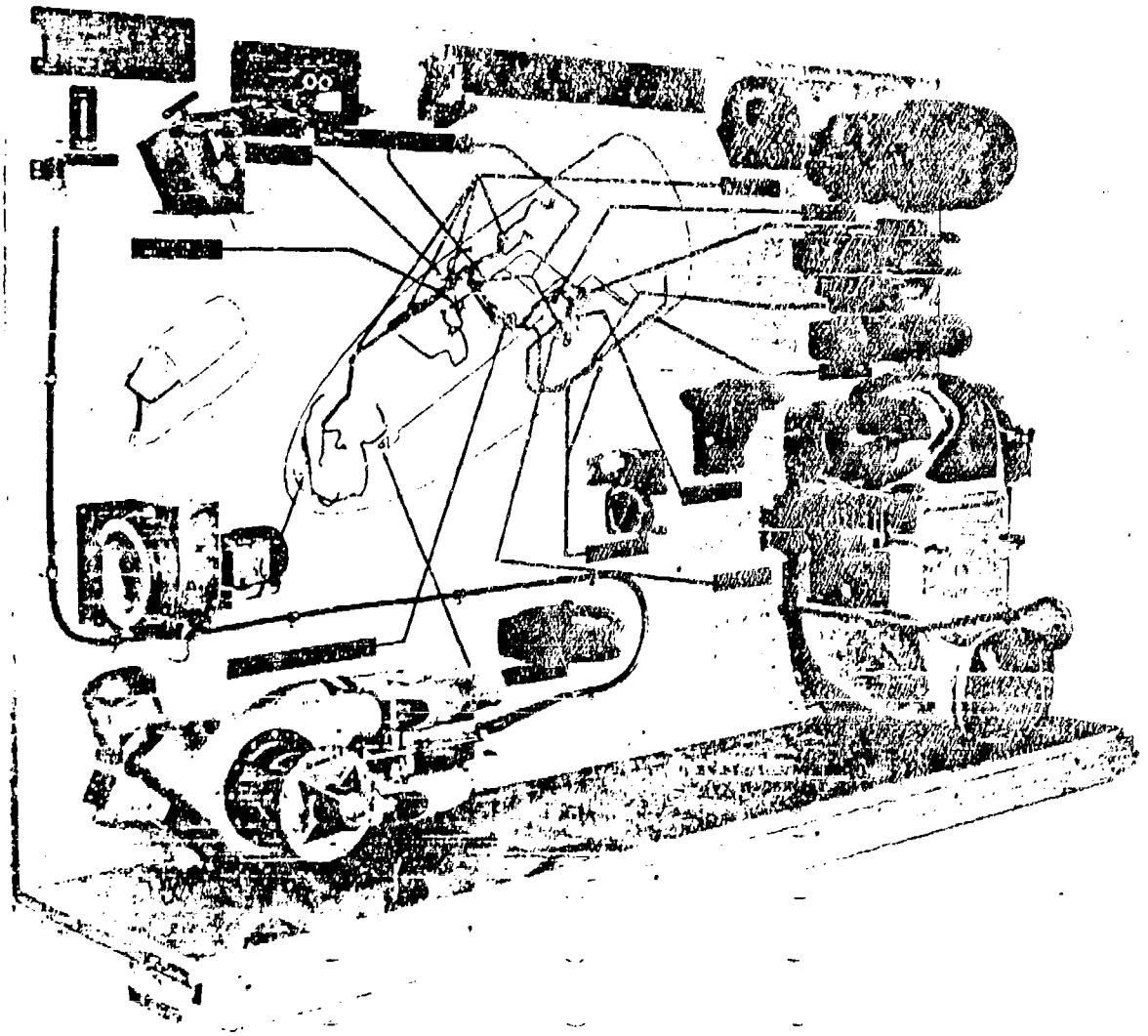


Fig. 5-78. Cabin air conditioning and pressurization system for B-47B.

RADIATION PROTECTION

Flight vehicles may be exposed to nuclear, cosmic, and solar radiation. At present, no severe problems are encountered in protecting flight vehicles and their associated equipment from the harmful effects of solar radiation. Therefore, the following paragraphs deal exclusively with protection against nuclear and cosmic radiation.

Protection against radiation can be accomplished by any or all of the following:

1. Use of radiation-resistant materials.
2. Taking advantage of the inverse-square law when locating components.
3. Limiting the exposure time.
4. Shielding.

The protection method used in a specific application depends upon the type, intensity and duration of the radiation. Generally, it is necessary to combine several of the methods to minimize the radiation hazard.

Selection of Materials

The most preferable method of radiation protection is to design equipment using materials

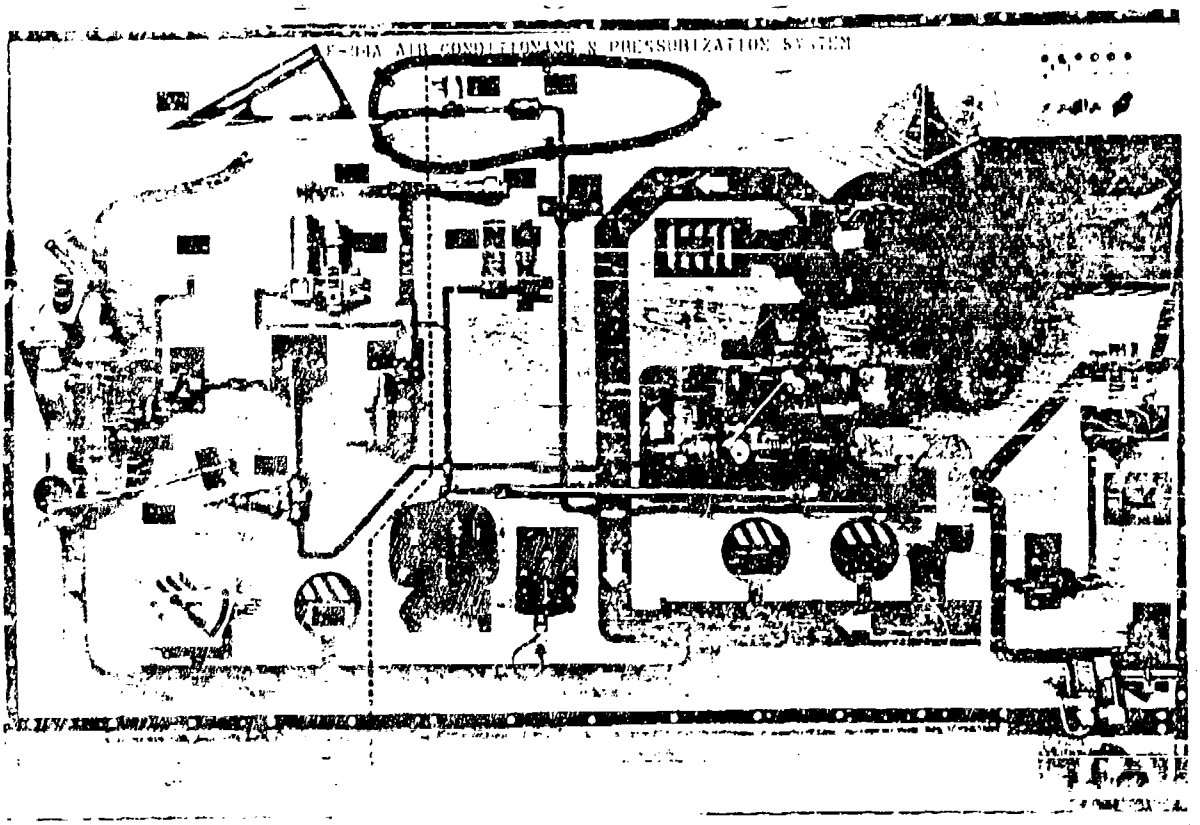


Fig. 5-79. Air-conditioning and pressurization system for F-94A.

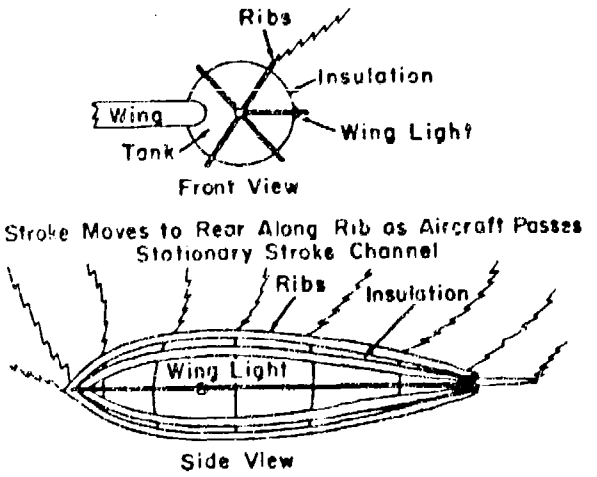


Fig. 5-80. Rib protection system for auxiliary fuel tank./50/

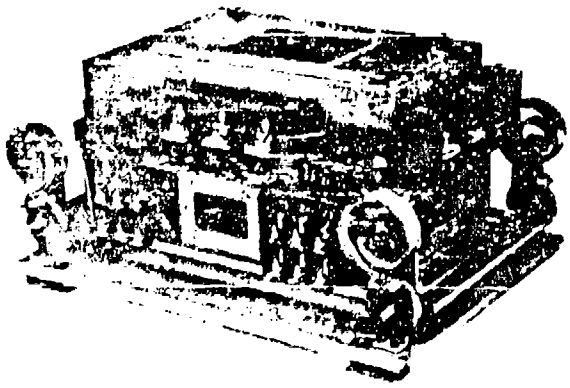


Fig. 5-81. Sintered metal screens used to protect equipment.

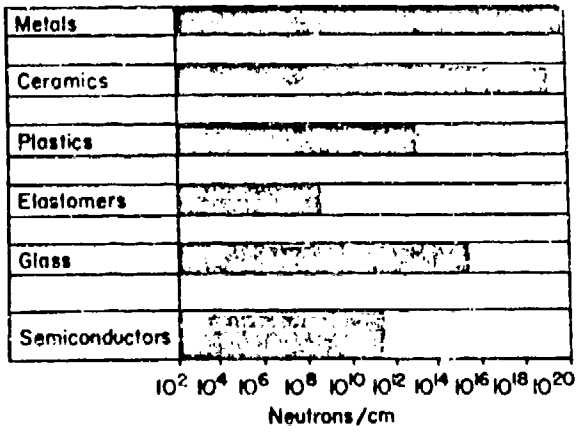


Fig. 5-82. Relative radiation stability of materials.

that are radiation stable. For example, Formex may be substituted for Teflon in certain applications involving a radiation environment. Another example is the substitution of soft glass for hard glass in vacuum tube envelopes. Figure 5-82 shows the relative stability of materials subjected to radiation exposure. A more detailed discussion of radiation-resistant materials and components is contained in Chapter 3.

Location of Components

The second method of minimizing the effects of radiation is to take advantage of the fact that the intensity of radiation varies inversely as the square of the distance it travels from the source (Fig. 5-83.) Thus, by simply relocating a component to a greater distance from the radiation source, the intensity of the radiation will be reduced. For example, by moving a component to a location 100 feet from the source, the intensity is reduced to one hundredth of what it was at 10 feet.

Exposure Time

Another means of radiation protection is to control the time of exposure. Relatively high intensities of radiation can be tolerated for short periods of time if the need arises. As a typical example, in space operations, equipment can be designed to withstand the radiation exposure encountered in passage through one of the radiation belts. Should operations be conducted in this area for extended periods of time, however, radiation damage would be expected to occur. In the case of pulse-radiation exposure, such as that occurring as a result of a nuclear explosion, the total radiation dosage received is generally not sufficient to cause permanent damage to materials; however, certain types of transient effects may occur that are due mainly to ionization.

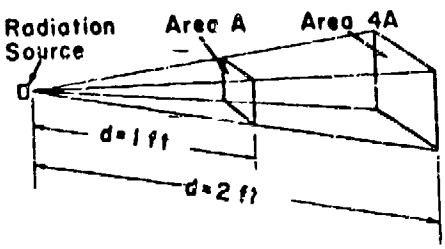


Fig. 5-83. Representation of inverse-square law.

Shielding

The effectiveness of a material as a shield against radiation depends upon its physical properties and the characteristics of the radiation it must resist. Each type of radiation is most effectively stopped by a particular shielding material. The energy of the radiation is the principal factor in determining the amount of shielding required. In the case of a reactor, the radiation consists of many different types and energies. Accordingly, a reactor shield will probably be of a sandwich construction and will differ considerably from one designed for the "Van Allen" or space radiation. Shielding for various types of radiation is discussed in the following paragraphs.

Alpha Particle Shielding. Alpha particles are readily absorbed by thin sheets of material. For example, 1/64-inch thick aluminum will stop most alpha particles. Their range in air is only a few centimeters. Alpha particles are not absorbed according to the exponential law as are other particles. Since the alpha particle is

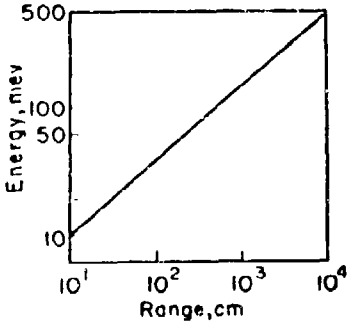


Fig. 5-84. Range of alpha particles in air.

relatively heavy (7440 times that of the electron), in collision with orbital electrons the alpha particle loses little momentum. The range of alpha particles varies directly as the 3/2 power of the energy. This can be represented by the equation:

$$R = AV^3$$

where R = range, cm

$A = 9.67 \times 10^{-28}$

V = velocity, cm/sec

In summary, alpha particles present very little shielding problems. Figure 5-84 indicates the range of alpha particles in air. The range would be reduced proportionately in other, more dense materials.

Electron or Beta Particle Shielding. It has been demonstrated experimentally that the charge-to-mass ratio of beta particles closely resembles that of electrons. It has also been shown that the spin of beta particles is the same as the spin of electrons. Based on this evidence, this paragraph treats beta particles and electrons identically.

Unlike alpha particles, electrons do not follow straight line paths and have discrete ranges in materials. Instead, they generally experience considerable multiple scattering. Figure 5-85 shows the relationship between the penetration range in aluminum and the energy of electrons or beta particles. Protons are included in the illustration for comparison purposes.

Beta particles are slowed down by their interaction with orbital electrons. Thus, the heavy molecular weight materials and those with closely packed electrons are most effective for shielding purposes. However, classical electromagnetic theory predicts that as a charge undergoes an acceleration, it emits radiant energy whose amplitude is proportional to the acceleration. The acceleration produced by a nucleus of charge Ze on an electron of charge ze and mass m is proportional to Zze^2m. The intensity, which is porportional to the square of the amplitude, will vary as Z^2z^2m. An electron in the coulomb field of a nucleus can experience a large acceleration because of its small mass, the acceleration being proportional to the nuclear charge, Z, divided by the electron mass. Thus, more X-radiation is emitted when high Z materials are used to shield against electrons. This hazardous by-product of the electron interaction is more of a problem than the original electrons, because of the penetrating power of X-rays.

The quantity of X-radiation produced is directly proportional to the square of the atomic number of the absorbing material, and is more significant when electrons with energies greater than several mev are involved. For shielding, it is therefore preferable to use materials with low atomic numbers that are also effective in stopping beta radiation. Aluminum is a good beta absorber. It has an atomic number of 13, as compared to lead with an atomic number of 82. Even though lead is more effective as an electron absorber, the difference between atomic numbers (squared) makes the aluminum the preferred shield because of X-radiation production.

Positron Shielding. Positions are equal in mass to beta particles and electrons, but are oppositely charged. They produce ionizations similar to their negative counterparts. However, an additional problem is involved in that, as the positron slows down, it unites with an orbital electron, and an annihilation reaction takes place. Two gamma photons are produced with energies of 0.5 mev, or, in certain cases under the influence of a massive nucleus, a single 1.0 mev photon is emitted. This annihilation characteristic decreases the positron's range in a material but presents the problem of shielding against the 0.5 or 1.0 mev gamma photons. Hence, the total shielding thickness must be sufficient to stop the gamma photons.

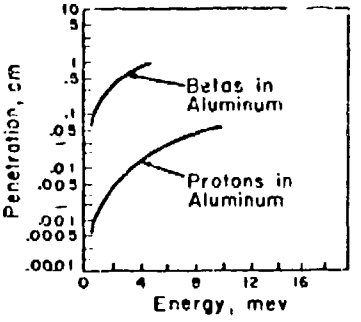


Fig. 5-85. Penetration depth of beta particles and protons in aluminum as function of particle energy.

Proton Shielding. Protons undergo two interactions as they traverse material: nuclear scattering and/or ionization and excitation. The ionization caused by protons is so intense that the ranges of these particles in air are normally only a few centimeters (Fig. 5-86).

The stopping power of materials is sometimes expressed in the number of milligrams per square centimeter required to stop the incident particles. The densities of some materials are listed in Table 5-27. Since the stopping of protons is largely an electronic process, and since the number of electrons per gram of a material does not differ greatly between elements, it might be expected that the shielding power of various elements is constant. In actual cases, however, it takes a much greater amount of lead, in terms of grams per square centimeter, to stop protons than it does aluminum. For example, it takes over one thousand milligrams per square centimeter of lead to stop 20 mev protons, but a little over half this amount of aluminum produces the same effect. The reason for this is that the tightly bound electrons in the inner orbital shells of the heavier elements are not as easily displaced and are therefore less effective in the stopping process. Figure 5-87 indicates the advantage of using low Z materials for shielding against protons.

Neutron Shielding. Neutrons are uncharged and are capable of penetrating materials to great depths. They affect matter either by entering the nucleus or by being sufficiently close to it for nuclear forces to act. Neutrons may be encountered with energies as high as 14 mev. Generally, neutrons are attenuated and finally stopped in a material by the following process: inelastic collision, elastic collision, and then absorption or capture. Fast neutrons interact by inelastic collision with the medium weight nuclei. When the neutron collides with the nuclei of the shield material, it is absorbed, causing the nucleus to recoil and emit gamma radiation and a neutron of less energy. This slow neutron interacts by elastic collision with light weight nuclei, such as those of hydrogenous materials, causing the nucleus to recoil as a proton. The neutron may then be captured. General practice is to use some light material, such as a hydrocarbon, polyethylene, beryllium, or carbon, to slow the fast neutrons by elastic scattering, in order that they may be readily absorbed by materials with high capture cross sections, such as boron, cadmium or lithium. In summary, a neutron shield would probably consist of a laminated structure, such as a hydrocarbon to slow the neutrons; then cadmium or boron to

Table 5-27. Densities of a Few Selected Elements

Element	Atomic number	Density (gm/cm^3)
Carbon	6	1.62
Silver	47	10.5
Cadmium	48	8.6
Uranium	92	18.7
Lead	82	11.34
Iron	26	7.86
Boron	5	3.3
Aluminum	13	2.7

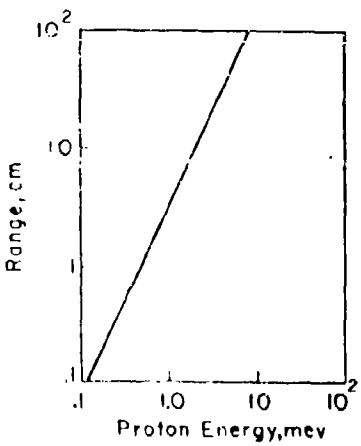


Fig. 5-86. Range of protons in air.

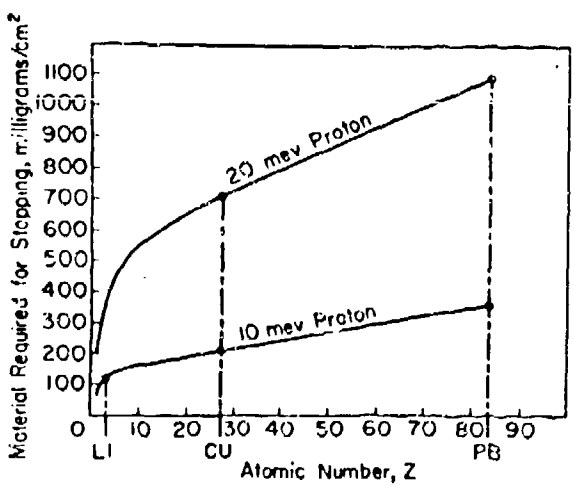


Fig. 5-87. Amount of various materials needed to stop protons.

capture the slowed neutrons; followed by some heavy metal, such as iron, to capture the gamma radiation.

Gamma Shielding. For shielding against gamma radiation, the most effective materials are those consisting of elements having high atomic weights and densitites, such as lead tungsten, thorium, etc. In cases where costs or other factors predominate, iron may be used, but the amount must be increased accordingly. Where weight is a problem, boron or lithium may be used. The probability of gamma radiation being absorbed by the nuclei of atoms is very slight for low energy gamma photons. The shield therefore reduces the intensity of the radiation by some factor. The thickness of a material required to reduce the intensity of gamma radiation by one half is called the half thickness. The use of additional layers will reduce the radiation intensity by one half again. For example, two half thicknesses will reduce the radiation intensity to one fourth, and three layers will reduce the intensity to one eighth. The half thicknesses of various materials are listed in Table 5-28.

HUMAN PROTECTION

Reproducing Natural Environments/52/

The best way to protect the human occupant of a flight vehicle is to simulate his natural environment in the vehicle. For flights within aero space, this does not present too severe a problem. But when outer space flight is contemplated, the problem of human protection becomes difficult to solve. Human factors that should be considered are physical, metabolic and functional requirements.

Table 5-28. Half Thicknesses of Various Materials

Photon energy	Material	Half thickness (cm)
1.0	Lead	1.40
	Iron	2.49
	Concrete	8.1
	Air	1.44×10^4
2.0	Lead	2.15
	Iron	3.61
	Concrete	13.4
	Air	2.37×10^4
5.0	Lead	1.76
	Iron	3.77
	Concrete	17.3
	Air	3.8×10^4

Physical environmental requirements include: pressurization, oxygen control, temperature control, humidity control, ventilation and odor control, illumination, acceleration, radiation protection, and noise and vibration. Metabolic requirements include: food and water intake, dietary supplements and waste disposal. Functional requirements refer to such items as the amount of room crew members need in a vehicle, and human perception or reaction to various instruments. Once these requirements are considered, it then becomes necessary to determine their cost of inclusion. Since weight and proper space utilization is of the utmost importance in vehicle design, the cost might be considered in terms of pounds and cubic feet. /53/

Physical Environment. Some idea of the weight involved in cabin pressurization, and the control of oxygen, temperature, odors and noxious gases can be obtained from existing equipment. However, it may be assumed that technological advances in materials and design will lower the equipment weight for manned vehicles. It appears that, exclusive of the pressure vessel that houses him, man's physical environment may be controlled with about 100 pounds of equipment per day.

Controlling the radiation hazard in a manned vehicle is another problem. Since certain chemicals in the body are more sensitive to radiation than others, a means might exist for increasing radiation resistance through the use of drugs. Cysteine, for example, may tend to increase man's radiation resistance. The alternative would be providing radiation shielding for each crew member in the form of suits or capsule-like chambers. The shields or chambers would add a minimum of 100 to 200 pounds per crew member and might be prohibitively high in terms of weight.

Metabolic Requirements. Man's most critical need is his oxygen supply; next is his water intake; and lastly, the solid elements in his diet. For relatively short duration flights, the gaseous, liquid and solid needs of the crew may not create a problem because they can be supplied through storage. As flight duration increases beyond a time period of one day, weight and space become critical, so that greater reliance must be placed on recycling the body's waste products.

Functional Requirements. Recent developments in miniaturization techniques make it possible to supply the vehicle's crew with compact or integrated instruments for communication, orientation and computing purposes. For space flights, each crew member will require approximately 350 cubic feet of working space.

Human Tolerances

Pressurization./54,55/ Since, in many instances, it may not be practical to simulate man's natural environment precisely, the environment within a vehicle may be controlled only within a certain range that approximates man's natural environment. This will often allow simpler design, lower cost and less weight. However, the extreme ranges of these environments must never be allowed to exceed man's limitations. The sealed pressurized cabin does not necessarily have to be a single living space, but rather each crew member could have his own individual compartment or capsule. The normal or ideal pressure is 760 mm of Hg, and the lowest barometric pressure that a human can tolerate without decompression sickness is approximately 380 mm of Hg. The pressure should be somewhere between these limits, with the minimum pressure not lower than 500 mm of Hg. A secondary pressurization system should also be provided in case an emergency develops during the flight.

Oxygen Control. /56/ A crew member uses about 0.9 cubic foot of oxygen each hour. For space flight, the oxygen can be stored as either a liquid or a compressed gas. However, careful attention must be given to the design of a liquid oxygen storage tank to insure uninterrupted supply during weightless conditions. Since man may develop some secondary physiological effects due to extended exposure to a pure oxygen atmosphere, a mixture of oxygen and nitrogen may be desirable, depending on the partial pressure of oxygen and fire hazards.

Temperature and Humidity Control. /53/ One man will release about 12,000 Btu of heat per day, about 20 percent of which will be in water vapor. The rate may vary from 240 Btu per hour while sleeping to 800 Btu per hour during light exercises. The cabin temperature should be cooled and maintained between 70 and 80 F (21 and 27 C), with relative humidity between 40 and 80 percent. The worst period of temperature control will be during a reentry phase.

The best method of humidity control is by condensation of the water vapor generated by crew members and their activities. Figure 5-88 shows the approximate human time-tolerance as a function of both temperature and humidity. The hatched curves in Fig. 5-88 are the transition areas between safe and unsafe areas.

Ventilation and Odor Control. /52, 57/ Odors emanating from the human body, as well as volatile and toxic fumes, must be removed, and proper ventilation must be supplied to maintain a tolerable environment. Activated charcoal can be used to absorb many of the organic gases, including those emanating from the human body. For ventilation around crew members, a velocity of 40 to 80 feet per minute around the face, and about 40 feet per minute over the remainder of the body is sufficient for a comfortable environment.

Illumination. /5, 10/ The average general illumination should be approximately 50 foot-candles, with wavelengths between 440 and 680 millimicrons. The daily cycle should be maintained in a space flight vehicle. To simulate man's natural environment, the level of illumination should be reduced at night, and at noontime it should be raised to the highest level.

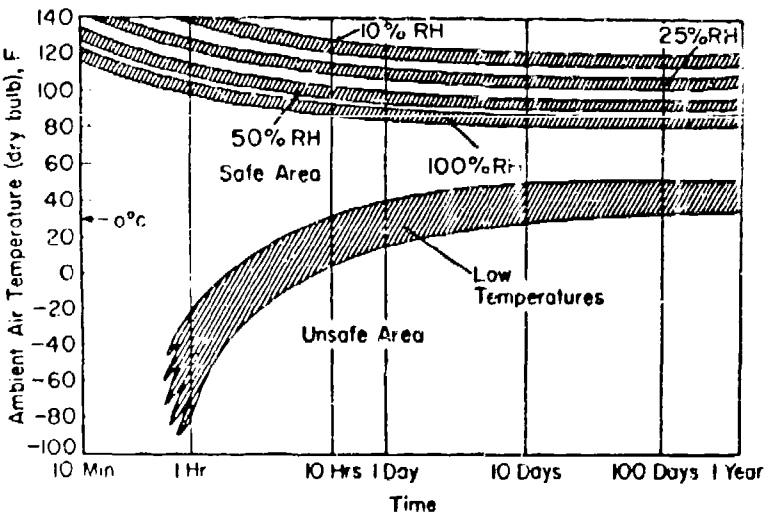


Fig. 5-88. Approximate human time-tolerance as function of temperature and humidity./53/

Acceleration. /11/ For positive acceleration, man in a supine position can tolerate 15 g's for 5 seconds, 10 g's for 125 seconds and 5 to 6 g's for 330 seconds. Higher g-levels for longer durations can be tolerated if the man is in a semi-supine position. The problem of negative acceleration is greater, but a comfortable tolerance level can be achieved by proper vehicle design.

Radiation Protection. /58, 59/ From all available data, man's exposure to cosmic and X-ray radiation above 100 miles appears to be within the present acceptable exposure of 0.3 Rem per week. Except for solar flares and unforseen problems, solar radiation presents no problem to man in outer space. Additional protection against radiation in the form of a lead shield 1 mm thick, either incorporated in the crew member's pressure suit or covering the space vehicle, may provide 6 months protection against expected forms of cosmic radiation.

Noise and Vibration. A maximum of 40 decibels is the normal operational noise limit for man. However, the limits for performance of complicated tasks varies for each individual. Various methods and devices can be used for protecting the individual crew member against excessive noise. They are: controlling the noise at or near the source; development of remote control mechanisms and protective structures for crew members; and finally, use of ear plugs. Vibration will present no problem to the vehicle crew if it does not exceed 0.16-inch double amplitude at a frequency under 23 cps.

Food and Water Intake. /52/ For extended flights, each crew member requires 3000 calories per day or approximately 1.5 pounds per day per man of solid food. To conserve weight, the food should be stored in a dehydrated condition. Approximately 2500 cubic centimeters or 0.66 gallon of water are required per day per crew member for internal consumption. Hygienic needs per crew member are small for short duration flights, but are approximately 15,000 cubic centimeters or 4 gallons per day for longer flights. However, with the use of recycling water systems, 100 to 200 pounds of water per man will be adequate for the longest space flights.

Waste Disposal. /11/ For short flights, human waste products will probably be stored aboard the vehicle. The waste products consisting of urine, wash water and feces must be collected in a sanitary fashion. On longer flights, the liquid waste products can be purified and reused. The recycling of liquid waste products may be accomplished through distillation, chemical process and sublimation.

REFERENCES

1. Grundfest, Irving, "Plastics for Nose Cones," SAE Journal, November 1958.
2. Javits, A. E. and Paul G. Jacobs, "Electronic Materials and Components for Extreme Environmental Problems," Electrical Manufacturing, Vol. 62, No. 5, November 1958.
3. Marshall, R. F. and P E. Ritt, "Inorganic Loading of Teflon for Improved Thermal Properties," Electronic Equipment Engineering, September 1955.
4. "Preview of Space Metals," Metal Progress, October 1958.
5. Lucks, C. F., J. Matolich and J. A. Van Velzor, The Experimental Measurement of Thermal Conductivities, Specific Heats and Densities of Metallic, Transparent and Protective Materials, Part III, AF Technical Report No. 6145, ASTIA Document No. AD 95406, Battelle Memorial Institute, Contract No. AF 33(616)-311, Project No. 1367, Task No. 61299, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1954.
6. Ballard, James W., Electronic Materials at Elevated Temperatures, WADC TN 57-211, ASTIA Document No. AD 132104, Electronic Components Laboratory, Project 4150, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1957.
7. "Heat Expansion of Materials," Electronics, McGraw-Hill Publishing Co., Vol. 32, No. 22, 29 May 1959.
8. Henney, Keith, Craig Walsh and Harry Mileaf, Electronic Components Handbook, Volumes 1, 2 and 3, McGraw-Hill Book Company, Inc., 1959.
9. Goldberg, Morton E. and Harlan G. Hamre, Electronic Components Parts Research for 500 C Operation, Part I, WADC TR 57-382, ASTIA Document No. AD 142350, Armour Research Foundation, Contract No. AF 33(616)-3549, Project No. 4155, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, February 1958.
10. Torgeson, W. L., H. C. Johnson and N. B. Wright, Jr., Engineering Study of Air Conditioning Load Requirements for Aircraft Compartments, WADC TR 55-254, ASTIA Document No. AD 90530, Research Incorporated, Contract No. AF 33(616)-2261, Project No. 6146, U. S. Air Force, ADS, Wright-Patterson Air Force Base, Ohio, June 1955.
11. Handbook of Methods of Cooling Air Force Ground Electronic Equipment, RADC-TR-58-126, ASTIA Document No. 148907, U. S. Air Force, RADC, Griffiss Air Force Base, N. Y., June 1959.

12. Welsh, James P., Design Manual of Methods of Forced Air Cooling Electronic Equipment, Report No. HF-845-D-19, Cornell Aeronautical Laboratory, Inc., Cornell University, Contract No. NObsr 63043, Bureau of Ships Index No. NE-111611, Sub-Task 3, June 1958.

13. Lopatin, Irving and Harry Mileaf, Design Factors for Aircraft Electronic Equipment, WADC TR 56-148, ASTIA Document No. AD 142204, Contract No. AF 30(635)-2844, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1956.

14. Zimmerman, R. H. and W. Robinson, Equipment Cooling Systems for Aircraft, WADC TR 54-359, Part 2, ASTIA Document No. AD 93161, Part 3, ASTIA Document No. AD 93398, The Ohio State University Research Foundation, Contract No AF 33(616)-147, Task No. 61181, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, September 1954.

15. Riley, Frank C., Jr. and Paul F. Walker, Temperature Criteria for Airborne Equipment, WADC TN 55-96, Booz, Allen and Hamilton, Contract No. AF 33(616)-2689, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

16. Hess, Robert W., Robert W. Fralich and Harvey H. Rubbard, Studies of Structural Failure Due to Acoustic Loading, National Advisory Committee for Aeronautics, Technical Note 4050, Langley Aeronautical Laboratory, Langley Field, Va., July 1957.

17. Riley, C. Frank, Jr. and Fred W. Schwartz, Jr., Acceleration, Shock and Vibration Criteria for Aircraft and Airborne Equipment, Booz, Allen and Hamilton, WADC TN 55-99, Contract No. AF 33(616)2378, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

18. Jacobson, Robert H., Vibration and Shock Evaluation of Airborne Electronic Component Parts and Equipment, Armour Research Foundation, WADC TR 56-301, ASTIA Document No. AD 123658, Contract No. AF 33(616)-223, Project No. 4157, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1956.

19. Barbiere, Robert E. and Wayne Hall, Electronic Designer's Shock and Vibration Guide for Airborne Applications, RCA Service Company, WADC TR 58-363, ASTIA Document No. AD 204095, Contract No. AF 33(616)-3257, Project No. 4157, Task No. 41572, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1958.

20. Markowitz, J., "Shock or Vibration Isolators?", Product Engineering, June 1953.

21. Gardner, Annesta R., "Fungi Are Your Product Problem," Product Engineering, 18 January 1960.

22. Greathouse, C. A. and C. J. Wessel, Deterioration of Materials, Causes and Preventive Techniques, Reinhold Publishing Corporation, 430 Park Ave., N. Y., 1954.

23. Riley, C. F. Jr. and P. F. Walker, Moisture Criteria for Aircraft and Airborne Equipment, WADC TN 55-97, Booz, Allen and Hamilton, Directorate of Laboratories, Contract No. AF 33(616)2688, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

24. Blake, John T. and Donald W. Kitchin, Industrial Engineering Chemistry, Vol. 41, pages 1633-1641, 1949.

25. Blake, John T., Donald W. Kitchin and Orison S. Pratt, Electrical Engineering, Vol. 69, pages 782-787, 1950.

26. ZoBell, Claude E., Bacteriological Reviews, Vol. 10, pages 1-49, 1946.

27. ZoBell, Claude E. and Josephine D. Beckwith, Journal of American Water Works Association, Vol. 36, pages 439-453, 1944.

28. Blake, John T., Donald W. Kitchin and Orison S. Pratt, The Microbiological Deterioration of Rubber Insulation, American Institute of Electrical Engineers, New York City, Technical Paper 53-59, December 1952.

29. Fungus Growth on Rubber, Neoprene and Butadiene-Acrylonitrile Type of Synthetic Elastomer, BL-41, duPont de Nemours (E.I.) and Company, Wilmington, Del., May 1942.

30. Stief, J. L., and J. J. Boyle, Industrial Engineering Chemistry, Vol. 39, pages 1136-1138, 1947.

31. Dawson, T. R., Journal of Rubber Research, Vol. 15, pages 1-9, 1946.

32. Vanderbilt News, Vol. 15, (3) page 3, 1949.

33. Mildew and Fungus Resistance of Rubber and Neoprene Coated Fabrics, BL-66, duPont de Nemours (E. I.) and Company, Wilmington, Del., January 1943.

34. Allen, Fraser H., The Biological Deterioration of Thiokol Linings for Gasoline Storage Tanks, U. S. Naval Research Laboratory Report P-2902, 1946.

35. Handbook of Instructions for Ground Equipment Designers Part A-General, Chapter 3, AF Contract 33(616)-2497, RDO 657-442, 28 December 1954.

36. Reference Data for Radio Engineers, Fourth Edition, 1956, International Telephone and Telegraph.

37. Abstract of Effects of Moisture on Guided Missile Systems, Appendix B, AF TR 53-124, Booz, Allen and Hamilton, 1 June 1953.

38. "Environmental Testing, Part II," Electromechanical Design, Vol. 3, No. 6, June 1959.

39. An Investigation of Fundamental Circuit Factors Which Influence Spurious Response and the Generation of Spurious Radiation, Final Report, The Electro-Mechanics Company, 6 December 1955.

40. Riley, F. C., Jr and P. F. Walker, Atmospheric Contaminant, Radiation, and Electricity Criteria for Aircraft and Airborne Equipment, WADC TN 55-118, ASTIA Document No. AD 92498, Booz, Allen and Hamilton, Contract No. AF 33(616)-2689, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

41. Pauly, J., The Dust Environment and its Effect on Dust Penetration, WADC TR 56-556, ASTIA Document No. AD 110472, Contract No. AF 33(616)-3280, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, September 1956.

42. General Environmental Criteria for Guided Missile Weapon Systems, U. S. Air Force Specification Bulletin No. 106 A, 18 March 1957.

43. Bodenholzer, R. A., I. B. Fieldhouse, T. E. Wateman and J. Yampolsky, Study of High-Energy-Air Anti-Icing Systems for Flight Surfaces, WADC TR 54-35, ASTIA No. AD 43759, Armour Research Foundation, Illinois Institute of Technology, Contract No. AF 18(600)-195, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1953.

44. Segin, H. H., A Design Manual for Thermal Anti-Icing Systems, WADC TR 54-313, ASTIA Document No. AD 90156, Illinois Institute of Technology, Contract No. AF 33(616)-444, IIT Project No. 6066, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1954.

45. Knoernschild, E. M. and L. V. Larson, Defrosting of High Performance Fighter Aircraft, AF TR 6118, ASTIA Document No. AD 90759, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1950.

46. Dornbrand, H., Infrared Defrosting and Deicing, AF TR 5874, ASTIA Document No. AD 47410, Republic Aviation Corporation, Contract No. AF 33(038)-12917, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, January 1953.

47. Hasinger, S. H. and L. V. Larson, Infrared Heating for Anti-Icing, De-Icing and Defrosting of Aircraft Transparent Areas, AF TR 6113, ASTIA Document No. AD 79631, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1950.

48. Di Taranto, R. A. and J. J. Lamb, Preliminary Investigation of Hyper Environments and Methods of Simulation, Part I, Natural and Induced Environments Above 75,000 Feet, WADC TR 57-456, ASTIA Document No. AD 142002, Radio Corporation of America, Contract AF 33(616)-3915, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, July 1957.

49. Aircraft Protection from Atmospheric Electrical Hazards, 8th Interim Report, Lightning and Transients Research Institute, Contract No. AF 33(616)-3391, U. S. Air Force and Navy Bureau of Aeronautics, April 1959.

50. Aircraft Protection from Atmospheric Electrical Hazards, WADD TN-60-34, Lightning and Transients Research Institute, Contract No. AF 33(616)-3991, Project No. 8(77-4357), U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1959.

51. WADC TR 52-35 and supplements 1 to 4, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

52. Wolbers, H. L., Human Factors Design Requirements for Manned Satellite Vehicles -- A Survey of Equipment Requirements, ASME Paper Number 59-AV-14, presented at Aviation Conference, Los Angeles, California, 9-12 March 1959.

53. Dole, S. H., Environmental Requirements for Extended Occupancy of Manned Satellites, ASME Paper Number 59-AV-12, presented at Aviation Conference, Los Angeles, California, 9-12 March 1959.

54. Nau, R. A., Environmental Control Systems for Manned Space Vehicles, ASME Paper Number 59-AV-11, presented at Aviation Conference, Los Angeles California, 9-12 March 1959.

55. Kendricks, E. J., "Men Are Now Flying in Space, Medical Problems of Space Flight," Instructors Journal, ASTIA Document No. AD 159052, Publication of the Air Training Command, Air University, USAF School of Aviation Medicine, Randolph Field, Texas, August 1955.

56. Strughold, H., "Living Room In Space, Medical Problems of Space Flight," Instructors Journal, A Publication of the Air Training Command, Winter 1954, Air University, United States Air Force School of Aviation Medicine, Randolph Field, Texas, ASTIA Document No. AD 159052, August 1955.

57. Hickey, A. E., Jr., The Nuclear Submarine as a Manned Satellite Laboratory, ASME Paper Number 59-AV-9, presented at Aviation Conference, Los Angeles, California, 9-12 March 1959.

58. Cacioppo, A. J., Psycho-Physiologically Centered Space-Vehicle Design, ASME Paper Number 59-AV-13, presented at Aviation Conference, Los Angeles, California, 9-12 March 1959.

59. Halloweli, D., D. H. Eldredge, A. Glorig, E. B. Newman, H. O. Parrack and C. P. Phoebus, High-Intensity Noise and Military Operations, ASTIA Document No. AD 45872, Contract NONR-1151(01), Project NR 140-069, Armed Forces National Research Council Committee on Hearing and Bio-Acoustics, January 1954.

BIBLIOGRAPHY

A Mission Oriented Analysis of Aircraft Icing, The American Power Jet Company, WADC TR 55-263, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1955.

A Mission Oriented Analysis of Aircraft Icing -- An Extension of Methodology, The American Power Jet Company, WADC TR 57-60, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1 June 1959.

A Proposed Refrigeration Unit for Space Vehicles, Progress Report No. 1, Enclosure No. 3, Republic Aviation Corporation, System Requirement 123, February 1959.

A Study of the Performance of Aircraft Air-Cycle Refrigeration Units with Internally Controlled Turbomachine Components, WADC TR 56-58, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Abstract of Effects of Atmospheric Pressure on Guided Missile Systems, Appendix C., Booz, Allen and Hamilton, AF TR 53-124, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1953.

Adams, C. C., "Nutrition in Space Flight," Missiles and Rockets, November 1957.

Air Conditioning of Aircraft at High Altitude, SAE Aeronautical Information Report No. 33A.

Airplane Air Conditioning Engineering Data, Thermodynamics, SAE Aeronautical Information Report No. 25.

Airplane Air Conditioning Engineering Data, Heat Transfer, SAE Aeronautical Information Report No. 24.

Airplane Heating and Ventilating Equipment Engineering Data, Fluid Dynamics, SAE Aeronautical Information Report No. 23.

American Standard Acoustical Terminology (Including Mechanical Shock and Vibration), No. S1.1-1960, American Standards Association, Sponsor -- Acoustical Society of America, approved 25 May 1960.

Artificial Cabin Atmosphere Systems for High Altitude Aircraft, WADC TR 55-353.

Bakanauskas, S., Resistance of Microorganisms to High Vacuums, WADC TN 59-142, Materials Laboratory, Project No. 7312, Task No. 73128, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1959.

Bateman, J. T., A Solid Rotor A. C. Generator for High Temperature Electrical Systems, Paper No. 59-848, presented at AIEE Summer and Pacific General Meeting and Air Transportation Conference, Seattle, Washington, 21-26 June 1959.

Benjamin, F. B. and O. Bailey, The Effect of Seating and Changes in Blood Flow on the Heating of the Human Skin, Report No. NADC-MA-5510, ASTIA Document No. AD 75722, Aviation Medical Acceleration Laboratory, Bureau of Medicine and Surgery, Project NM 001-103-301, Report No. 6, U. S. Naval Air Development Center, Johnsville, Pennsylvania, 30 August 1955.

Bishop, F. C., "Space Age Materials," The Tool Engineer, August 1958.

Bolt, R. H., L. L. Beranek and R. B. Newman, Handbook of Acoustic Noise Control, Volume I, Physical Acoustics, WADC TR 52-204, ASTIA Document No. AD 12015, Bolt, Beranek and Newman, Contract No. AF 33(038)-20572, RDO No. 695-83, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, December 1952.

Bradley, C. D., Bearing Systems for High Temperature Aircraft Generators, Paper No. CP 59-865, presented at AIEE Summer and Pacific General Meeting and Air Transportation Conference, Seattle, Washington, 21-26 June 1959.

Butz, J. S., "Hypersonic Aircraft Will Face Technical Problems," Aviation Week, Vol. 70, No. 25, 22 June 1959.

Cabin Air Moisture Removal, AF TR 5887.

Conner, J.C., "AF Pushes Beryllium Studies," Aviation Age, September 1958.

Control of Odors in Evacuation Aircraft, AF TR 6565.

Cooling Methods and Equipment for Supersonic Aircraft, WADC TR 57-619.

De Biasi, V., "Radiation-Tolerant Electronic Materials," Aviation Age, August 1958.

"Design Techniques for Interference-Free Operation of Airborne Electronic Equipment," Frederick Research Corporation, AF Contract 33(038)-23341.

Dixon, F. and J. L. Patterson, Determination of Accelerative Forces Acting on Man and in the Human Centrifuge, ASTIA Document No. AD 39383, U. S. Naval School of Aviation, Naval Air Station, Pensacola, Florida, Project No. NM 001 059.04.01, 1 July 1958.

Drushel, H. V. and D. J. Toft, Quantitative Determination of Fluorinated Fungicidal Agents in Air Force Material, WADC TR 58-59, ASTIA Document No. AD 155524, Mellon Institute, Contract No. AF 33(616)-3998, Project No. 7360, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1958.

Eckert, E. R. G. and Robert M. Drake, Jr., Heat and Mass Transfer, McGraw-Hill Book Company, Inc., 1959.

Effects of Cabin Atmospheres on Fire Hazards, WADC TR 59-456, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Electronic Interference Analyzer, A series of bulletins published by the General Engineering Laboratory, Electronic Development Division, Rome Air Development Center, Rome, N.Y.

Equipment Cooling in Present and Immediate Future Civil Transport Aircraft, SAE Aeronautical Information Report No. 64.

Equipment Cooling Systems for Aircraft, WADC TR 56-353, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Evans, J., "Vibration and Acoustical Problems in Missiles," Noise Control, Vol. 4, No. 6, November 1958.

Frederick, J. K., Jr., R. E. Otto and D. H. Pfister, Evaluation of Fungicidal Vinyl Coated Cotton Duck, WADC TR 57-366, ASTIA Document No. AD 155686, Lowell Technological Institute Research Foundation, Contract No. AF 33 (616)-3929, Project No. 7312, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1958.

Gazley, C., Jr., W. W. Kellogg and E. H. Vestine, Space Vehicle Environment, RAND Report No. P-1335, The RAND Corporation, 1700 Main Street, Santa Monica, California, 7 July 1958.

Geankoplis, C. J., W. B. Kay, A. W. Lemmon and W. Robinson, Heat-Transfer Fluids for Aircraft-Equipment Cooling Systems, WADC TR 54-86, ASTIA Document No. AD 50566, The Ohio State University Research Foundation, Contract No. AF 33(616)-147, RDO No. 664-803, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, February 1954.

Goldberg, M. E., H. G. Hamre and R. D. Noble, Electronic Component Parts Research for 500 C Operation, Part II, ASTIA Document No. AD 132118, Armour Research Foundation, Contract No. AF 33(616)-3549, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1957.

Gordon, S. A., The Selection of Materials for High-Temperature Applications in Airframes, Titanium Metallurgical Laboratory, Battelle Memorial Institute, Columbus 1, Ohio, ASTIA Document No. AD 69675, 5 August 1955.

Greiner, L., J. Rabinowitz and A. Zuckerman, Performance Estimation of the Coolant-Fuel System, AFOSR TR 58-43, ASTIA Document No. AD 154150, Odin Associates, Contract No. AF 18(600)-1501, Directorate of Advanced Studies, ARDC, Pasadena, California, December 1957.

Guide Manual of Cooling Methods for Electronic Equipment, NAVSHIPS 900,190, Bureau of Ships, Navy Department, March 1955.

Hamilton, F. L., A Compilation of Data from Evaluations of the Fungus Resistance Properties of Air Force Materials, WADC TR 55-72, ASTIA Document No. AD 75796, Materials Laboratory, Project No. 7312, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1955.

Hann, J. P., and J. F. Scoville, Component Parts Status for 600 F Aircraft Generator Control, Paper No. CP 59-906, presented at AIEE Summer and Pacific General Meeting and Air Transportation Conference, Seattle, Washington, 21-26 June 1959.

Heat Storage Cooling of Electronic Equipment, WADC TR 56-473, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Henschel, L. H., "Electronic Hardware," Electronic Industries, Vol. 18, No. 9, September 1959.

High Velocity Filter Design, WADC TR 55-457.

Hoffman, George A., Materials for Space Flight, The RAND Corporation, Report No. P-1420, 1700 Main Street, Santa Monica, California, July 1958.

Ingram, W. T., Orientation of Research Needs Associated with Environment of Closed Spaces, AFOSR TN 58-106, ASTIA Document No. AD 152015, presented before a meeting of American Astronautical Society in New York, 30 January 1958.

"Interference Fields About Aircraft," Phases I and II, Lightning and Transients Research Institute, Contract Nos. AF 18(600)-183 and AF 33(038)-17622.

Investigation of Aircraft Ducting Components at High Subsonic Speeds, WADC TR 56-187.

Islinger, J. S., Engineering Design Factors For Laminated Aircraft Windshields, Part 1, Delineation of Design Factors, WADC TR 53-69, ASTIA Document No. AD 51601, Armour Research Foundation, Illinois Institute of Technology, Contract No. AF 33(038)-6429, E. O. No. 664-771, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1954.

Jaller, R. W. and J. M. Ciccotti, Aircraft Operation in Icing Weather, The American Power Jet Company, WADC TN 55-226, ASTIA Document No. AD 80238, Contract No. AF 33(616)-2605, Project No. 1111, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, June 1955.

Jakob, Max, Stothe P. Kezios, Carleton H. Paul, Robert L. Rose and Karl Bruegmann, Aircraft Windshield Heat and Mass Transfer, AF TR 6120, Part I, ASTIA Document No. AD 93866, Illinois Institute of Technology, Contract No. W 535-ac-40626(10520), RDO No. 664-751, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1955.

Javitz, A. E. and P. G. Jacobs," Electronic Materials and Components for Extreme Environmental Problems," Electrical Manufacturing November 1958.

Kemp, N. H., and F. R. Riddell, Heat Transfer to Satellite Vehicles Re-entering the Atmosphere, ARDC Research Report No. 2, ASTIA Document No. AD 150546, Avco Research Laboratory, Contract No. AF 04(645)-18, Air Research and Development Command, October 1956.

Kline, D. D. and J. A. Walker, Meteorological Analysis of Icing Conditions Encountered in Low-Altitude Stratiform Clouds, TN 2300, Lewis Flight Propulsion Laboratory, Cleveland Ohio, March 1951.

Lane, Arthur F., Study, High Performance Cabin Cooling Unit, WADC TR 54-389, ASTIA Document No. AD 95419, Fairchild Engine & Airplane Corporation, Contract No. AF 33(600)-23989, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1954.

Lapp, R. R., D. H. Thorpe, R. H. Stutzman and N. E. Wahl, The Study of Erosion of Aircraft Materials at High Speeds in Rain, Part 1, WADC TR 58-185, ASTIA Document No. AD 155501, Cornell Aeronautical Laboratory, Contract No. AF 33(616)-2758, Project No. 7340, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1958.

Lear, Robert E., Development Study of a Titanium Air-to-Air Heat Exchanger, WADC TR 54-453, ASTIA Document No. AD 151156, Surface Combustion Corporation, Contact No. AF 33-(616)-2245, Project No. 54-670-036, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1958.

Little, E., An Evaluation of Fungicidal Treatments in Cotton Cargo Parachute Webbings Stored At College, Alaska, Part II, WADC TR 56-384, ASTIA Document No. AD 155857, Materials Laboratory, Project No. 7312, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, August 1958.

Lowe, Russell T., The Role of Damping in Structural Design, Barry Report No. 370, Barry Controls Incorporated, Watertown 72, Massachusetts, April 1959.

Lucks, C. F., H. B. Thompson, A. R. Smith, F. P. Curry, H. W. Deem and G. F. Bing, The Experimental Measurement of Thermal Conductivities, Specific Heats, and Densities of Metallic, Transparent, and Protective Materials, Part I, USAF Technical Report No. 6145-1, ASTIA Document No. AD 117715, Battelle Memorial Institute, February 1951.

Macdonald, J. A. and B. L. Rigney, Jr., Test Evaluation of External Air Blast Air Foil Anti-Icing Method, WADC TR 55-148, ASTIA Document No. AD 95577, The Glenn L. Martin Company, Contract No. AF 33(616)-2648, U. S. Air Force, ASD, Wright-Patterson Air Force Base, March 1955.

Mason, J. L., W. L. Burriss and T. J. Connolly, Vapor-Cycle Cooling for Aircraft, WADC TR 53-338, ASTIA Document No. AD 62383, Airesearch Manufacturing Company, Contract No. AF 33(616)-2016, RDO No. 664-803, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1953.

Mauch, H. A., J. F. Hall and F. K. Klemm, A Ventilating System for Clothing, WADC TR 55-152, ASTIA Document No. AD 62084, Aero Medical Laboratory Project No. 6330, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1955.

Moder, J. J. and C. W. Stuckey, Evaluation of Fungicidal Treatments for Cotton Fabrics, WADC TR 57-711, ASTIA Document No. AD 151127, Georgia Institute of Technology, Engineering Experiment Station, Atlanta, Georgia, Contract No. AF 33(616)-3867, Project No. 7312, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, April 1958.

Nelson, S. T., A Brief Survey of Cosmic Ray Data with Regard to Space Vehicle Protection, Report No. DV-TR-259, Physics and Astrophysics Section, Research Projects Laboratory, Army Ballistic Missile Agency, Redstone Arsenal, Alabama, 15 April 1959.

Newton, W. S. and C. G. Makrides, Environmental Criteria for Ground Support Equipment, WADC TR 54-113, ASTIA Document No. AD 39436, Contact No. 33(616)-2278, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, May 1954.

Osmanski, Joseph T., Experimental Investigation to Correlate the Recurrence of Fatigue Failures in a Typical Aircraft Structure with Vibratory Amplitude, Cook Electric Company, WADC TR 56-551, ASTIA Document No. AD 110462, Contract No. AF 33(616)-2532, Project 1370, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1958.

Pearson, R. G., The Effects of Motion-Sickness Preventives on Orientation in Space, Report No. 58-7, ASTIA Document No. AD 152815, Air University School of Aviation, U. S. Air Force, Randolph Air Force Base, Texas, November 1957.

Penn, W. B., R. L. Balke and F. M. Precopio, Generator Insulation Systems Development for Hypersonic Aircraft, Paper No. 59-864, presented at AIEE Summer and Pacific General Meeting and Air Transportation Conference, Seattle, Washington, 21-26 June 1958.

Pierro, John J., Design and Development of an Airborne Alternating Current Generation and Distribution System for Use in 600 F Ambients, Paper No. CP 59-902, presented at AIEE Summer and Pacific General Meeting and Air Transportation Conference, Seattle, Washington, 21-26 June 1959.

"Preview of Space Metals," Metal Progress, October 1958.

Schaefer, H. J., Theory of Protection of Man in The Region of The Primary Cosmic Radiation, ASTIA Document No. AD 17902, U. S. Naval Air Station, Pensacola, Florida, Project No. 001 059.13.06, 5 August 1953.

Space Handbook: Astronautics and its Applications, Staff Report of the Select Committee on Astronautics and Space Exploration, U. S. Government Printing Office, Washington, D. C., 1959.

Stalder, Jackson R., "A Survey of Heat Transfer Problems Encountered by Hypersonic Aircraft," Jet Propulsion, Vol. 27, No. 11, November 1957.

Study of Evaporative Heat Transfer in Air-to-Air Heat Exchangers, WADC TR 56-200, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Study of Heat Exchanger Pressure Drop and Ram Air Circuit Parameters, WADC TR 57-612, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Study of Supersonic Radial Compressors for Refrigeration and Pressurization Systems, WADC TR 55-257, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Study of Vapor-Cycle Refrigerants for High Performance Aircraft, WADC TR 56-93, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Teresi, J. D. and C. L. Newcombe, A Study of Maximum Permissible Concentrations of Radioactive Fallout in Water and Air Based Upon Military Exposure Criteria, TR US NRDL-TR-162 NS 083-001, ASTIA Document No. AD 153804, U. S. Naval Radiological Defense Laboratory, San Francisco 24, California, 27 August 1957.

Schaeve, Donald K., Cabin-Air-Conditioning, and Wing Anti-Icing Temperature Control, WADC TR 54-410, ASTIA Document No. AD 66387, The Barber-Colman Company, Contract No. AF 33(038)-27968, RDO No. 664-803, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, July 1954.

Shinn, D. A., Materials-Property-Design Criteria for Metals, WADC TR 58-150, Part I, ASTIA Document No. AD 90286, The Battelle Memorial Institute, Contract No. AF 33(616)-2303, Project No. 7360, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, January 1956.

Sibulkin, Merwin, "Estimation of Turbulent Heat Transfer at the Sonic Point of a Blunt-Nosed Body," Jet Propulsion, Vol. 28, No. 8, August 1958.

Slote, Lawrence and William D. Murray, A Method of Predicting Skin, Compartment, and Equipment Temperatures for Aircraft, WADC TR 53-119, ASTIA Document No. AD 19722, New York University, Contract No. AF 33(616)-122, RDO No. 560-76, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, July 1953.

Smith, P. W., Jr., "Sound-Induced Vibration," Noise Control, Vol. 4, No. 6, November 1958.

Study of Limited-Type Ice Removal and Prevention Systems -- Chemical Phase, WADC TR 55-261, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Study of Limited-Type Ice Removal and Prevention Systems -- Mechanical Phase, WADC TR 55-262, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Teumer, K. A., Electrical Components for a 600 F Control Circuit, Paper No. CP 59-905, presented at AIEE Summer and Pacific General Meeting and Air Transportation Conference, Seattle, Washington, 21-26 June, 1959.

"The Prevention and Elimination of Certain Electrical Interferences in Missiles," General Electric Company Report No. R 53A0511, Schenectady, N.Y.

Turbomachine Dynamics, WADC TR 57-611, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Water-Mist Separation in Cabin Air Conditioning Systems, WADC TR 53-324, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Water Vapor Pump Study, WADC TR 59-254, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Welsh, James P., Design Manual of Natural Methods of Cooling Electronic Equipment, Report No. HF-845-D-8, NAVSHIPS 900,192, Cornell Aeronautical Laboratory, Inc., Contract No. NObsr-63043, Bureau of Ships -- Index No. NE-111611, Sub-Task 2, November 1956.

Wilkes, G. B., Total Normal Emissivities and Solar Absorptivities of Materials, WADC TR 54-42, ASTIA Document No. AD 88066, Massachusetts Institute of Technology, Contract No. W33-038-20486, RDO No. 664-805, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, March 1954.

Wind Tunnel Evaluation of Limited-Type Ice Removal and Prevention Systems, WADC TR 56-413, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

Yeager, C. C. and J. C. Chapin, Development of Effective Non-Toxic Fluorinated Fungicidal Formulations for Cotton Materials, WADC TR 58-303, ASTIA Document No. AD 203525, The Scientific Oil Compounding Co., Materials Laboratory, Project No. 7312, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1958.

CHAPTER 6

ENVIRONMENTAL TESTING

Environmental testing is needed to determine that the flight vehicle and all its equipment will function properly under the natural and induced environments that may be encountered. The test requirements are based on the environmental requirements described in Chapter 4. The environmental extremes determined by an environmental analysis are generally increased to provide a safety factor, or decreased because an operational analysis indicates that the occurrence of the extreme is rare.

The ideal environmental test would expose the system and all its parts to the actual environments for the exact periods they would be encountered during the life of the system. But this is impractical, since (1) the exact environments to be encountered are generally unpredictable, (2) the testing time required would render the system obsolete except for extremely short-life items; and (3) the number of facilities and people required to make the tests would be astronomical.

The most practical environmental test is an accelerated one, which compresses long-term effects into a short period. However, there are various ways of accelerating environmental tests, and a method must be chosen which would not destroy the validity of the test. For example, the sunshine test is accelerated by long-term exposure to the maximum expected solar energy level, instead of increasing the energy to a higher level. This type of environmental test is accelerated in this manner because many materials will withstand a certain maximum solar energy level for prolonged periods, but will deteriorate very rapidly if the test is accelerated by increasing the energy level. On the other hand, the humidity test is accelerated by increasing the temperature and humidity combination above that actually encountered in operation or storage. This provides for greater humidity penetration and for many years has been a standard test for equipment qualification. Past experience proves that equipment passing this type of humidity test is capable of long-term storage or operation in tropical areas. The vibration tests are accelerated by testing at the major resonant frequencies for long periods. This provides some assurance against the resonant frequencies.

Sometimes there is an attempt to reproduce the actual environment in a test chamber, but more often an attempt is made to reproduce the effects that a long period of exposure to an environment has on an item. There is no definitive assurance that a certain period in a test chamber equals a certain storage or operational period, even though many attempts have been made to ascertain such exact correlation. Most environmental tests establish a standard that equipment must meet, and from an environmental standpoint this separates poorly designed items from those of good design.

The effects of all environments encountered, as determined by the environmental analysis, should be considered during the design phase. All materials and components used must be evaluated to see if they have been tested for use under the anticipated environments; and all equipment must pass qualification tests before the flight test program begins in order to minimize the number of failures or malfunctions. During the flight test phase, sufficient environmental instrumentation should be provided to determine whether the earlier predictions of environments to be encountered were realistic. Environmental testing is also required on production samples to assure that the design requirements are not compromised during the production phase. Static climatic tests are accomplished in the Climatic Hangar at Eglin Air Force Base, Florida, on complete weapon systems to determine whether they are satisfactory for flight. Flight tests are then carried out under extreme temperature conditions at the Air Force Flight Test Center, California, as well as in Alaska, to check equipment operation and correct any equipment deficiencies that show up under actual high- and low-temperature operating conditions.

Up to now, single or very simple combinations of environmental tests have been used. However, some research and development on combined environmental testing is presently being carried out, and much more is needed. An ideal test is being sought that could employ either or both of the following methods:

1. Environments could be programmed into a test chamber in the same order and intensity as they are encountered during actual flight.

2. Significant interacting environments could be combined and be of sufficient intensity so that the integrated effects of very long missions or operational lifetimes could be concentrated in a relatively short test time, on the order of 10-, 20-, or 30-to-1, depending of course on the length of the basic missions.

The above tests are generally referred to as mission profile combined environmental tests, and accelerated combined environmental tests, respectively. Equipment, or complete weapon systems, having short mission profiles could then be put through the desired cycle of environmental conditions of a designated mission profile. Long mission profiles might be more adaptable to the accelerated combined environmental tests, since the length of the testing time becomes a problem in the application of the mission profile test.

A combined environmental test must produce effects equal to those produced under single environments before it could be used with equal confidence. An attempt to determine the confidence level for various combined tests must first be made by testing similar items with the combined test and then with the gamut of individual tests; then the results must be correlated. Much effort is required, but eventually combined environmental testing procedures and combined test facilities will be established.

The hyper environments that will be encountered by satellites and space vehicles, and which are not well-defined at the present, should be handled as the atmosphere-associated environments have been handled in the past. The extremes must be clearly defined and their effects on Air Force material determined. If deteriorating effects are expected, applicable testing procedures and testing facilities must be established. An important difference between atmosphere-associated environments and hyper environments in developing environmental technology is that combinations of hyper environments can be made immediately because of the experience presently being gained through research with the atmosphere-associated environments.

TEST REQUIREMENTS

As mentioned previously, environmental testing begins with the basic materials and continues on through components, equipment, subsystems, the complete weapon system and the ground support equipment. The types and severity of tests used during the various stages of development of a particular weapon system are evolved from the environmental criteria set for the system. These environmental criteria, in turn, are arrived at by carrying out environmental and operational analyses (Chapter 4). Once the environmental criteria are determined suitable tests are established, in many cases using the existing military specifications as guides. When using military specifications, it should be noted that the test requirements differ from the design requirements, and to test towards the design requirements instead of the test requirements often results in overtesting of the equipment or component. Materials are tested to determine their resistance to all the environments that may be encountered. Depending largely on its intended use, each type of material is tested under different environments, provided that there is no general test requirement specification available. Components are generally tested to tests specified by MIL-STD-202, "Test Methods for Electronic and Electrical Component Parts." Aeronautical equipment is tested to a number of different specifications, including some that are contractor-prepared. Specification MIL-T-5422 "Environmental Testing, Aircraft Electronic Equipment," is used for testing electronic equipment in accordance with the requirements of specification MIL-E-5400. Specification MIL-E-5272 is the primary specification for testing all aeronautical and associated equipment. Other specifications have been developed from the basic document. The requirements for testing ground support equipment are found in specification MIL-E-4970, "Environmental Testing Ground Support Equipment, General Specification for."

Standard testing procedures do not presently exist for all environments, particularly the hyper environments. Contractors use the applicable standard procedures, modify existing procedures or write new procedures where required; modified or new procedures require the approval of the procuring agency.

The requirements for testing subsystems are essentially the same as those for equipment. Larger facilities are required for subsystem testing and there are no standard requirements designed specifically for subsystems. Contractors are responsible for the development of most weapon systems, and the trend in environmental testing is to qualify complete subsystems, instead of the individual equipments, to the satisfaction of the procuring agency. This though, does not obviate the equipment environmental testing required during development. The flight test program affords the first opportunity to check the operation of the complete weapon system under actual flight conditions. Flight test programs are generally instrumented according to specification MIL-I-5289.

ENVIRONMENTAL TEST INSTRUMENTATION

Instrumentation here refers to all the auxiliary devices used in testing a weapon system and its parts to monitor both the performance of the system and the environmental conditions under which it is performing. The instrumentation can be used to measure vehicle compartment temperatures, or the operating temperatures of detail parts. Other uses include measurements of the vibration spectrum or radiation levels imposed on equipments or certain parts. In essence, the

instrumentation is used to measure all environments of interest, particularly those which the environmental analysis determined to be critical.

The complexity of the instrumentation equipment varies considerably, depending on the system and type of test. A relatively simple system might require only transducers and indicators that personnel can observe. In a complex system, where great numbers of environments are almost continuously monitored, data storage equipment might be used to hold the data for later evaluation. In many cases during flight testing, particularly where there is a chance of losing the data due to destruction of the flight vehicle, provision is made for recovering the stored data by parachute, or the data is continuously telemetered back to ground stations. This is a necessity with one-shot vehicles such as non-recoverable missiles.

Typical Sensing Instruments

Perhaps the most important part in any instrumentation system is the environment sensing device, generally known as a transducer. The sensing device, which converts the environmental phenomena to a form of energy that can be more easily processed and measured, must be the most accurate part of the instrumentation system. The sensing device may provide a visible indication, a sample for analysis, or an electrical signal for data processing. There are many types of sensing devices, designed for a variety of applications. Some typical ones which may be used for the various environments are listed in Tables 6-1 and 6-2. Various vibration pickups and accelerometers are shown in Figs. 6-1 and 6-2, respectively. For further data on environmental sensing devices refer to reference/1/.

FLIGHT TEST INSTRUMENTATION

For accumulating data during vehicle test flights it becomes necessary to provide a means of guaranteeing against the loss of information in the event of a crash. A wide variety of instruments have been employed for recording flight test data. The instruments and techniques used have ranged from the pad and pencil to fully automatic systems. However, emphasis will be placed here on the multichannel photographic oscillograph and the magnetic tape recorder, since these instruments are used extensively in modern recording techniques.

Records of the flight test data may be obtained by two methods. The first method is radio telemetering. The second is termed airborne recording, in which a device capable of making a permanent record of the data is installed in the flight vehicle. At the conclusion of the test flight, the device is recovered from the vehicle and the information is analyzed.

The advantage of the airborne recording method is that the complex radio telemetry link can be eliminated, thus simplifying the entire operation. The advantage of the telemetry method is that the data is obtained during the flight, and therefore the risk of losing it in case of a crash or runaway vehicle is avoided.

Telemetered Data Recording and Processing

The demand for multichannel radio telemetry first arose in the testing of military aircraft of fighter size. The two original requirements of the radio telemeter were (1) to transmit information as to the state of flight of the aircraft (slowly varying data), and (2) to transmit the more rapidly varying data, such as flutter, which the test flight was set up to obtain.

In early systems flight data at the receiving station were displayed in a manner similar to the instrument panel of the aircraft and then photographed. The more rapidly varying data were recorded on an oscillograph. More recently due to the need for rapid data reduction, automatic data reduction methods have been introduced. A diagram of a typical automatic data handling system is shown in Fig. 6-3.

Some data are recorded directly on tape while in flight, some are telemetered to the ground for recording, and some are recorded directly on the ground. The central data processing system reduces all of the recorded data from the many sources. There are two sections to this system. One, called the "quick look" section, reduces the data to the form of oscillographic plots, punched tape or ink traces for visual inspection. This information is not calibrated or corrected, but serves to identify those sections of the data that have significant information and require refinement.

The establishment of a time code on the data allows the significant portions to be automatically identified and reproduced on the digital section of the data processing system. Here, the data are digitized and the necessary corrections and scale factors are applied. The output of the data processing system is available in four general forms:

1. Tabulated data in a form suitable for direct use in reports without a need for further editing or transcribing.

2. Point plots of the corrected data.

3. Magnetic tape in binary form suitable for use by a high-speed digital computer.

4. Punched cards for further statistical and sorting operations, or for entry to a card-programmed digital computer.

Radio telemetry is a complex, highly specialized field in itself, and only a brief, general description is presented here.

Table 6-1. Typical Sensing Devices for Natural Environments

SENSING DEVICE	Pressure	Altitude	Temperature	Gas dissociation	Gas ionization	Chemical composition	Solar radiation	Salt spray •	Wind	Sand and Dust •	Rain	Fog	Dew •	Humidity	Blown snow	Frost •	Sleet •	Hail	Ice •	Ozone •	Static electricity	Lightning	Insects	Fungus	Magnetic field	Aurorae •	Meteoric particles	Marine growth
Barometric device	x																											
Pressure gage	x	x																										
Manometer	x																											
Altimeter		x																										
Surveying devices		x																										
Thermometer			x					x											x									
Thermopile			x					x											x									
Thermoresistive device			x					x											x									
Thermoelectric device			x					x											x									
Bimetallic element			x					x											x									
Dissociation apparatus				x																								
Mass spectrometer				x	x♦	x		x				x																
Ionization detectors					x																							
Analysis apparatus						x		x				x														x		x
Spectograph							x													x								x
Photoelectric device							x																					
Photoemissive device							x																					
Photoconductive device							x																					
Pyrheliometer							y																					
Vane device								x	x	x																		
Anemometer								x	x	x																		
Sieves										x																		
Analytical balance device										x																		
Rain gage											x		x•		x•	x•	x•	x•	x•									
Dew point apparatus													x															
Sling psychrometer								x					x	x														
Hygrometer								x						x														
Wet & dry bulb thermometer								x						x														
Depth gage															x	x			x									
Accumulation analyzer																	x		x									
Inch rule																		x										
Electrometer																					x							
Magnetic devices																						x						
Oscillograph																						x						
Visual magnifier																							x	x				x
Magnetometer																									x			
Microphone																											x	
Masked photocell																											x	
Measuring scale																												x

• Not normally measured.
• May be detected by oxidizing effects on various compounds.
• For measuring water equivalent.
♦ Modified mass spectrometer.

Table 6-2. Typical Sensing Devices for Induced Environments

Sensing Device	Temp.	Acceleration	Mech. vibration	Mech. shock	Zero gravity	Acoustic vibration	Nuclear radiation	Radio interference
Thermometer	X							
Thermopile	X							
Thermoresistive device	X							
Thermoelectric device	X							
Bimetallic element	X							
Optical pyrometer	X							
Spectograph	X							
Strain gages		X	X	X				
Differential transformer		X	X	X				
Piezoelectric accelerometer		X	X	X				
Mass-type accelerometer		X						
Velocity flux pickup			X					
Optical pickup			X					
Mechanical oscillators			X					
Spring-mass accelerometer					X			
Microphone						X		
Sonic analyzer						X		
Vibration meter						X		
Ionization detectors							X	
Photosensitive emulsions							X	
Antenna								X
Field intensity meter								X
Radio test set								X

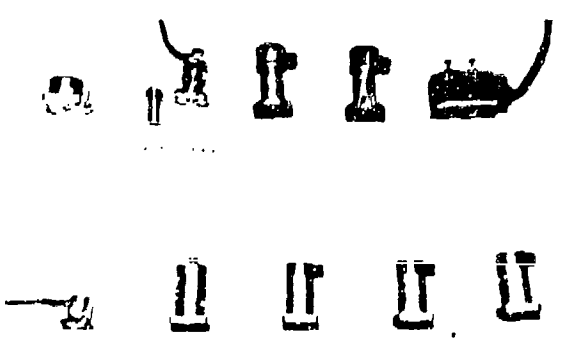


Fig. 6-1. Typical vibration pickups.

There are many types of transducers employed in radio telemetry systems due to the numerous quantities which require measurement. The vibration, shock and sustained acceleration at various positions on a missile are only a few of the variables requiring measurement during flight. In addition, measurements of temperature and pressure, as well as monitoring the performance of the guidance system by means of measuring electrical signals, are of equal or often greater importance. In man-carrying vehicles the data are normally collected magnetically within the vehicle.

Because of the many information channels required, and the fact that it would be inefficient to use a separate radio link for each channel, some method of transmitting several channels on one link is required. This technique is called multiplexing. The two general methods of multiplexing in use are frequency division and time division.

A frequency division system uses a separate subcarrier frequency for each channel. Figure 6-4 is a block diagram of such a system. The subcarrier frequencies are modulated by the information supplied by the transducers, mixed and transmitted. The receiving equipment separates the subcarrier frequencies, demodulates each carrier and records the information.

A time division multiplex system allots a portion of time in a cyclic sequence to each channel. Figure 6-5 is a block diagram of such a system. The information supplied by each transducer is sampled by the commutator, which can either be electromechanical or electronic. These modulated pulses are reproduced at the output of the receiving commutator. Passage of the pulses through the low pass filter allows recovery of the original signal.

Airborne Recording

The early method of obtaining data during flight testing of aircraft was to have the pilot read the control panel instruments and periodically record these indications on a pad strapped to his leg. As the need for more extensive data

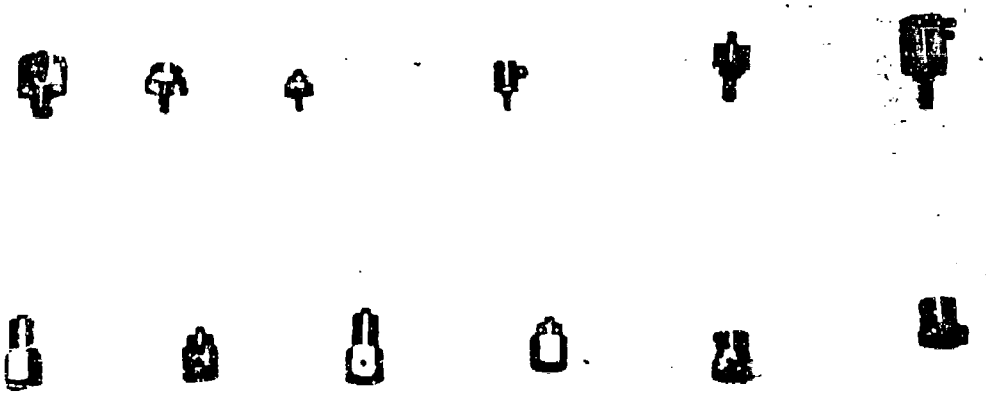


Fig. 6-2. Typical accelerometers.

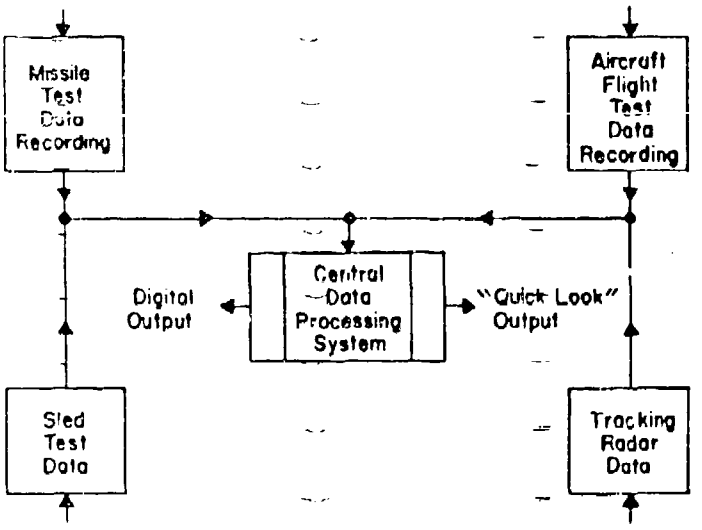


Fig. 6-3. Typical data handling system.

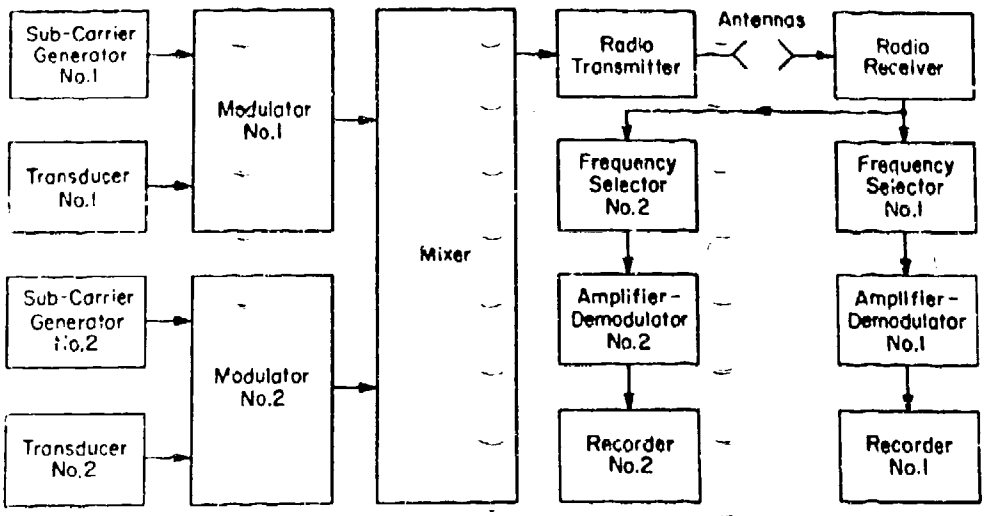


Fig. 6-4. Typical frequency division multiplex telemetry system.

grew, the data on flight quantities such as air speed and altitude were obtained by photographing the cockpit instruments with movie cameras. In order to record the more rapidly varying data, multichannel recording oscillographs have been used. The most extensively used oscillograph recorder employs D'Arsenval galvanometers with mirrors attached to the coils. A permanent magnet supplies the magnetic field. The mirror reflects light from an incandescent light bulb on to a photosensitive film or paper, which is driven at a constant rate at right angles to the plane in which the light beam swings. The light beam swings as a result of rotation of the galvanometer coil. This arrangement is shown schematically in Fig. 6-6. These recorders may have as many as fifty channels. Galvanometer movements are available with natural frequencies in the neighborhood of 3 to 5 kc.

Another, newer method of obtaining the more rapidly varying data is the application of magnetic recording techniques. The tape can be coiled into a small armored drum for those cases where recovery is a problem. The basic elements of the magnetic tape recorder are shown in Fig. 6-7. The electronic coding devices prepare or encode the signal information for optimum recording, and decode it on playback to recover the signal in its original form. The magnetic head, or transducer, converts the electrical signal into a pattern of varying states of magnetization on the tape medium during the recording process. During playback, the transducer reconverts the varying states of magnetization on the tape into an electrical signal. The tape transport drives the tape across the magnetic heads at a constant linear speed.

An attractive feature of the magnetic recorder is that several recording processes are possible: direct, fm, pulse duration and digital. The direct recording process has the widest frequency spectrum, but is subject to amplitude instability due to tape drop-outs caused by imperfection in the tape. With the fm recording process, normal amplitude instabilities will have little or no effect on the recording. This process also has the ability to record low-frequency signals down to dc. Good fm also has the added feature of a dynamic range of 55 db, whereas the direct recording dynamic range is 35 db. The pulse duration modulation recording process is used to record large numbers of slowly varying data signal channels. The digital recording process is used for the processing of edited data involving digital computer techniques, and can be used as an input device, output device and internal storage for digital computers. Probably the best telemetry system is one that combines both the frequency division multiplex telemetry system and the time division multiplex telemetry system. Such a system is shown in Fig. 6-8.

Tape recorders come in various sizes according to the desired application. They may be classified as laboratory recorders, portable recorders, mobile recorders, shipboard recorders and airborne recorders.

Tape Playback and Analysis System

In order to be able to playback and analyze the noise and vibration recordings and to reduce these to frequency and amplitude plots, the Environmental Division, Engineering Test Directorate, Deputy for Test and Support, ASD, Wright-Patterson Air Force Base has recently acquired a playback and analysis system capable of handling any size tape from any recorder.

Space-Research Instrumentation

Satellites and lunar probes have employed many types of instruments and measuring ap-

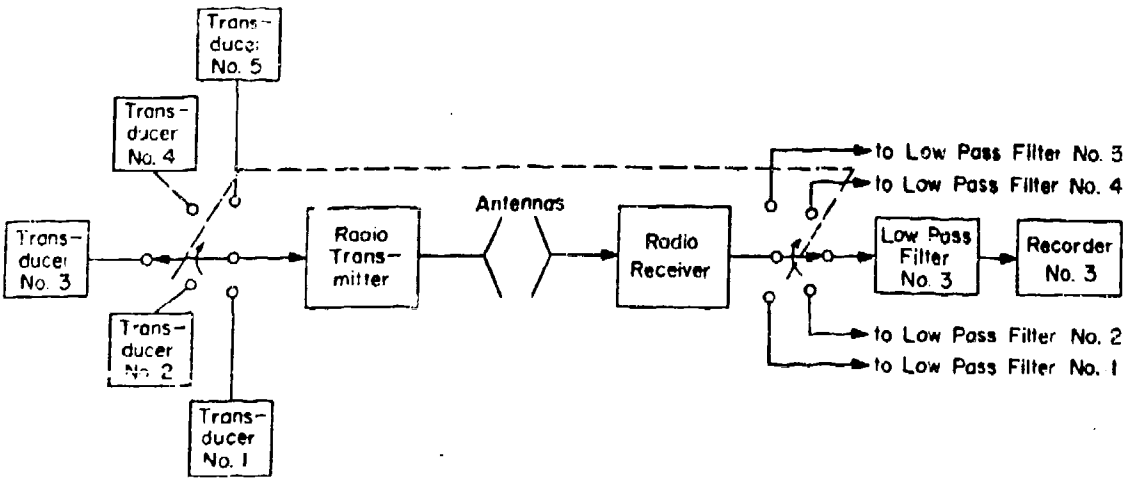


Fig. 6-5. Typical time division multiplex telemetry system.

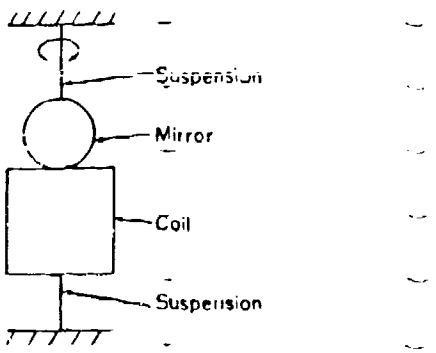


Fig. 6-6. Typical D'Arsenval galvanometer transducer.

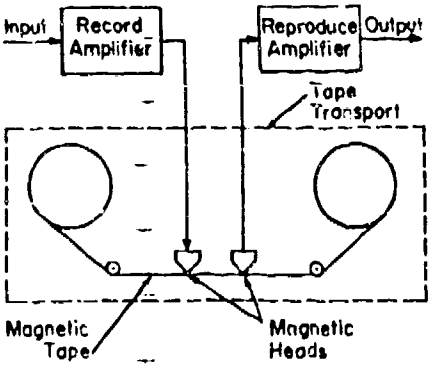


Fig. 6-7. Typical tape recorder system.

paratus to further knowledge of the space environment and its effects on vehicles and equipment. These instruments range from simple thermistors to more complicated Geiger-Mueller counters. In the future, complex television cameras, which already have been used successfully to transmit pictures of the Earth's cloud cover from satellites, will be used to take close-up pictures of the Moon and planets. The instrumentation used in space vehicles must be compact, efficient, reliable and compatible with the telemetry system used with the vehicle. The specific instruments contained in a space vehicle very widely, depending on factors such as the mission of the vehicle, its size, and the power sources available for the instrumentation. Additional information on space-vehicle instrumentation is contained in reference /2/.

Future Trends in Flight Test Instrumentation

It can be concluded that the future trend in flight test instrumentation will lean heavily towards electronics. However, because of inherent resolution limitations in electronic systems, optical systems will still be employed extensively. Therefore, it is probable that sophisticated combinations of electronic and optical systems will be used, with the emphasis on electronics.

The refinement and development of totally electronic omnidirectional trajectory systems will: (1) permit complete independence from atmospheric conditions; (2) improve tracking distances; (3) permit automatic acquisition of targets; (4) reduce the manpower required for

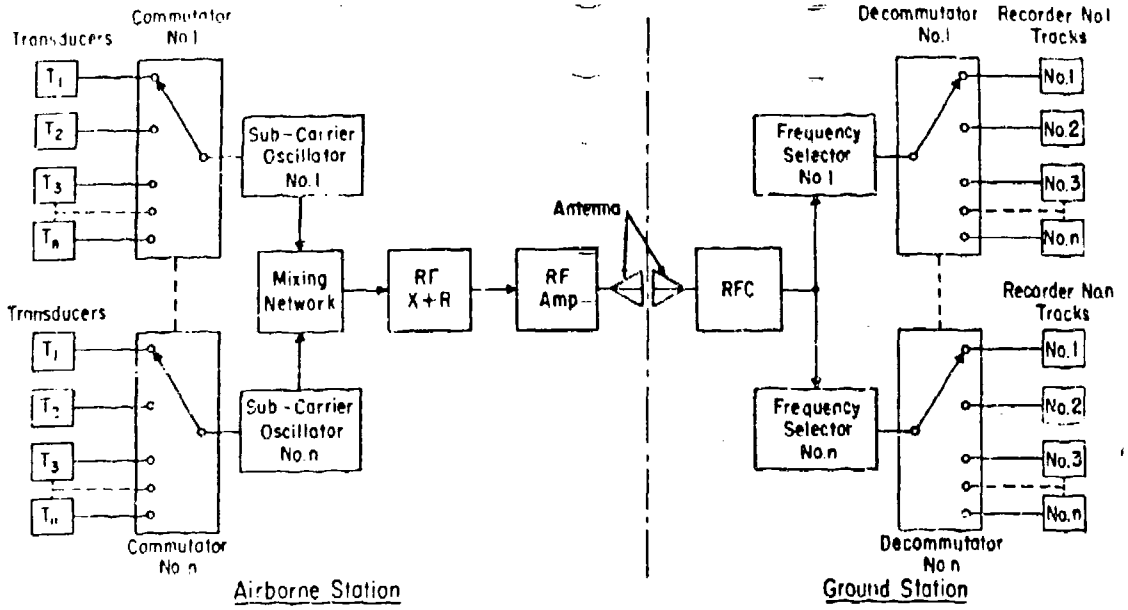


Fig. 6-8. Combination frequency and time division multiplex telemetry system.

instrumentation, even perhaps to the extent of complete remote station operation; and (5) produce electrical data outputs suitable for magnetic recording and subsequent automatic processing, or for real-time computations for test control.

Fully automated theodolites, which dispense with photographic images for attitude, intercept, and event information, can be expected in the future. This instrumentation output will consist of fully digitized azimuth and elevation shaft angles, and digitized tracking error information, which can be fed directly into the computer center

ENVIRONMENTAL SIMULATION AND FACILITIES

In order to make the environmental tests necessary to evaluate flight vehicle systems, facilities for exposing the various equipments to the environments must be available. In choosing to purchase or design an environmental facility, or to rent the use of an existing military or commercial facility, certain information concerning the facility's requirements should be understood by the engineer so that environmental testing can be realistically performed. There are various methods of simulating environments, both in the field and in the laboratory. There are also many important factors concerning the facility's instrumentation, general design and location.

Laboratory Environmental Simulation

Laboratory simulation of the environments encountered in flight was given its greatest impetus during World War II. The Korean War and the launching of the Sputniks provided additional impetus, with the latter putting particular emphasis on the importance of simulating space environments. The need for environmental simulation first became significant during World War II because of the need to supply Russia with suitable cold weather equipment, and subsequently because of the increase in design complexity of military equipment, with a corresponding increase in its cost. During the above periods, there developed a race for military technological achievements, which required advancing the state-of-the art in scientific fields that were relatively unknown prior to that time. Consequently, the demand for knowledge and superior equipment under accelerated conditions resulted in reduced research and development time.

Another condition first imposed by the military during these periods was the specification of a "reliability factor," which required the suppliers of military equipment to develop and accumulate data to illustrate adequately that the system would satisfy all requirements.

In order to comply with the new military requirements, industry had to abandon older design and manufacturing concepts and seek new ways of producing reliable and highly complex

equipment in a short time, as well as in the most economical manner possible. This resulted in the widespread use of laboratory simulation, which allows the selection and evaluation of materials, components, equipment and subsystems that can be depended upon to meet service conditions, to be made while the weapon is in the early development stages.

Having selected the correct materials and components, the items produced by various manufacturers can be evaluated under simulated conditions, and the specific item and manufacturer providing the best performance possible in the equipment can be determined. Subsystems or complete systems can be tested to determine and correct deficiencies during the breadboarding or development stages of the program. While this does not guarantee a successful field operation, it greatly improves the chances of success.

By using laboratory simulation, the time necessary for the research and development of military systems has been reduced to the point where it is now almost compatible with military requirements. The use of the laboratory to prove the success of a design prior to field testing has resulted in considerable cost savings. A relatively small number of systems can be used continuously in the laboratory to prove design feasibility, but for the same amount of data to be obtained in the field, a great number of systems would be required, particularly in the case of non-recoverable missiles. The simulation capabilities used during the development program can also be used to evaluate the product during the production phase of the program to assure the military that quality levels are being maintained.

Environmental Test Techniques

There are three basic approaches to the environmental evaluation of an electronic or electromechanical system. The three approaches are termed: (1) black box method; (2) subsystems method; and (3) system method. Each of these approaches is best adapted to distinct stages of system development as shown below:

Approach	Development Stages
Black box	Breadboard engineering prototype
Subsystem	Manufactured prototype and qualifications
System	Justification, reliability and qualification

In addition to the three basic approaches, the equipment under test may be operating or non-operating. Whether the equipment is to be operating or non-operating during the test depends upon the environment to which it is subjected. For example, the equipment is not operating during normal transportation. Therefore, the equipment would be non-operating during the simulated test under the shock and vibration levels normally encountered in transportation and handling. Another example of non-operative testing is "temperature soak." This is one of the environments encountered during storage of the equipment. Conversely, if the equipment is normally operating in service under a certain environment, the equipment should be operating when this environment is reproduced in the laboratory.

Reproduction of an environment in the laboratory is accomplished through the use of specially designed equipment, generally referred to as environmental facilities. These facilities, are covered later.

Black Box Method. In the black box method, all packaged equipments comprising the system are subjected to the environments separately. Figure 6-9 is a diagram of a typical laboratory setup during black box testing. The black box is subjected to the required environment, and all outputs from the box are monitored during the test for indications of malfunction. Aside from the environmental facilities, some additional equipment may be required. During a shock and vibration test, for example, a holding fixture is required to provide the mechanical connection between the black box and facility. Figure 6-10 is a diagram of a typical development-type vibration test being conducted on a black box basis. The black box is set in its holding fixture and connected to the moving element of the shaker. An accelerometer is placed adjacent to the mounting points of the black box for the purpose of monitoring and controlling the vibration input levels. In the case shown in Fig. 6-10, the black box is equipped with vibration isolators. The vibration levels at critical places within the black box are monitored to obtain engineering information for development purposes. All the black boxes of the system are tested in a manner which will point up the inherent weaknesses in the design.

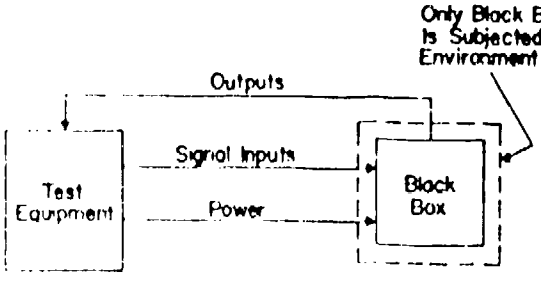


Fig. 6-9. Typical black box laboratory test.

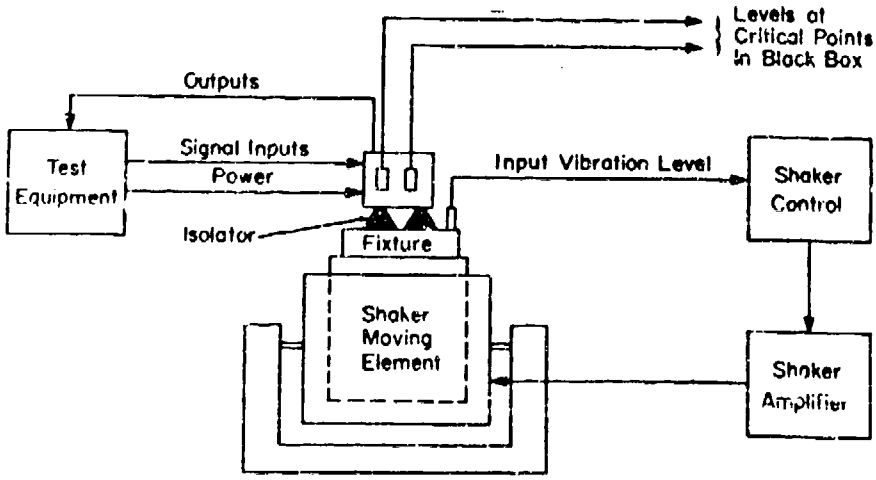


Fig. 6-10. Typical laboratory vibration test.

One disadvantage of the black box method of evaluation is that test equipment capable of monitoring many signals simultaneously is required. In some cases, the production test equipment is not capable of simultaneous measurement and some modifications are required. Another disadvantage is that the interacting effects among the black boxes of the complete system cannot be determined or readily predicted.

The advantages of the black box method are that performance of development work is convenient, trouble-shooting problems are kept to a minimum, and system operating time does not become excessive since only one box is operating during a test.

Sub-System Method. In the subsystem method, the sub-system is connected to the test equipment as shown in Fig. 6-11. Wherever possible all the black boxes are subjected to the environment simultaneously. In the case of the vibration environment, this may not be possible due to the limited capability of the shaker. In either case, all the boxes must be operating to test subsystem operation. Trouble-shooting is more difficult with this method, and environmental development work is normally not employed due to the complexity of the setup.

System Method. In the system method, an entire system is integrated. A typical example of this is shown in Fig. 6-12. The operation is on a "closed loop" basis. System performance may be monitored by observing (in this case) the search, lock-on and track modes of the system. Although application of this method depends upon the number of boxes comprising the system, the method has the advantage that the type of test results obtained are more meaningful in terms of overall system performance. For example,

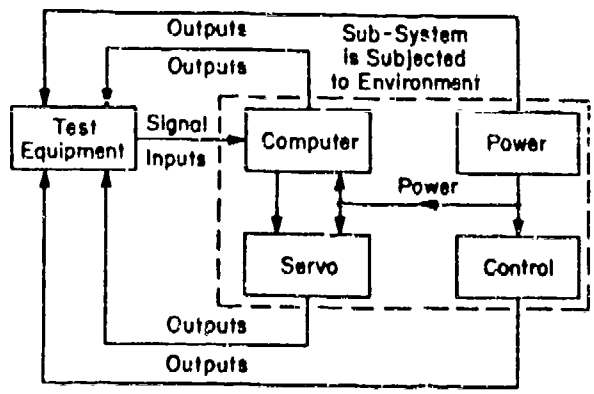


Fig. 6-11. Typical subsystem laboratory test.

a voltage which is out of specification at some point in the system may cause violent oscillations of the turret assembly.

The system method is particularly advantageous for qualification testing, where the aim is to demonstrate that the system will function satisfactorily in the environments to be encountered. The system should have been "debugged" during the design and development tests, and little difficulty is anticipated during the system qualification test, unless combined environments are also imposed on the system.

The disadvantages of this method are: (1) testing requires the use of large environmental facilities, (2) there is a long setup time required for system integration, and (3) troubleshooting is more complex. A malfunction of the system may be traced to the particular box causing the

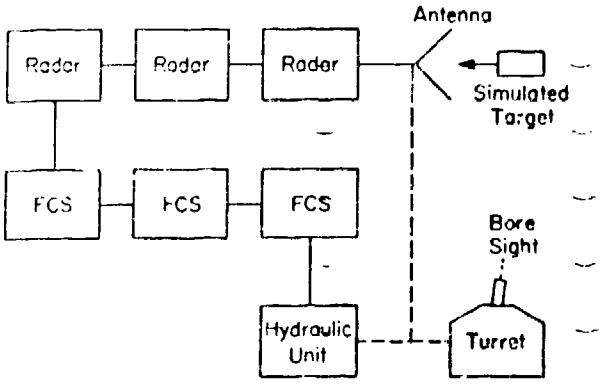


Fig. 6-12. Typical system laboratory test.

trouble, but isolating the failure within the box requires that it be disconnected from the system. This results in down time of the environmental chamber. If the box is removed and replaced in the system, and the test is continued, the chamber down time is avoided, but then it becomes necessary to supply system spares. Also, the faulty box will not be exposed to the full duration of the test. Back-up tests may be required on the box removed from the system for the purpose of failure analysis and development work.

System life becomes a problem with this method. In the case of vibration, where each box is tested separately, the system must be in operation during the entire time required for testing all the boxes. Repeated failure and replacement of parts under a given environment may result in additional failures, which are due to excessive exposure and not equipment design.

The system method outlined above is also applicable to flight vehicle system tests involving missiles, satellites, or space vehicles. The greatest problem in the flight vehicle test (Fig. 6-13) is correlating the environments of an actual mission profile to those around the vehicle in the test chamber as well as to those of the equipment within the vehicle, and of condensing the testing time for long duration vehicles. Such testing will help uncover subsystem integration problems, if correlation can be developed.

Single Environment Testing

Single environment testing is the exposure of the equipment to the environments one at a time. Usually, each test is carried out by successively increasing the severity of the environment to either the point of failure or to a point that will give assurance that the equipment will perform satisfactorily within the range of environment expected. In the case of low temperature testing, a motor may be operated sequentially at ambients of -40 F, -20 F, 0 F, +20 F, +40 F, +50 F, +65 F, +100 F, or any other selected points in the expected range of service life. The graduated change in exposure severity permits a definitive failure analysis.

The advantages of single environmental testing are: (1) isolation of the cause of failure is relatively easy since there are less variables to contend with; and (2) reasonably simple and straightforward laboratory simulation and instrumentation facilities are required.

The disadvantages of single environment testing are numerous. The tests are generally stretched over a longer span of time which sometimes may approach the equipment's valid service life. Also, although facilities for simulation are reasonably simple, more facilities may be necessary to make the required tests in the required time; and since the true service environment is not simulated, numerous other single environment tests must be made, and then multiple or actual service tests must be run to obtain true correlation. Another disadvantage of single environmental testing is that the interaction of two environments cannot be checked. For example, a fuel pilot valve for the Atlas missile performed satisfactorily under single vibration, temperature and acceleration

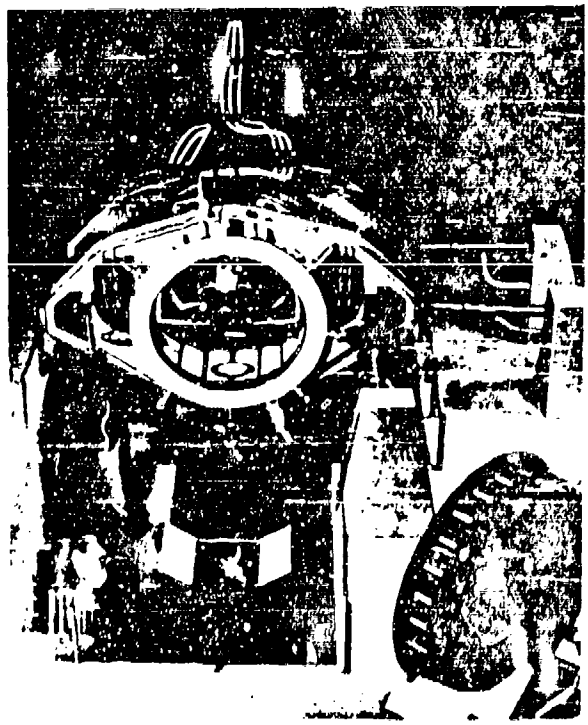


Fig. 6-13. System test -- "paddle wheel" satellite in Dynamic Analyzer.

tests, but failed in flight. It was found that the combined vibration and acceleration caused the valve shaft to bind.

Another important consideration when making single environment tests is the sequence of the individual tests. To obtain as much test data as possible from a test item, the tests should be made in the order of increasing damage potential. This sequence should be established because such tests as vibration, shock, acceleration and salt spray are more destructive than the remaining environments. Therefore, if the equipment is subjected to these destructive environments first, there is a possibility that the equipment will be more susceptible to failure during the less destructive environmental tests. Studies have been performed to determine the best sequence of environments for testing. One of these studies is described in reference /3/. The sequencing that resulted from this study has been included in MIL-E-5272C.

The reliability of single environment testing is limited. Extrapolation of the test data and correlation to service life have inherent shortcomings as compared to the combined environment approach.

Combined Environment Testing

Combined environment testing might produce better correlated data since, when combined, the environments more precisely duplicate the actual service conditions. However, correlation factors for combined environment testing need to be developed. Another advantage of combined environment testing is that since various environmental tests are conducted more or less simultaneously, less overall time is generally required for combined testing than for single testing. This also brings about a savings in the time and cost required for setting up, checking, and planning the tests. In addition, since less setup time is required and fewer test procedures are followed, less inaccurate data results with the single ones.

At present, the primary disadvantage of combined environment testing is the difficulty in establishing the cause of test failures that occur during combined testing. Another disadvantage is that a combined facility has a high initial cost. Purchasing equipment necessary to perform tests on a single environment basis might reduce the initial costs considerably; but this initial saving is less real than it appears at first. The individual pieces of equipment purchased for single environments would require more floor space than a combined facility. In addition, the time required to move around and set up equipment for the various single tests might take up a good portion of the overall testing schedule. The cost of this type of nonproductive activity should be considered when the economies of combined versus single environment tests are estimated.

A combined environment test failure may require several costly, time-consuming single environment diagnostic tests before the cause of the failure is found. This is compensated for to some extent, though, by the possibility that a combined environment test may produce a failure that would not have been detected under single environment testing.

The degree and rate of combination of the service environments may be difficult to simulate. What is more, the degree and rate of combination may not always be known. These conditions result in a higher-cost facility. The cost of obtaining quantitative data or calculating expected data should be considered as a part of the overall problem.

Many combined test facilities have been built, but very little work has been done to determine the confidence level of combined environment testing. The United States Testing Company has, however, completed under Air Force contract a study to determine this confidence level. The results of the study are not conclusive.

It appears that combined environment testing has greatest application in qualification and reliability testing. The single or simple combined test facilities will always be required for research and development, as well as for isolating problem areas encountered in combined tests.

Correlation of Actual to Test Environments

Correlation, as applied to the field of environmental engineering, refers to the effects of a simulated environment upon a subject under test as compared to the effects of an actual environment. True correlation occurs when the same type of failure can be produced by simulation testing under controlled laboratory conditions as occurs under actual service conditions.

Ideally, correlation can be established if the service environment is exactly duplicated in the laboratory. However, this approach is not generally practicable for most tests, since the time of exposure must be considered. Most often, accelerated tests are used in the laboratory, and this is the major cause of the difficulty in obtaining true correlation. This acceleration is required to enable qualification of equipment and subsystems to match the development schedule of the weapon system. An example of this is the vibration environment. A part may fail in the actual environment after six months of use and the cause of failure may be attributed to fatigue. To duplicate this condition in the laboratory, a continuous test is generally run at vibration resonance until failure occurs. Correlation of the test and actual failures is possible, but is not exact. Nevertheless, as long as the limitations are recognized, enough correlation data can generally be obtained so that the part can be effectively redesigned.

Correlation can be improved when combined environments are used to simulate the closest approximation possible to the service environment. For many types of missiles, laboratory simulation of combined environments has advanced to the point where simulated missile flight profiles can be reproduced that are very close to true service environments and real time cycling. This is possible mainly because of the relatively short time duration of missile flights. For other flight vehicles, which have a longer life and are used under many varied conditions, combined environment simulation is more difficult. Much research is needed to develop correlation factors so that a long service life, such as that experienced by parts in orbital or space vehicles, can be reduced to a short time laboratory test.

For the best design, the engineer must recognize where correlation may be weak, and compensate for it with experience and judgment. The laboratory results must be extrapolated to parallel the service environment results. The accumulation of data, experience, and test verification, plus a continued effort to produce true environment simulation, will all lead eventually to the best correlation possible. Work in this area is currently being conducted on the selection of standard environmental test specimens. /4/ These standard test specimens are items that will react in a predictable and specific way to each environment and only to that environment. They will integrate both the intensity of the stress and the time of exposure. It is believed that development of such specimens will allow development of realistic combined environment tests for reliability assurance purposes, and will allow development of more accurate correlation factors than is now possible.

SIMULATION

For environment simulation to fulfill its function it must provide correlated data. The reliability of simulated test results is determined to a great extent by how the environment is simulated. The following paragraphs describe various methods of simulating different environments, both in the field and the laboratory.

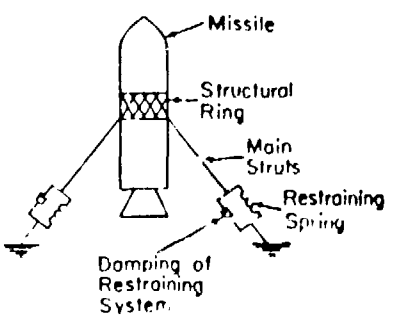


Fig. 6-14. Typical setup for captive missile test.

Field Methods

There are definite limitations on reproducing environments in the laboratory. In general, larger and more massive items have greater limitations. The laboratory reproduction of a single environment is impossible in many cases due to the weight and size capacities of present environmental facilities. Since a degree of operational confidence is required, field facilities have been built that will simulate an operational environment to a greater extent than is now possible in the laboratory. The principal disadvantage of this type of simulation is that in some cases it takes too long to execute a reliable test.

Natural Weather Methods. Nature itself provides a good means of duplicating some of the natural environments that will be encountered by equipments. For tests involving temperature, wind, and dust, altitude, rain, snow, sleet and humidity the environmental engineer can take advantage of natural weather conditions that more or less systematically recur at various locations. Certain polar, tropical and desert geographic locations provide useful environmental extremes for reliable testing. In cases where such remote areas are uneconomical to use, the United States itself provides weather extremes that are often sufficient, particularly in the northwestern and southwestern parts of the country.

These natural weather extremes are not too difficult to simulate by means of environmental facilities, and such facilities provide control, which is not true for any natural condition. Such facilities will be discussed in later paragraphs.

Captive (Static) Tests. Captive tests provide a means of approximating very closely actual flight conditions while testing a complete vehicle system. During such a test, the complete system can be operating, except that the vehicle is restrained from flight. The basic needs of a captive, or static, test facility are similar to those at a flight test base, except for the addition of a flight restraining structure and an exhaust dispersion means. A diagram of a typical restraining system used with a missile is shown in Fig. 6-14. The purpose of the captive test is to discover and solve any development problems that may arise under simulated flight conditions. The primary advantage of this type of test is that it is inexpensive compared with a flight test. Also, with one-shot vehicles such as missiles, several tests can be accomplished without danger of damage or loss of data due to a crash, so that simpler instrumentation can be used.

At present, it is still considered impractical to carry out captive tests of conditions such as stage separation, aerodynamic loading due to maneuvers, acoustic noise due to aerodynamic

turbulence, and high altitude pressures. Probably the greatest deficiency in this type of simulation, as well as in all other types, is lack of correlation factors. Present techniques limit the simulation of flight conditions to firing the propulsion system and limited closed loop maneuvers.

The design of the restraining system is a key factor in conducting a satisfactory captive test, since it influences vehicle response to control system forces and vibration forces generated by the engine. There are cases on record where the resonant response of undamped rigid mounts led to disastrous effects. Computer studies have been carried out for the purpose of analyzing the effects of the restraining system upon both the vibration environment and the vehicle response. The results of one particular study involving only vertical vibrations showed that a restraint stiffness could be specified that would allow duplication of the freeflight vibration environment above 6 cps. Below 6 cps, the error is in the direction of undertesting the vehicle.

Rocket-Sled Tests. The basic rocket-sled test facility consists of a rocket driven sled that "rides" on precision rails. This arrangement is shown in Fig. 6-15. Sled test-track facilities up to 7 miles long are available, and are capable of attaining speeds up to Mach 4. Programming of the acceleration profile of the sled is accomplished by the use of fuel-programming for liquid propellant rockets, shaped charges for solid propellant rockets, and aerodynamic and water-braking techniques. The sled facilities are equipped with count-down checkout circuitry, telemetry, on-board test equipment, high speed cameras, and high speed computing and recording equipment.

The supersonic sled is the most practical way to produce the dynamic loads of free flight tests and still allow recovery of the test item. A reproduction of the vehicle acceleration and velocity profile in this manner allows a study of the equipment response to the acceleration profile, aerodynamic studies of airframes, evaluation of aerodynamic heating effects, and evaluation of seat ejection apparatus. The advantages of this type of facility are: (1) the test item is recovered intact for examination; (2) test conditions are repeatable; and (3) it is more economical than a flight test since many runs may be made with a single item. One of the disadvantages of this method is the severe vibration environment, generated primarily by the high velocity sled passing over discontinuites in the rail. Slipper clearances and wear on contact surfaces also result in shock and vibration inputs to the sled. The severity of this shock and vibration environment may be greater than that which occurs in the vehicle. Trials were recently performed to find a satisfactory method of controlling the vibration environment. The results indicate that the precision rails used are as true and as smooth as can be practically attained, and that the most promising approach is the vibration isolation of the vehicle from the rails and the vibration isolation of the rocket motor system. Test data show a reduction of about one order of magnitude through the use of an isolation system. With this recent development, the value of the sled test has been extended to include a reasonable simulation of the vehicle acceleration profile and vibration environment.

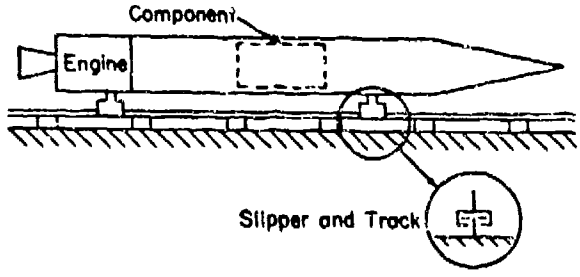


Fig. 6-15. Rocket-sled setup.

Other disadvantages of rocket-sled tests are the short test time for each run and the lack of correlation factors to actual service conditions. Information concerning the use of available sled facilities is contained in reference/5/.

Specialized Field Facilities. The captive and sled tests are fairly general and may be used for a variety of applications. There are also some specialized facilities designed for use in conjunction with a specific vehicle. One such specialized device is a 200,000-pound gimbaled simulator designed and fabricated for use with the Polaris missile. This device is capable of duplicating the following ship motions:

heave ±8 feet

roll ±14 degrees

pitch ±14 degrees

The purpose of the simulator is to test the missile components while under a ship's motion, and to determine the conditions under which a missile with moderate take-off accelerations can be launched safely from a moving platform.

Another special field facility is the "G-shooter," designed and fabricated for use with the X-7 ram jet missile, which is air-launched from a larger vehicle. A rocket boost is provided to bring the missile to a speed greater than Mach 1, which is required for ram jet operation. The purpose of the G-shooter is to simulate the shock of the rocket boost and thus allow evaluation of the X-7's electronic equipment under this environment. The facility produces a velocity of 23 feet per second after 6 inches of travel by means of a pressurized piston. The braking is accomplished with nylon bands. The total travel involved is only 2 feet.

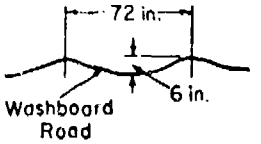


Fig. 6-16. Washboard road.

Ground Vehicle Proving Grounds. The Ordnance Automotive Testing Center at Aberdeen Proving Ground, Maryland, is available for performing complete ground-vehicle field tests. Specially constructed roads containing such hazards as embedded rock, staggered bumps, corrugations and vertical walls are provided for evaluation of a complete ground vehicle under a shock and vibration service environment. There is also a "frame twister" road that imparts severe torsional stresses to the vehicle structure. One such specially constructed road of interest is the six-inch coarse washboard. This road consists of 6-inch waves 72 inches apart. A diagram of the road is shown in Fig. 6-16. The frequency of the vibration imparted to a vehicle may be varied by varying the speed of the vehicle. For example, a vehicle travelling at 5 mph will be subjected to a vibration frequency of 1.22 cps.

In addition to the rough roads, there are cross-country courses embodying hills, mud and severe terrain. Fording and swimming tests are conducted in special "bath tubs."

Extreme-environment tests are conducted at Yuma, Arizona (desert environment) and Fort Churchill, Canada (arctic environment). The desert course at Yuma has hill, sand dune, and sand and dust slope vehicle courses. The arctic course provides deep snow and frozen lakes for the operating areas. Temperatures on the order of -35 F (-37.2 C) are normal. Tests are usually conducted during winter to insure that vehicles are checked under the most severe conditions available.

Laboratory Methods

In the laboratory, environments are generally simulated in chambers or on excited platforms. Typical techniques and facilities for reproducing the various environments are covered in the following paragraphs. These techniques and facilities are covered in the following categories:

1. Component, equipment and subsystem test facilities for single environment testing.

2. Component, equipment and subsystem test facilities for combined environment testing.

3. Hyper and space environment test facilities.

4. Full-scale environmental test facilities.

5. Environmental test facilities for humans.

Component, Equipment and Subsystem Test Facilities -- Single Environments

Low Temperature. Low temperatures are generally produced in a straightforward manner. Where the required temperatures are not too low, the test duration too long, or the test specimen too large, chambers employing dry ice as the cooling agent may be used (Fig. 6-17). Otherwise, chambers cooled by refrigeration equipment similar to that used for air conditioning are usually employed (Fig. 6-18).

High Temperature. High temperature can be produced in a test chamber by convective or radiant means. Convective ovens, which use electrical resistance elements to heat the air in a chamber, are inexpensive and easy to control. With radiant-type ovens, the walls of the chamber are heated.

Temperature Shock. Most often, the temperature shock environment is produced by moving the equipment from a hot chamber to a cold one, and vice versa. Temperature shock can also be simulated in one chamber by combining refrigeration and oven devices, or by releasing compressed gas into the chamber. Thermal shock for liquid-handling equipment (pumps, etc.) can be accomplished by transfer to pump at drastically different temperatures than those in use.

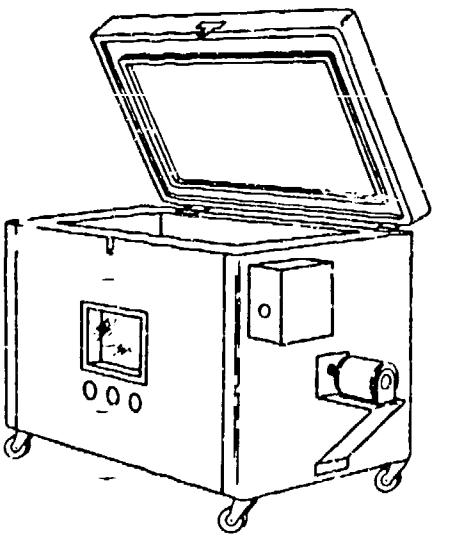


Fig. 6-17. High- and low-temperature test chamber employing dry ice cooling and convective heating.

Humidity. Humidity is generally produced within a chamber by: (1) steam injection, (2) vapor injection, or (3) vapor absorption. For steam injection, a boiler with an electric heating element is used to build up steam. When more humidity is required, a solenoid valve opens and permits steam to enter the chamber and mix with the circulating air. Vapor injection is accomplished by forcing water under pressure through a fine mist-producing nozzle. The resulting mist is so fine that it becomes a vapor upon mixing with the air of the chamber.

The vapor absorption method depends upon a dynamic balance of absorption and condensation. Water at 10 to 15 degrees F above the ambient temperature of the chamber is allowed to flow through a tray inside the chamber. The circulating air absorbs the water vapor as it passes over the tray. Next, the air passes over a condensing coil which removes as much water vapor from the air as is required to maintain the desired humidity. It is usual to have two sets of coils within the chamber: one, which operates at a low temperature, lowers the temperature of the air; and the second, which has a large surface area and operates at a warm temperature, removes water vapor from the air.

Altitude (Air Pressure). The producing of a simulated altitude is merely an air-pumping procedure; either rotary or piston type pumps may be used. Chambers utilizing this type of equipment are capable of simulating altitudes from sea level to five hundred thousand feet. At present, large-size chambers are limited to this range since lower pressures require laboratory-type equipment. Because of the characteristics of water vapor, it is not feasible to maintain control of both altitude and humidity in anything but a small laboratory controlled experiment. Cyrogenic techniques, oil-diffusion pumps and getter pumps are also used to obtain low pressures for altitude simulation.

The pressure within a given area can be reduced from 760 Torr (millimeters of mercury) to approximately 1 x 10-12 Torr by the employment, in succession, of several devices. These devices and their ranges are listed below. A brief description of each is also included.

Device or technique	Effective pressure range From	To
Mechanical (displacement) pump	760 Torr	1×10^{-3} Torr
Oil diffusion pump	1×10^{-3}	1×10^{-6} Torr
Oil diffusion pump with cold trap	1×10^{-6} Torr	1×10^{-8} Torr
"Getter" technique or Cryopumping system	below	1×10^{-8} Torr

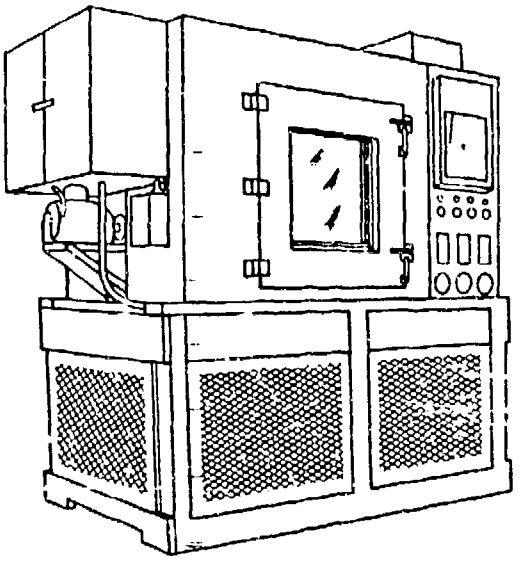


Fig. 6-18. High- and low-temperature test chamber employing refrigeration cooling and convective heating.

Mechanical Pump. The most common method of producing a moderate vacuum is by a mechanical production of a variable volume. When the volume is smallest, it is sealed off and expanded, reducing the pressure within. This volume at reduced pressure is then opened to the area to be exhausted, and upon equalization of pressure is again sealed off. It is then simultaneously reduced in size and opened to the atmosphere. After the gas has been expelled to the atmosphere, the cycle is repeated.

Oil Diffusion Pump. Hot oil vapor rises through a central tube, strikes an umbrella-shaped baffle, and is channeled by the configuration of the baffle back into the oil reservoir. Water cooled coils encircle the upper part of the pump on the outside, cooling the vapor that comes in contact with the upper part of the pump. A down-draft of cooler oil vapor and droplets is created around the central tube, traps air or other gas molecules from the area being evacuated, and carries them down to be exhausted through a line near the pump base. This line is usually connected to a mechanical pump that serves as a fore pump in the system.

Oil Diffusion Pump With Cold Trap. A diffusion pump operating at lower pressure ranges has a certain amount of "back diffusion" of various vapors. To improve the ultimate vacuum, a cold trap, usually cooled by liquid nitrogen, is placed between the diffusion pump and the area being evacuated (Fig. 6-19). Volatile vapors condense on the surface of the trap, and thus do not diffuse back into the area. Also,

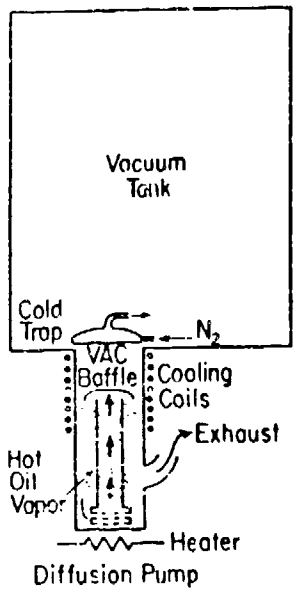


Fig. 6-19. Oil diffusion pump with cold trap.

molecules of gases with "freezing points" above that of nitrogen will condense on the cold plate, further reducing the pressure.

Getter "Technique". This technique involves the employment of chemically active metals, such as barium, aluminum, calcium, or magnesium, to remove residual gases. The getter is electrically volatilized and combines with the gases, which deposite as chemical compounds on the walls of the vessel. This technique is employed principally for vacuum systems that are to remain sealed for extended periods of time, such as electron tubes, cathode ray tubes, etc.

Cryopumping System. An arrangement or array of cold traps or cold surfaces cooled by cryogenic fluids and employed to condense molecules of higher-freezing-point gas is designated a cryopump. In a cryopumping system of greatest immediate use, liquid hydrogen is circulated through coils that are welded to the back of the cold plates. The hydrogen condenses gas molecules, and also removes radiant energy that may have reached the plates. Liquid-nitrogen cooled shields are commonly placed in front of the plates to reduce the amount of radiant energy that reaches them.

Shock. Mechanical shock is normally simulated by a free-fall-type shock testing machine consisting essentially of a guided drop carriage that impacts against a base in a controlled deceleration manner (Fig. 6-20). The deceleration shock is controlled by the impact of a calibrated plate spring against an anvil, by rubber pads, or by lead pellets. One type of shock machine applies hammer blows. Another machine uses hydraulic pressure or high pressure gas to apply a rapid acceleration shock rather than the conventional deceleration shock of the mechanical impact machines. The machines can be mounted within a chamber to produce one of several shocks, as required, while other environments are being simulated.

Vibration. Vibration can be simulated by the use of rotating eccentric weights, or a crank-type mechanism which translates rotary mechanical or hydraulic motion into approximate sinusoidal vibration. Mechanical or hydraulic shakers, however, are useful only up to about 800 cps.

The most popular method of producing sinusoidal vibration utilizes an electrodynamic shaker (Fig. 6-21) which operates on the same principle as the radio speaker. This type of equipment has a useful range of about 5 to 2000 cps. The armature, or moving element, is excited by an a-c signal while in a high d-c field. The a-c signal can be produced by a variable speed motor-generator set or through the use of an electronic signal generator and amplifier. The amplifier provides the flexibility of being able to build up any wave shape at various frequencies. However, sinusoidal vibration testing may not provide good correlation, since many actual vibration environments are aperiodic or

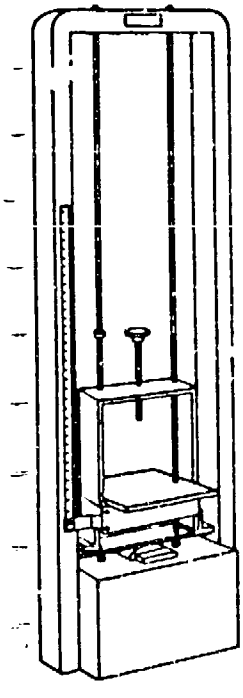


Fig. 6-20. Drop machine for shock simulation.

quasi-random in nature. As a result there is much controversy and some leaning towards shaped spectrum random-vibration testing, although adequate evidence is not available to support its superiority. A program initiated by the Environmental Division, Engineering Test Directorate, Deputy for Test and Support, Aeronautical Systems Division has not helped clear up the controversy. It has been shown that there is no apparent correlation between sine wave and random vibration testing.

Complex equipment is required to produce random vibration in order to compensate for the various responses of the holding fixture and to assure a proper input to the test specimens (Fig. 6-22). To operate inside a temperature and altitude chamber, the standard shaker must be modified.

A block diagram of a typical electrodynamic sinusoidal system is shown in Fig. 6-23, and a block diagram of a random facility is shown in Fig. 6-24.

Gases and Ozone. Bottled gas can be used to introduce various combinations and amounts of gases into a chamber when the gases are stable. Unstable gases must be produced within the chamber. Ozone, for example, can be produced through electrical discharges.

Acoustic Noise. At present, there are various techniques employed for generating realistic acoustic soundpressure. In general, an acoustic facility should consist of the following:

1. A noise source, which can be an engine, plasma jet, siren, etc., for random frequencies, or one or more horns, a tuned sound chamber, etc., for discrete frequencies. These sounds can be produced electrically or electronically by suitable signal generators or amplifiers.

2. A test panel, or area, on which the articles to be tested are mounted.

3. A sound chamber or chambers in which the test panel is placed. The chamber may be of the plane (progressive) wave or reverberant type.

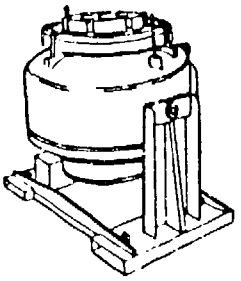


Fig. 6-21. Electrodynamic shaker for vibration testing.

4. A monitoring device to record sound levels and frequencies continuously. Microphones and electrical recording devices are normally used for this purpose.

The selection of the specific components will depend upon the requirements of the acoustic specification in use. Many commercial acoustic facilities are designed for rapid interchange of input signals and some provide for interchange of chambers. (Figure 6-25) is a block diagram of an acoustic facility employing a reverberant chamber. The equalizer and power amplifier shown in the figure are not required if the noise generator is adequate. Figure 6-26 is a block diagram of an acoustic facility employing a progressive wave tube.

Rain. Rain is generally simulated in test chambers by water flowing through controllable spray nozzles. A typical rain chamber designed

Fig. 6-22. Random-motion vibration system with Courier satellite interframe mounted on special fixture. (Courtesy of Philco Western Development Laboratories and U.S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey).

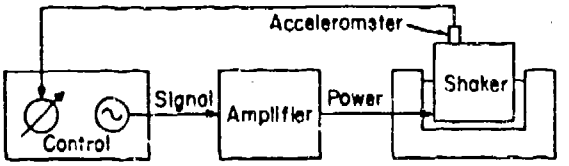


Fig. 6-23. Typical electrodynamic sinusoidal system.

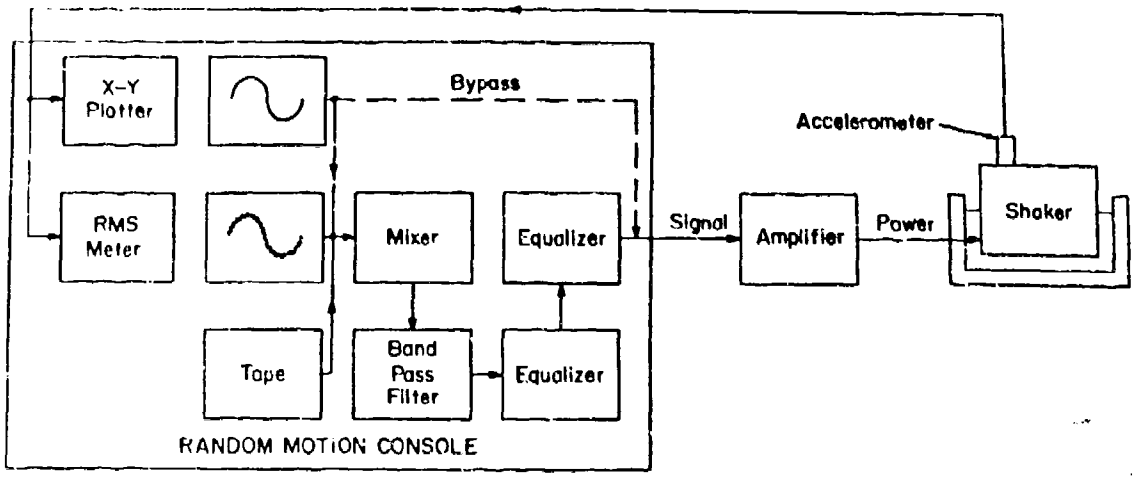


Fig. 6-24. Typical random vibration facility.

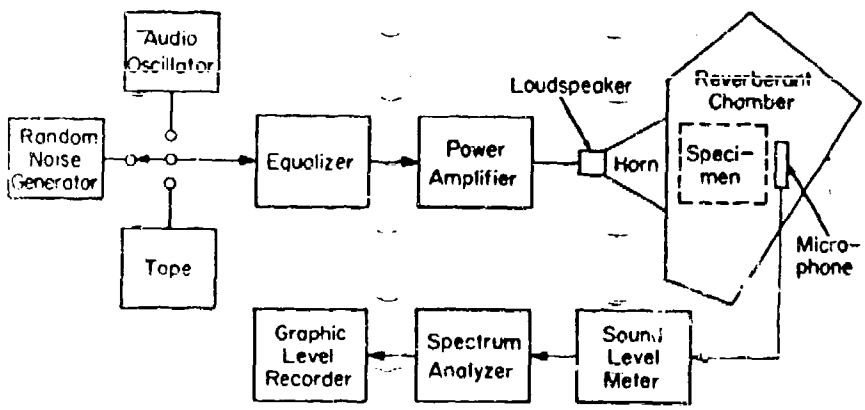


Fig. 6-25. Typical reverberant chamber acoustic facility

in accordance with the specifications of MIL-C-8811 (ASG), Chamber, Rain-Testing, is described below:

The chamber is a self-contained unit, with an insulated, well-lighted internal test space. It has a large observation window (one third the area of the wall on which it is located) equipped with a wiper to keep the glass clear for observation purposes. Provision is made for controlling the water temperature and rate of flow.

The chamber is equipped with water spray nozzles and provides simulated rainfall capable of variation from one to four inches per hour. The rainfall is dispersed uniformly over the test area, and is in the form of droplets having a minimum diameter of 1.5 millimeters. A variable-speed blower and refrigeration equipment are provided for simulating wind-driven rain and for cooling the test space, respectively.

Sand and Dust. The sand and dust environment is simulated by circulating dust throughout a test chamber at a specified velocity and concentration. A typical sand and dust chamber designed in accordance with the specifications of MIL-C-9436A(ASG), Chamber, Sand and Dust Testing, is described below.

The chamber (Fig. 6-27) is a self-contained unit consisting primarily of a dust-tight chamber, a dust supply, a blower and necessary ducting for producing the desired conditions. A

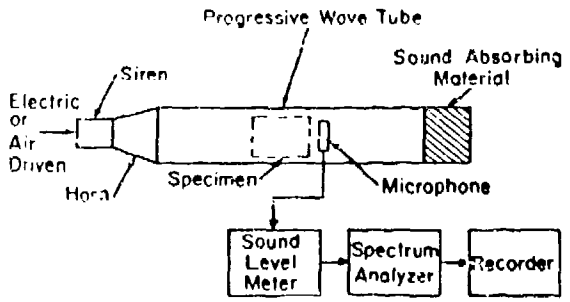


Fig. 6-26. Typical progressive wave acoustic facility.

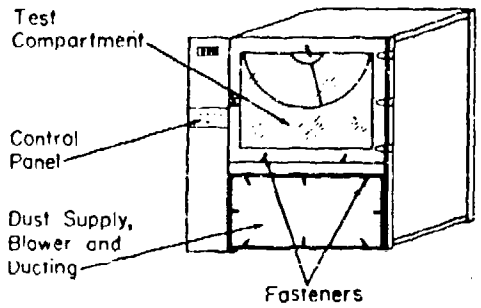


Fig. 6-27. Sand and dust chamber.

vibrator (Fig. 6-28) is installed on the dust hoppers to assure proper dust flow. The chamber is maintained at 160 F (71 C), and a desiccant is used for controlling relative humidity.

A wiper is mounted on the glass door-panel to keep the glass clear for visual inspection of the test specimen. Automatic cycling of chamber operation is provided to accomplish the exposure and shutdown required for the sand and dust tests of MIL-E-5272.

Explosive Atmosphere. Explosive atmospheres are produced in explosion chambers (Fig. 6-29 and 6-30) by simulating the various parameters involved in an explosive atmosphere. The more important of these parameters are:

1. Air/fuel ratios.
2. Temperature.
3. Altitude.
4. Air flow.
5. Humidity.

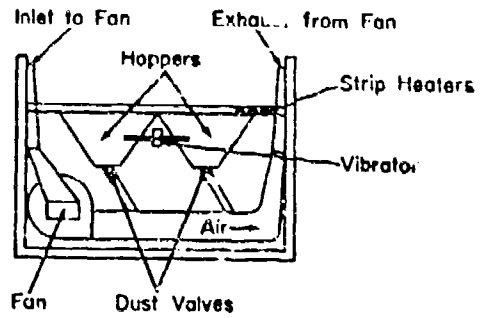


Fig. 6-28. Dust supply, blower and ducting for sand and dust chamber.

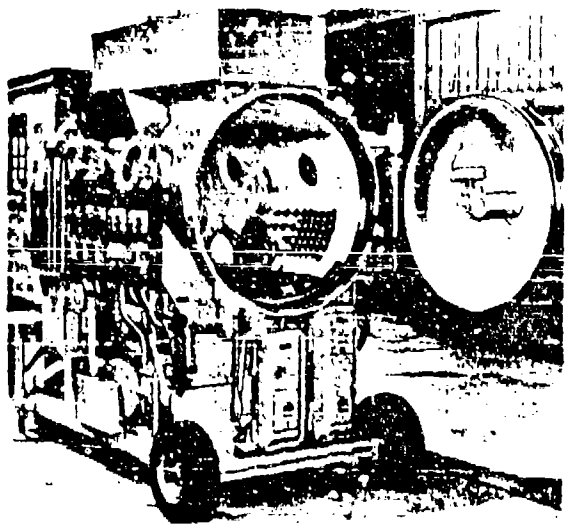


Fig. 6-29. Explosion chamber.

Several types of explosion chambers are now commercially available. They range in size from several cubic feet to approximately 300 cubic feet. A 35-cubic foot (3 feet in diameter by 5 feet long) and a 300-cubic foot (7 feet in diameter by 8 feet long) reach-in chamber with an altitude range from ground level to 500,000 feet and 100,000 feet, respectively, are presently in use at the Environmental Division, ASD. The temperature range of the smaller facility goes from normal room temperature to 160 F and the larger to 350 F. The smaller facility operates with aviation gas and jet fuel and the larger with jet fuel, commercial butane aviation gasoline, and chemical fuels. The temperature range of most explosive atmosphere chambers can be increased to 200 F (93 C) with the addition of heaters. Future requirements may

make "walk-in" chambers commercially available. Such chambers may be designed for temperatures up to 450 F (232 C) and altitudes up to 80,000 feet, and be adaptable for new, high-energy fuels.

Detail specifications for the design and construction of explosion chambers are contained in MIL-C-9435A(ASG), Chamber, Explosion-Proof Testing; and MIL-E-26854, Explosion-Proof Test Facility, Requirement and Procedure for Reconnaissance Equipment.

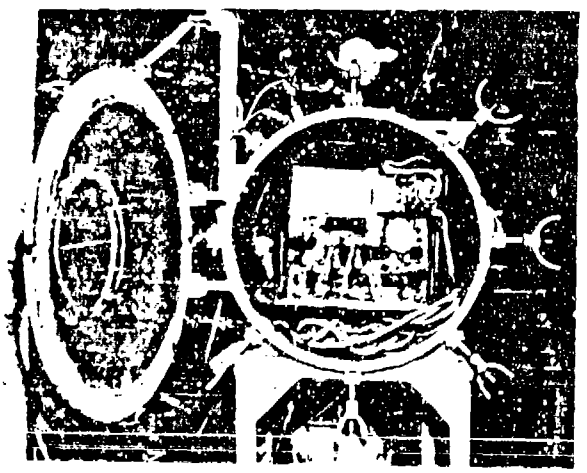


Fig. 6-30. Electronic equipment mounted in chamber for explosive-atmosphere test.

Nuclear Environment. The nuclear radiation environment is simulated by a nuclear reactor and associated chambers, or "hot cells," in which the test specimens being irradiated are located (Fig. 6-31). One of the most modern of this type facility, the Air Force Nuclear Engineering Test Facility, is currently under construction at Aeronautical Systems Division. Any modern nuclear engineering facility would include: (1) a 10-megawatt ORR-type reactor with two adjacent 330 cubic foot irradiation cells; (2) a multiple hot cell complex; (3) a remotely-operated irradiated materials handling system; (4) a waste processing plant; and (5) a laboratory building. In addition, an environmental conditioning system should be provided that should make it possible to control the temperature, humidity and altitude conditions during specimen irradiation.

Gamma facilities are also used to simulate the nuclear radiation environment. In these facilities, the specimen under test is placed in a chamber, or cell, with a radioactive source of gamma radiation. The gamma source can be fission products, spent fuel elements from nuclear reactors, or a radioactive element, usually Cobalt-60.

Some of the nuclear reactor test facilities presently in operation are listed in Table 6-3,

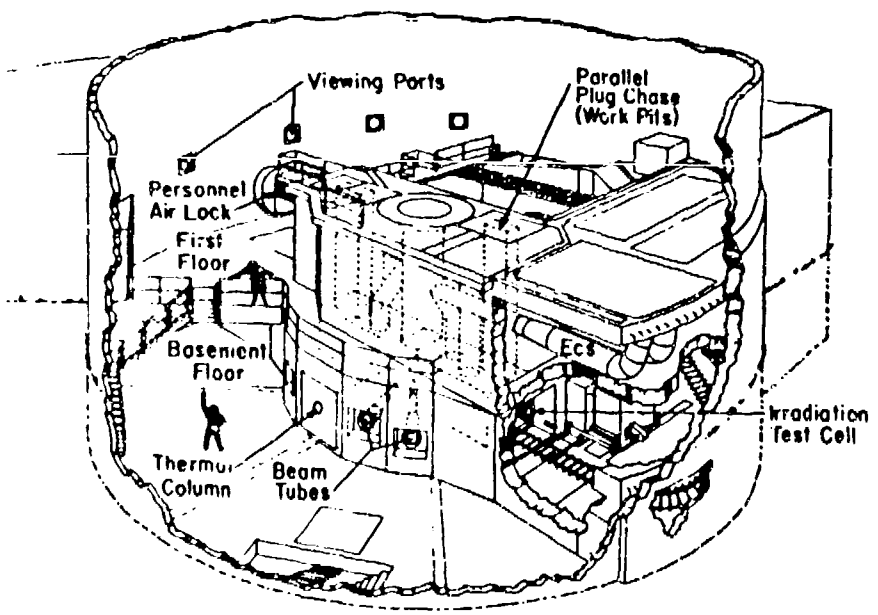


Fig. 6-31. Nuclear environment test facility.

and some gamma irradiation facilities in Table 6-4. Detailed information on all such nuclear test facilities is contained in reference/6/.

Salt Spray. Salt spray is simulated in a chamber by exposing the test specimen to a fine, thoroughly dispersed mist. The mist is derived from a salt solution whose concentration, pH value and specific gravity are controlled for proper test conditions.

Fungus. The fungus environment is produced in test chambers in which the temperature and humidity are carefully controlled to simulate the climate found in tropical areas. Species of fungi are introduced into the chamber with the test specimen and thrive in the simulated climate.

Table 6-3. Some Nuclear Reactor Irradiation Facilities /6/

Reactor	Location	Power level (megawatts)	Neutron flux		Comments
			Fast	Thermal	
Argonne Research Reactor CP-5	Argonne National Laboratory	2	10^{13} m/cm^2/sec (max)	2×10^{13} nv (max)	Available to outside organizations.
Battelle Research Reactor	Battelle Memorial Institute	2	10^{13} m/cm^2/sec (avg)	10^{13} nv (avg)	Available to any organization sponsoring research at Battelle Memorial Institute.
Engineering Test Reactor	National Reactor Testing Station	175	1.5×10^{15} m/cm^2/sec	4×10^{14} nv	
General Electric Test Reactor	Vallecitos Atomic Laboratory, Pleasanton, Calif.	30	10^{15}m/cm^2 sec (max)	2.4×10^{14} nv (max)	Available for customer usage.
Materials Testing Reactor	National Reactor Testing Station	40	2.5×10^{14} m/cm^2/sec	5×10^{14} nv (max)	Available to outside organizations.

Table 6-4. Some Gamma Irradiation Facilities /6/

Facility	Location	Max intensity (ergs/gm(C)/hr)	Source	Specimen environment
Argonne High Level Gamma Irradiation Facility	Argonne National Laboratory	1.7×10^8	MTR fuel elements	Water
Battelle Gamma Irradiation Facility	Battelle Memorial Institute	1.3×10^8	Cobalt-60	Water
Brookhaven Gamma Irradiation Facility	Brookhaven National Laboratories	8.7×10^7	Cobalt-60	Water or air
Southwest Research Institute Gamma Facility	Southwest Research Institute	2.6×10^9	Cobalt-60	Air
WADD Gamma Facilities	Wright-Patterson Air Force Base	Small source-3.5×10^7	Cobalt-60	Air
		Large source-6.8×10^7	Cobalt-60	Air

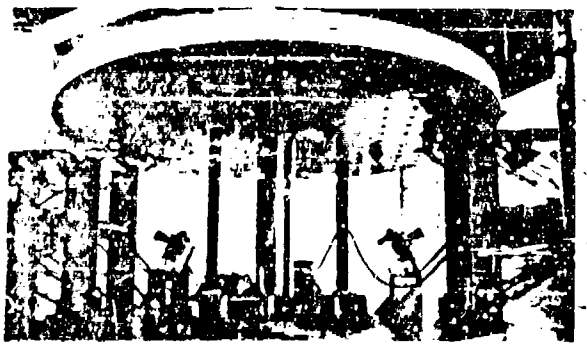


Fig. 6-32. Centrifuge set up to accelerate bomb specimens.

Acceleration. In the laboratory, acceleration is simulated by centrifuges (Fig. 6-32) or by linear accelerators, called air guns. Centrifuges are either hydraulically or electrically powered. The instrumentation is usually electrically connected to the test specimen by means of slip rings. For both centrifuges and air guns the acceleration and deceleration profiles can be instrumented to some extent.

Component, Equipment and Subsystem Test Facilities -- Combined Environments

The ideal laboratory simulation of combined environments would reproduce simultaneously the exact combination of environments that the equipment would be subjected to in service. Equipment capable of doing this is known as a "mission profile" facility. At the present time, however, such a facility is not available. As a substitute for the mission profile facility, various practical environment combinations are used. These combined environment facilities include:

Temperature-altitude chambers

Temperature-humidity chambers

Temperature-altitude-humidity chambers

Temperature-vibration chambers

Acceleration-vibration test stands (Fig. 6-33)

In addition, a combined environment facility that can simulate high and low temperatures, altitude, and vibration has been built by the United States Testing Company to conduct a study to determine the confidence level of combined versus single environmental testing. This study was conducted for the Environmental Branch, Engineering Test Division, Flight and Engineering Test Group, ASD. A photograph of this facility is shown in Fig. 6-34. The schematic layout of the facility is illustrated in Fig. 6-35 and the legend for the schematic layout is listed in Table 6-5. This facility is shown because it represents what can be done through modification of existing facilities.

Another combined facility is the Wyle Combined Environmental Centrifuge (Fig. 6-36) built by Wyle Laboratories. It consists essentially of two 16-inch-wide flange I-beams mounted on a hollow shaft through tapered roller bearings. Means are provided for installation of a vibration shaker, slip rings, swivels, tanks and plumbing. The arm can be removed from the hub assembly to permit preservation of a test setup or installation of a setup on an alternate arm while another test is in progress. Simultaneously, this facility can produce the following environments:

1. Vibration to 4000 pounds and 2000 cps.

2. Acceleration to 20 g.

3. Altitude to 250,000 feet.

4. Temperature range from -300 to 500 F (-175 to 260 C).

5. Humidity from 50 to 95 percent.

6. Liquid oxygen flow to 8000 gallons per minute; gaseous flow to 40 pounds per second; fuel flow to 1500 gallons per minute; hydraulic flow to 150 gallons per minute; or helium flow to 3 pounds per second and 3000 psi.

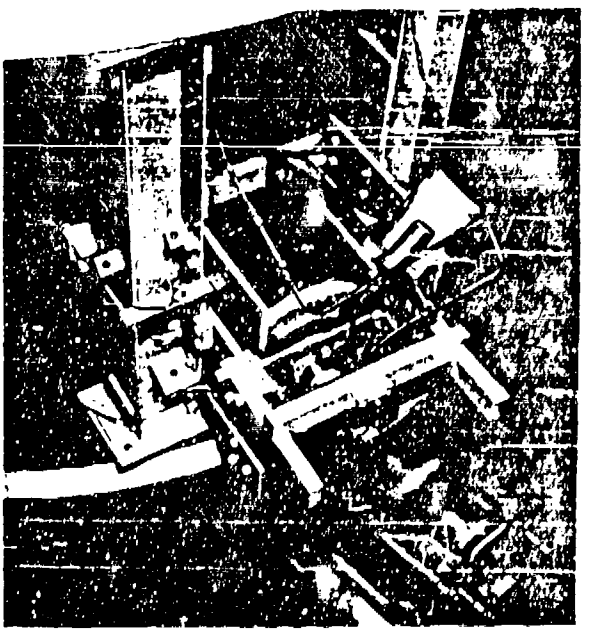


Fig. 6-33. Acceleration-vibration test stand (electro-magnetic vibrator mounted on centrifuge).

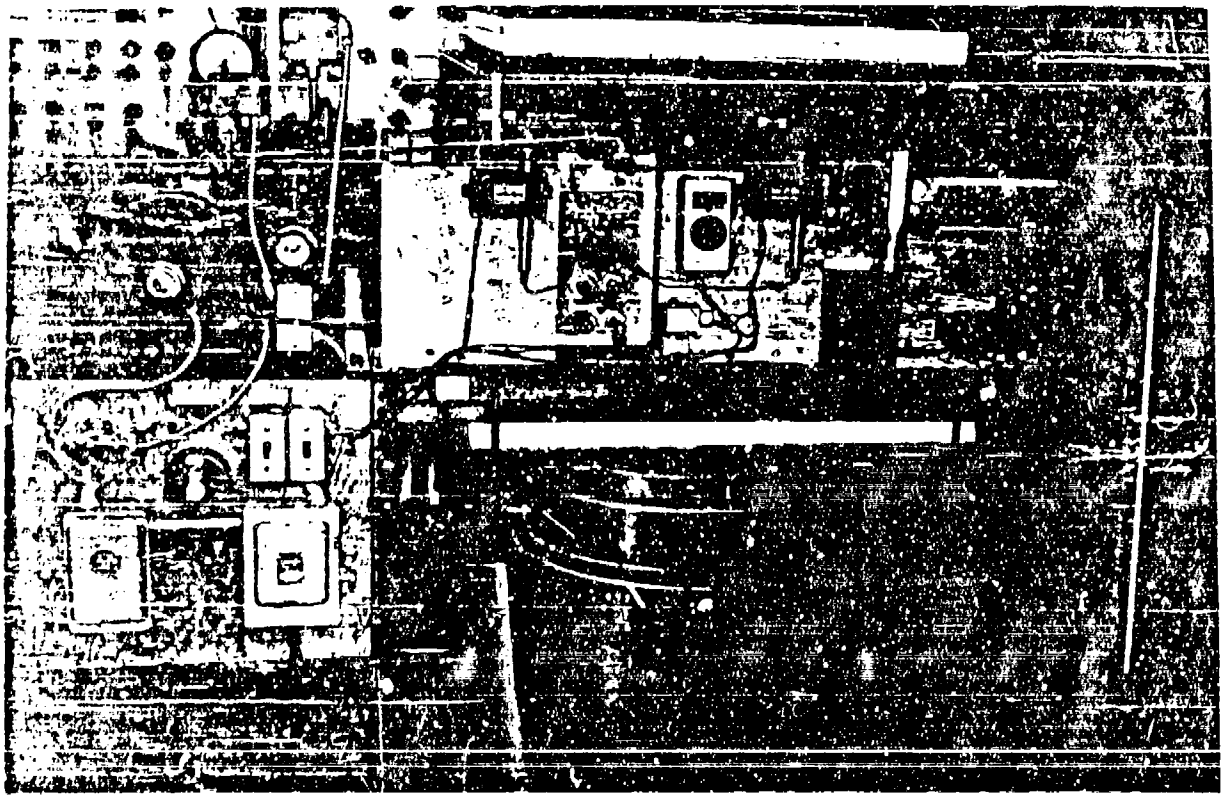


Fig. 6-34. Combined temperature, altitude and vibration test facility.

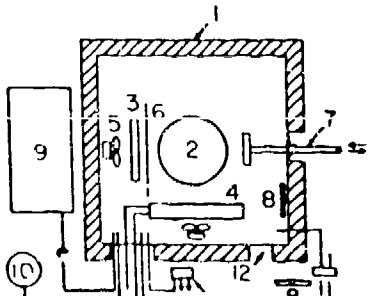


Fig. 6-35. Layout of combined temperature, altitude and vibration test facility (for legend see Table 6-5.

Hyper and Space Environment Facilities

In the area of hyper and space environment simulation some work has been carried out, but there is still much to be done. Some success has been achieved in developing facilities capable of providing altitudes of 10^{-6} to 10^{-9} millimeters of Hg, based on the 1959 Model Atmosphere/7/. In addition, some facilities that will produce the temperature ranges encountered in space are becoming available (Fig. 6-37). Beyond this, however, very few facilities have been developed for simulating other hyper and space environments.

One program, carried out by the Norair Division of the Northrop Corporation for the Environmental Branch, Engineering Test Division, Flight and Engineering Test Group, Wright Air Development Division (now Aeronautical Systems Division), has developed specifications for hyper and space test facilities. The proposed facilities are shown in Figs. 6-38 through 6-42. Their capabilities are listed in Tables 6-6 through 6-9. Additional information on hyper and space environment facilities can be found in the last three documents in the Test Facilities section of Table 4-1.

A hyper environment test facility that will be used for both functional and environmental testing of subsystems is presently in the design phase and will be built at Aeronautical Systems

Table 6-5. Legend for Fig. 6-35

Item No.	Description
1	Outline of sealed chamber. Inner dimensions are 24 inches x 24 inches x 18 inches high. Insulation consists of marinite sheets, two inches thick.
2	Inner vibration table. Consists of aluminum plate 9.5 inches in diameter and 0.5 thick. Vibration is transmitted from head of vibration machine by three 0.5-inch steel rods located on 8-inch diameter disc, 120 degrees apart. Seal is provided by 0.5-inch Teflon bellows.
3	Strip heaters. Provide maximum of 1500 watts.
4	Air condenser. 23.7 square foot surface.
5	Air circulation fan (located at either of two positions). 100 cubic feet per minute.
6	Radiation baffle.
7	Drive for mechanical operation of test item. Seal is provided by 0.5-inch Teflon bellows.
8	Terminal strips.
9	Steam generator, 3 kilowatt. Output is controlled thermostatically through solenoid valve.
10	Vacuum pump.
11	Mercury manometer.
12	Amphenol connectors.
13	Thermostats (temperature and humidity).
14 and 15	Cooling by CO_2 directly or indirectly through air condenser.
16	Switches (main, rotary heating selector, steam generator, and fan).

Division, Wright-Patterson Air Force Base. This facility will be called the Dynamic Analyzer. It combines both the operational environments and functional evaluation parameters into one facility. It has as its primary purpose the evaluation of reconnaissance equipment, but it also has capability for testing under combined environments any type of system, subsystem, or equipment that can be accomodated in the capsule. This facility will be completed early in 1962. The Dynamic Analyzer is shown in Fig. 6-43. Its capabilities are listed in Table 6-10.

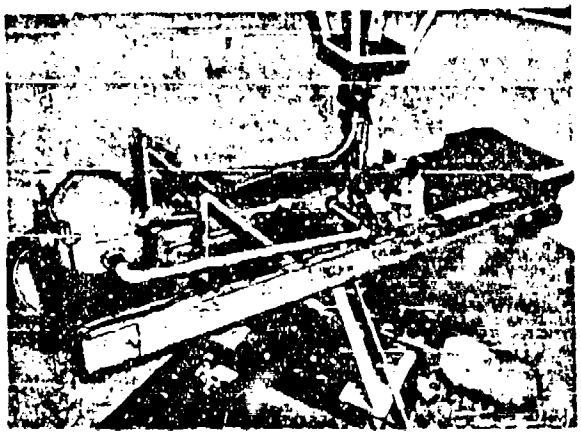


Fig. 6-36. Wyle Combined Environmental Centrifuge. (Courtesy of Wyle Laboratories)

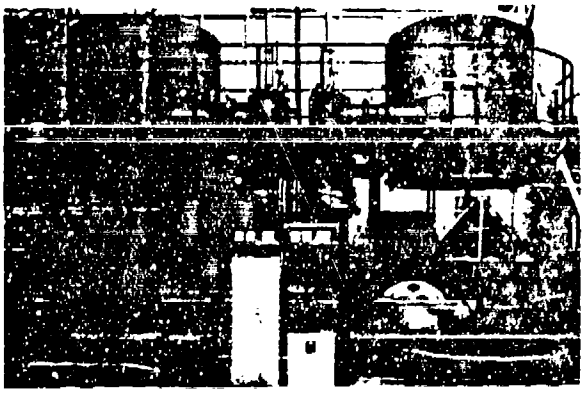
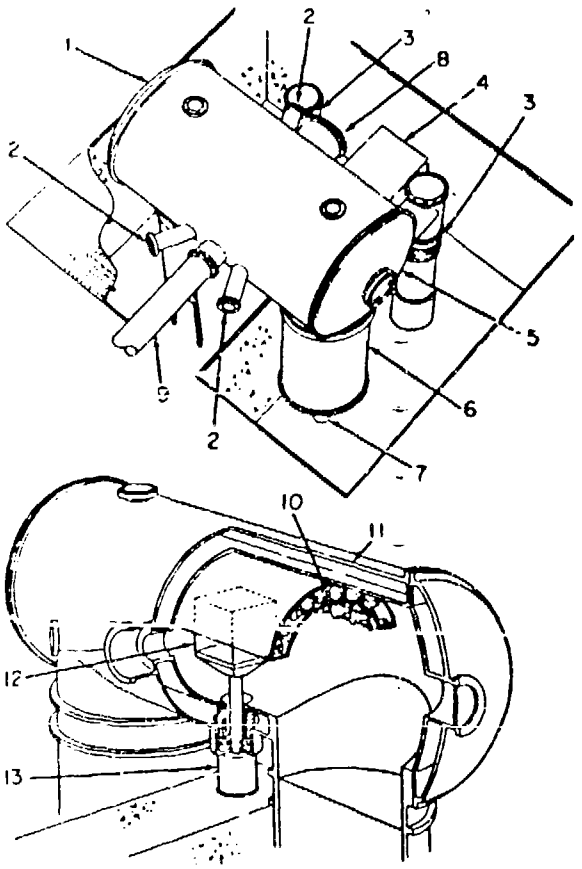


Fig. 6-37. Dual-chamber orbital temperature-altitude simulator with Courier satellite interframe mounted on chamber door. (Courtesy of Philco Western Development Laboratories and U.S. Army Signal Research and Development Laboratories, Fort Monmouth, New Jersey)

At present, the zero-gravity environment cannot be simulated for sustained periods by a fixed installation. Many systems have been proposed and several schemes have been used to provide accelerations, short periods of zero-g (weightlessness), or combinations of these. Some of these proposed methods are (1) a controlled free-fall elevator; (2) a shaft cut along a radius of the Earth; (3) a parabolic track on the Earth's surface; and (4) a circular-path zero-gravity device. None of these methods has been perfected, and at present, actual aircraft flight is the only means available to combine acceleration with the zero-gravity conditions. The primary drawbacks in aircraft flight programs are the



1. Chamber
2. Optical Windows
3. Oil Diffusion Pumps
4. Cryostat
5. Large Access Door
6. Cryopump Heat Exchanger Housing
7. Hydraulic Lift (for Removal of Heat Exchanger and Drip Pan)
8. Window and Small Access Door
9. Solid Particle Accelerator
10. Radiation Lamps
11. Chamber Shell
12. Specimen
13. Electro-Hydraulic Exciter

Fig. 6-36. Space research facility.

inability to obtain realistic acceleration and deceleration forces over the proper time periods, and an inability to provide a true weightless state during the full parabolic flight. Additional problems involved when using aircraft are maintenance, the use of special instrumentation, and the rather high cost per test.

Systems or Full-Scale Environmental Test Facility

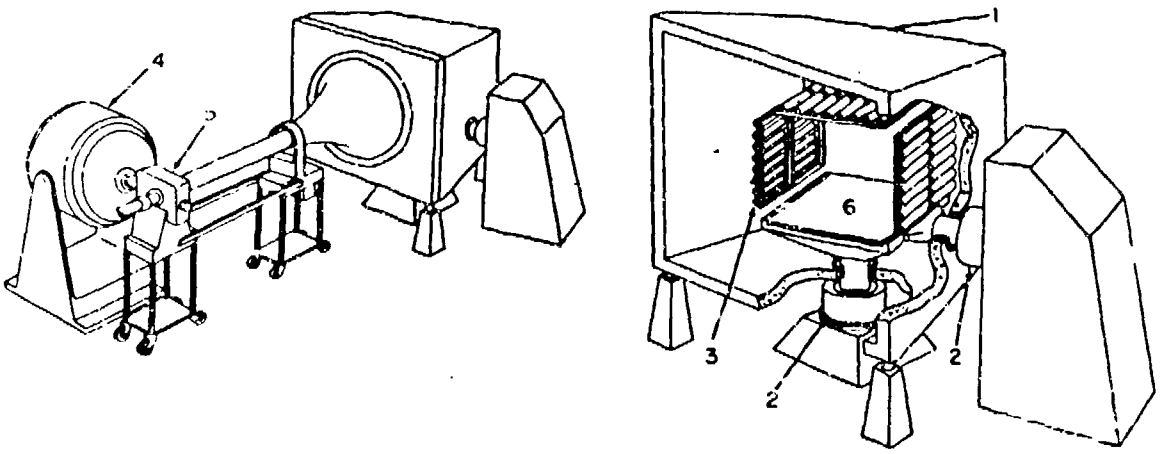
A systems or full-scale environmental test facility is one in which an entire weapon system or flight vehicle is exposed to either the exact environment it will experience during operation, or as much of the operational environment as it is technically feasible to simulate. It has been hypothesized that such a facility would make possible a much more reliable prediction of environmental effects on a system than is now possible with the single and simple combined facilities used to test materials, components and subsystems. In the case of low temperature to -65 F and high temperature to 160 F, the Climatic Hangar (Fig. 6-44) at Eglin Field, Florida, which can test complete systems, has been very useful in uncovering system integration problems under low and high temperature conditions. The correlation problem for these environments, however, is simple when compared to dynamic or space flight environments since they only depend on temperature stabilization. Whether or not a full-scale facility for simulating all operational environments would enable more reliable prediction of environmental effects remains to be seen. Because of the technical difficulties and large design and construction costs involved, an actual full-scale environmental test facility that would simulate the operational environment has not been built to date. Other problems are also involved, particularly that of correlating the external vehicle environment to that which would actually be encountered during the vehicle mission. This deficiency makes the correlation of the external simulated environment to the internal environment adjacent to or in equipment and subsystems within the airframe even more nebulous. Accelerating the test required, particularly for long flight-time satellites and space vehicles, poses even greater problems.

Preliminary study of a systems test facility for space vehicles has been carried out by Arnold Engineering Development Center, Tullahoma, Tennessee. This study has resulted in a proposed military space systems test facility, called Mark II. This proposed facility is shown in Fig. 6-45 and its capabilities are listed in Table 6-11. An interim facility, called Mark I, is presently in the preliminary stages. It is of much smaller design, but will allow testing of some of the smaller systems.

Environmental Test Facilities for Humans

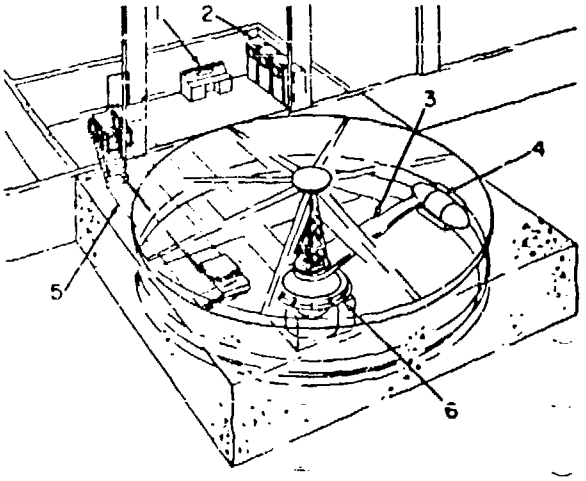
Full-scale environmental test facilities for humans will make it possible to determine the suitability of personnel protective assemblies, such as space suits, capsules, and life support systems, by testing them in the same extreme environments in which they will be used. Such facilities will also serve for selection and training of astronauts and for study of psychological and ecological problems related to survival outside the Earth's atmosphere.

A proposed environmental facility for life support systems is illustrated in Fig. 6-46. /8/ The legend for Fig. 6-46 is given in Table 6-12. This facility consists of three chambers: a cryo-cooled, high-vacuum chamber shown at the left; a safety chamber in the middle; and a solar and infrared radiation chamber at the right.



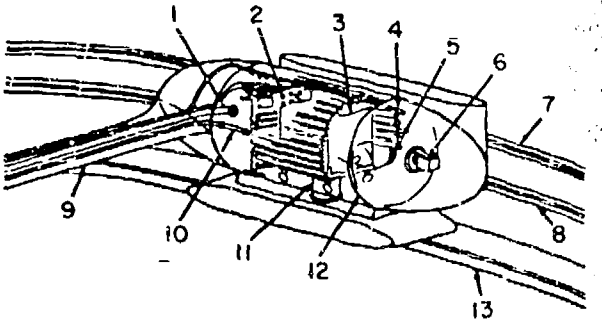
1. Reverberant Cell
2. Electro-Hydraulic Exciters
3. Radiation Lamps
4. Electro-Magnetic Exciters
5. Acoustic Generator
6. Specimen Table

Fig. 6-39. Acoustic-mechanical vibration facility.



1. Shock and Vibration Program Controls
2. Temperature and Altitude Program Controls
3. Instrumentation Boom
4. Specimen Vehicle (See Fig. 6-29)
5. Personnel/Instrumentation Tunnel
6. Central Hub and Slip Rings

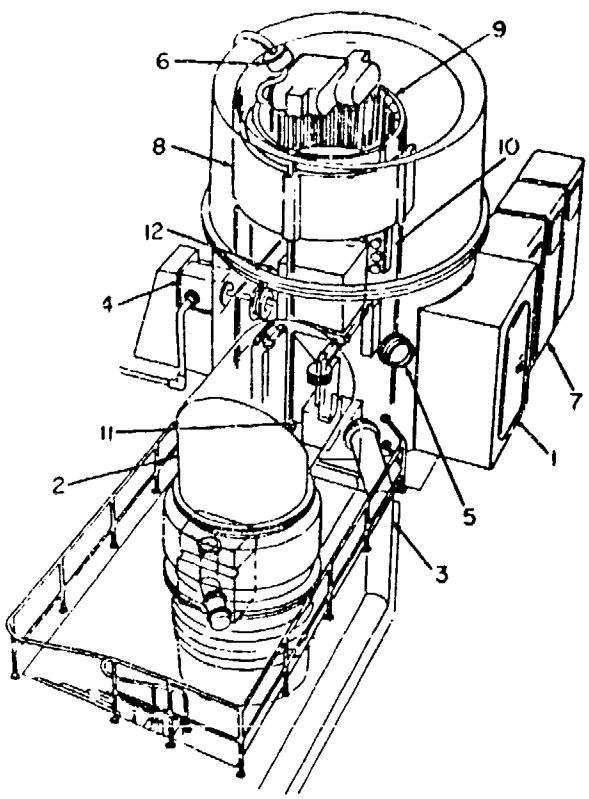
Fig. 6-40. Inertial dynamics facility.



1. Vacuum Line
2. Instrumentation Cables
3. Specimen
4. Cryogenic Injectors
5. Radiation Lamps
6. TV Camera
7. Vertical Rail
8. Power Rail
9. Instrumentation Boom
10. High Pressure Line
11. Electro-Hydraulic Exciters
12. Vacuum Chamber
13. Horizontal Rail

Fig. 6-41. Test-specimen vehicle for inertial dynamics facility.

In the left chamber, the low radiative temperature of outer space of almost absolute zero is simulated by cooling the black inner chamber walls with liquid or cold gases such as helium, liquid nitrogen, or liquid-air liquefied in recirculating cryostats. Cooling traps with liquid or cold helium refrigerant gas at a temperature of about 20 K will be provided to condense the air leaking and out-gassing from test objects, and to approach the near vacuum of outer space.



1. Entrance Hatch
2. Diffusion Pump
3. Roughing Pump Line
4. Horizontal Electro-Hydraulic Exciter
5. View Port
6. Vacuum-Tight Gland
7. Control Console
8. Cold Wall
9. Radiation Lamps
10. Solar Lamps
11. Vertical Electro-Hydraulic Exciter
12. Specimen

Fig. 6-42. Thermo-mechanical dynamic facility.

In the right chamber, the direct radiation from the sun is simulated on the upper hemisphere of the chamber by a combination of carbon-arc lamps, high-pressure mercury vapor lamps, tungsten lamps, filters and reflectors. Indirect solar radiation is simulated by reflectors and infrared radiators arranged in a ring on the chamber floor. By switching on different numbers of sun lamps and infrared radiators, the intensity of the simulated solar radiation can be varied without changing its spectral energy distribution. This allows simulation of the solar radiation level in the vicinity of various planets. The low-temperature background of the black sky is also simulated in the solar radiation chamber by cooling the upper hemisphere. Without this cooling, the chamber walls would be heated above room temperature and the actual conditions would be distorted.

Table 6-6. Specifications for Space Research Facility

Environment	Facility capability
Low pressure	10^{-9} mm of Hg (corresponds to 1,600,000 feet according to 1959 Model Atmosphere).
Electromagnetic radiation	Infrared, visible and ultraviolet radiation between 100,000 and 1800 angstroms will be simulated.
	Extreme ultraviolet radiation will be simulated to 1000 angstroms, and an attempt will be made to simulate it to 100 angstroms.
	As much of the X-ray spectrum as possible will be simulated.
Vibration	Frequency spectrum of 5 to 2000 cps, sinusoidal.
Dissociated and ionized gases:	Particle densities occurring from 60 to 400 kilometers (200,000 to 1,300,000 feet):
Ionized gases	10^3 to 4×10^6 particles per cubic centimeter.
Oxygen dissociation	From 0 to 80 percent.
Nitrogen dissociation	From 0 to 50 percent.
Ozone	Concentration from 8 to 500 parts per million at altitudes from 60,000 to 130,000 feet.
Atomic particle radiation	Secondary X- radiation will be simulated.
Solid particle impact	Solid particles from 10 to 250 microns in diameter and at velocities of 10,000 to 20,000 feet per second. Rate of particle injection is indeterminate at this time.
	With further development, particle velocities in the meteorite range (35,000 to 225,000 feet per second) can be achieved.

Space research facility to be 6 feet in diameter by 13 feet in length.

Aerodynamic heating occurring during reentry can also be simulated in the solar radiation chamber at any desired low pressure by arranging special heat lamps around the reentry body.

Table 6-7. Specifications for Acoustic-Mechanical Vibration Facility

Environment	Facility capability
Acoustic	Sound pressure level up to 170 db, with wide-band random capability over frequency range of 20 to 10,000 cps in reverberant field. With further development, sound pressure level of 180 db can be maintained for short period, followed by 170 db continuously.
Aerodynamic heating	Programmed heating of test specimen perimeter surfaces to vehicle flight profile requirements. Maximum surface temperature of 2400 F (1300 C).
Vibration	Programmed sinusoidal and random vibration in vertical and lateral axes. Frequency of 2 to 2000 cps. Magnitude of ±40 g sinusoidal and ±0.2 g per cycle random.
Shock	0 to 500 g over 1 to 30 millisecond period.

Internal volume of acoustic-mechanical vibration facility is 32 cubic feet.

Table 6-8. Specifications for Inertial Dynamics Facility

Environment	Facility capability
Altitude	To 120,000 feet, programmed to vehicle flight profile.
Aerodynamic heating	Programmed heating of test specimen perimeter surfaces to vehicle flight requirements. Maximum surface temperature of 2400 F (1300 C).
Vibration	Programmed sinusoidal and random vibration in vertical and lateral axes. Frequency of 2 to 2000 cps. Magnitude of ±40 g sinusoidal and ±0.2 g per cycle random.
Programmed shock	0 to 500 g over 1 to 30 millisecond period.
Acceleration	Variable from 0 to 100 g. May be programmed to vehicle flight profiles from 0 to 100 g with 3-second onset.

Test area of inertial dynamics facility is 50-foot diameter pit.

Table 6-9. Specifications for Thermo-Mechanical Dynamic Facility

Environment	Facility capability
Low pressure	10^{-6} mm of Hg (corresponds to 550,000 feet according to 1959 Model Atmosphere). Modifications will ultimately allow low pressure of 10^{-9} mm of Hg to be achieved if desired.
Solar heating	130 watts per square foot on one-half of test specimen perimeter. Will cover principal heating spectrum of 100,000 to 2000 angstroms.
Aerodynamic heating	Programmed heating of test specimen perimeter surfaces to flight vehicle profile requirements. Maximum surface temperature of 2400 F (1300 C).
Vibration	Programmed sinusoidal and random vibration in vertical and lateral axes. Frequency of 5 to 2000 cps. Magnitude of ±40 g sinusoidal and ±0.2 g per cycle random.
Programmed shock	0 to 500 g over 1 to 30 millisecond period.

1. Thermo-mechanical dynamic facility to be 8 feet in diameter by 10 feet in length.
2. Provisions for later addition of other hyper environments, such as ozone, ionized and dissociated gases, and high-velocity solid particles, will be considered in design of facility.

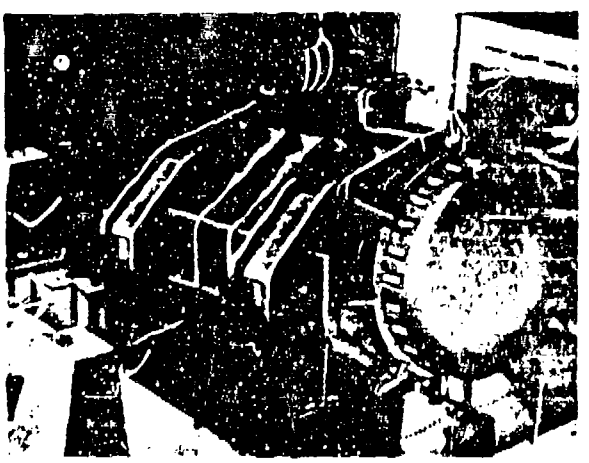


Fig. 6-43. Dynamic Analyzer.

Table 6-10. Capabilities of Dynamic Analyzer

Environment or operational parameter	Facility capability
Pressure	Ground level to 3.8×10^{-7} mm of Hg in 100 minutes.
Temperature (high)	From ambient to 450 F (232 C) in 45 minutes, measured on internal wall of radiating surface. Heat will be radiated from clam-shell type radiating surface.
Temperature (combined high and low)	One-half of radiating surface will heat to 400 F (205 C) and other half will cool to -40 F (-40 C) simultaneously. These temperatures will be measured on internal walls of radiating surfaces.
Vibration	Frequency from 2 to at least 800 cps. Low-frequency double amplitude will not be greater than 0.5 inch, with maximum acceleration of 5 g available from cross-over point to end of high-frequency spectrum.
Modular package cooling system	Will provide 15 pounds of air per minute at controlled temperatures from -40 to 200 F (-40 to 93 C) at equipment.
Roll, pitch and yaw:	
Roll	±20 degrees from 30 minutes per cycle to 5 cycles per second.
Pitch	±20 degrees from 30 minutes per cycle to 5 cycles per second.
Yaw	±2 degrees from 5 minutes per cycle to 5 cycles per second.
Size of work space	Seven feet in diameter by eight feet in length.

Rapid heating of the skin of the reentry body by various degrees and with different temperature distributions can also be obtained by using high-frequency coils or radar heating.

The safety chamber provides for instantaneous reversal of test conditions and rescue of the test subject within a few seconds in case of an emergency.

DESIGN AND SELECTION OF FACILITIES

It is not the purpose of this handbook to give detailed information on the design and construction of environmental testing facilities. However, in designing and selecting such facilities, certain general factors must be kept in mind if the facility is to operate effectively and efficiently. These factors are:

1. Mechanical features.
2. Instrumentation.
3. Safety features.
4. Economic considerations.

Mechanical Features

Use of the most up-to-date materials and techniques is essential to the design of environmental testing facilities. Usually, the test equipment must be designed and constructed so that it can simulate the desired environment many times in order to economically justify its existence. A salt spray chamber designed to test corrosion resistance must not itself fall apart after a few exposure tests. This same philosophy applies to all types of environmental testing facilities except a few, such as certain types of rocket sleds used in "one-shot" applications. However, even in the case of such an expendable test equipment, the materials and techniques used in its construction must be such that it will perform its function reliably and effectively. In effect, environmental facilities must be simple and economical, and at the same time capable of producing repeatable environments to assure similar test results.

Instrumentation

At the time a testing facility is being built or purchased, the instrumentation requirements should be reviewed, not only in the light of immediate need, but also with respect to future needs and flexibility. Percentagewise, instrumentation cost relative to facility cost is usually small. However, in terms of potential savings in man-hours and elapsed-time, a judicious selection of instrumentation can have a considerable effect during the useful life of the test facility. As an example, for certain test chamber applications programmed instrumentation can effect savings in elapsed-time and man-hours, while at the same time providing a permanent record of the cycle produced.

The accuracy of instrumentation should also be considered in terms of both the present and future usage of the facility. Instrumentation of low accuracy may be acceptable now, but this may not be so at some future date when the facility is used for another project. In the long run, it may be far less expensive to initially install instrumentation of greater accuracy than required, than to convert from low to high accuracy instrumentation in the future.

Safety Features

Because of the extreme environments produced by many testing facilities, the safety of operating

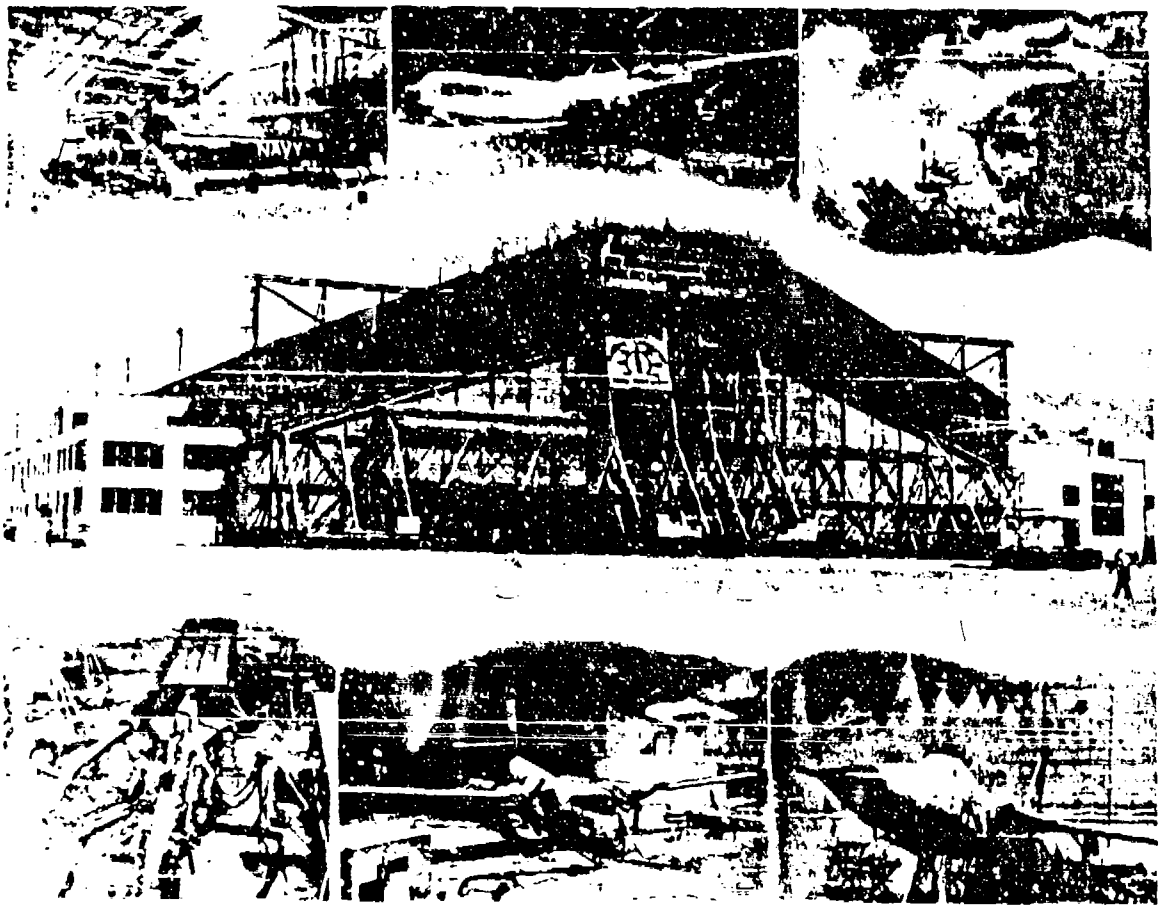


Fig. 6-44. Climatic Hanger at Eglin Field, Florida.

personnel is an important consideration and should never be compromised for reasons of economy. Applicable military specifications should be used as the primary guide in determining what safety features a particular facility requires. These specifications cover items such as circuit breakers, temperature safety controls, automatic drains, relief valves, etc. Two such specifications are MIL-C-7915A, "Chamber; Altitude, Humidity, and Temperature Test," and MIL-C-9435A, "Chamber, Explosion Proof Testing."

Economic Considerations

In procuring or designing test equipment for any environment, several basic factors should be considered before the final size or capacity is decided upon.

1. What are the present capacity requirements?

2. What will be the future capacity requirements?

3. Is the same test equipment to be used for production models as well as for prototype work?

4. Will it be necessary to increase the severity of the environment in the near future?

The answers to these questions define the test equipment parameters and should result in facilities that are economically feasible for present operation and which will not become obsolete within a year or two. An example of this is altitude chambers. Although existing specifications call for a simulated altitude of 60,000 feet for manned aircraft components and equipment, it might be desirable in the near future to use the same facility for missile work, thus making it necessary to have altitude simulation capabilities of 200,000 feet or more. This added altitude range can be obtained for a small percentage increase in cost over that of a chamber of 60,000 feet capability when the equipment is first built.

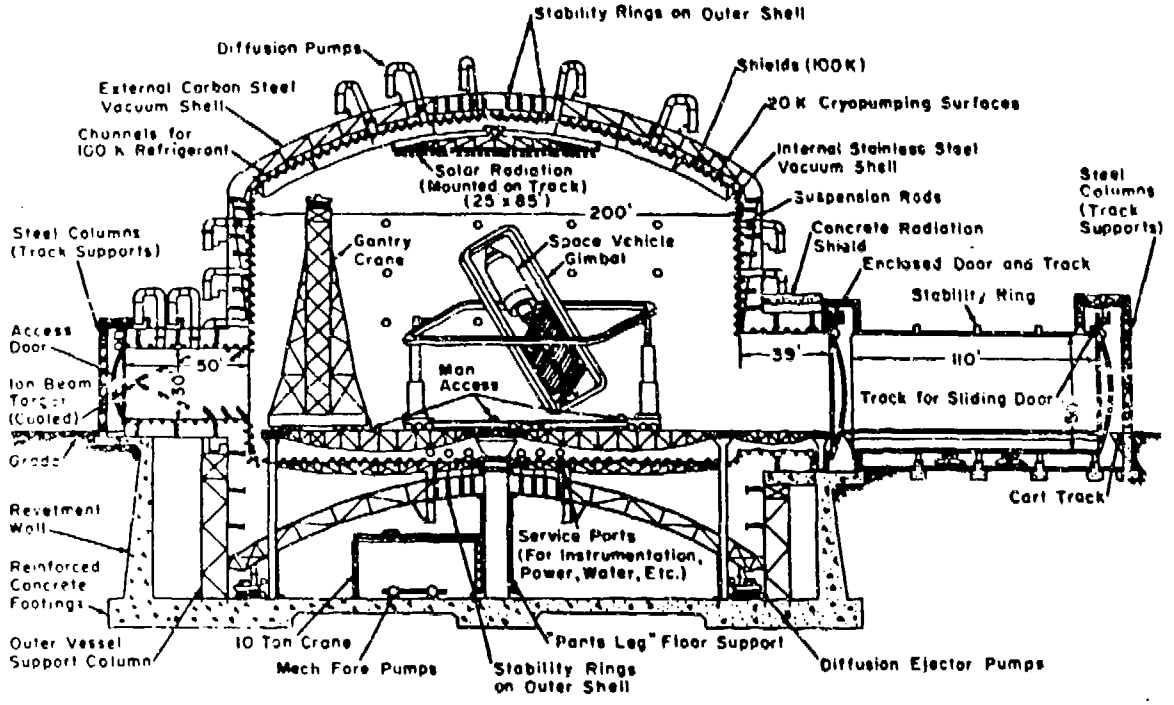


Fig. 6-45. Proposed military space systems test facility.

Table 6-11. Capabilities of Proposed Military Space Systems Test Facility

Environment	Facility capability
Pressure	10^{-6} to 10^{-8} mm of Hg dependent on load.
Temperature (heat sink)	T_{wall} = 100 K.
Solar radiation	144 watts per square meter over a 175-square meter projected area.
Atmospheric composition	N_2, O_2, and H_2.
Dynamic atmosphere	Velocity of approximately 12,000 meters per second with mass flows 80 to 150 km, approximately 1 to 0.0001 kilogram per second.
Magnetic fields	0 to 21 Gauss.
Vibration	Two 10,000 kilogram shakers to simulate actual excitation.
Shock	200 g for 1 millisecond, to 15 g for 11 milliseconds.
Angular velocity and acceleration	Power-driven gimbal mount.

Likewise, in the area of vibration testing, although some specifications require tests to 500 and 600 cps, it is often advantageous to obtain generator equipment that operates up to 2000 cps and costs only slightly more.

Costwise, the advantages and disadvantages of test equipment versatility should be weighed. A combination temperature, altitude and humidity facility can be contained in one chamber. Is it worth tying up an expensive piece of test equipment for a long humidity run when it could be used for other test work on temperature and altitude? Or does it pay to get a separate humidity chamber for this purpose at a fraction of the cost of the temperature-altitude box? These questions indicate the type of thinking that must be done to insure economical procurement of test equipment. Table 6-13 is a checklist of things to be considered when procuring environmental test equipment.

Environmental Laboratory

The layout of an environmental laboratory is shown in Fig. 6-47. Generally, the test equipment is divided into the four following categories, each of which can be located in a separate area:

1. Climatic.
2. Shock.
3. Vibration.
4. Acceleration.

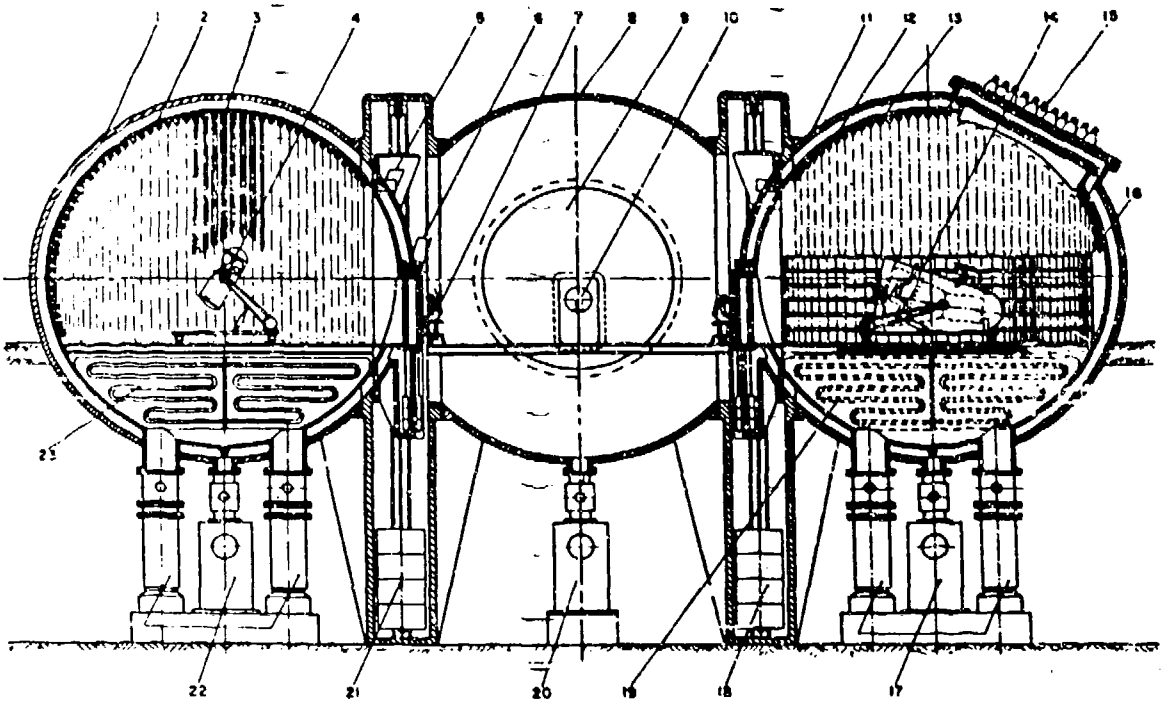


Fig. 6-46. Proposed environmental facility for life support systems. (For legend see Table 6-12) /8/

Table 6-12. Legend for Fig. 6-46

Item no.	Description	Item no.	Description
1	Outer wall of cryo-cooled chamber.	12	Inner wall of solar radiation chamber.
2	Inner wall of cryo-cooled chamber.	13	Refrigerant coils for freon.
3	Refrigerant coils for liquid nitrogen.	14	Manned compartment of space vehicle.
4	Extendable space-worker cabin.	15	Solar radiation simulators.
5	Large chamber doors.	16	Infrared radiators.
6	Small chamber doors.	17	Vacuum pumps and cryostats in basement.
7	Observer in safety chamber.	18	Counter weights for chamber door.
8	Outer wall of safety chamber.	19	Helium cooling trap.
9	Large chamber door.	20	Vacuum pump.
10	Small chamber door with outside observer.	21	Counter weight for chamber door.
		22	Vacuum pump.
11	Outer wall of solar radiation chamber.	23	Vacuum pumps and cryostats in basement.

Table 6-13. Testing Facility Check List

Materials and equipment
Location of test equipment.
Dissipation of equipment under test; intermittent or constant.
Dead mass, material and weight.
Noncorrosive chamber lining for particular application.
Special "footings" for some equipment, such as compressors, shock machines, etc.
Blowers or fans to prevent stratification of air in chamber.
Layout
Viewing windows (number, type, size and location).
Doors (number, type, size and location).
Sufficient working area.
Illumination (type and level).
Waste and water supply lines.
Ports for cables.
Dummy mounting panels.
Instrumentation, power and control
Type and capacity of power supply.
Terminals for power, signal, high-voltage and coaxial leads.
Pull-down time or steps.
Sensing elements (number, type and accuracy).
Recorders (number, type and accuracy).
Recorder controllers, programming controllers, type of heaters.
Safety
Non-hazardous location of facility in event of failure.
Personnel safety devices.
Equipment safety devices.

Climatic. The environments falling into this category have been discussed previously and will not be repeated; however, it is important to locate these facilities in a separate section of the laboratory in an arrangement satisfactory

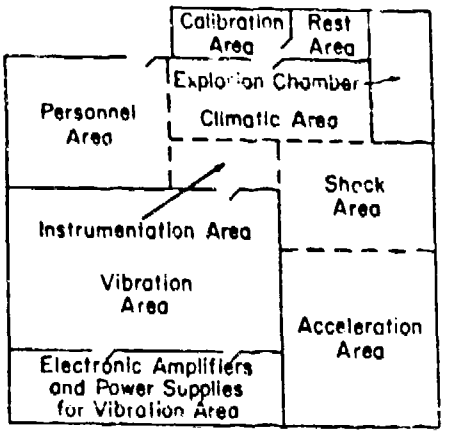


Fig. 6-47. Layout of typical environmental laboratory.

to the physical size and purpose the equipment is to perform. Advantages can sometimes be gained in floor space by grouping and double or triple decking such auxiliary equipment as pumps, compressors, meters, etc. Do not locate climatic facilities in the vicinity of doors leading to the outside. If possible also, this section of the laboratory should be air conditioned to permit uniform conditions of temperature and, relative humidity to be maintained.

Shock. Examples of equipment in this category are the Navy medium- and high-impact machines, sand drop machines, and lead pellet machines, which produce shock pulses in varying magnitudes and durations. This type of equipment is often noisy and is sometimes hazardous since parts may fly off the equipment during the test cycle. For these reasons, as well as from a functional standpoint, this type of equipment should be grouped. Depending upon the location within the laboratory, it may be necessary to build a wire mesh screen in front of the machine to protect personnel from flying parts.

Vibration. There are several major reasons for segregating this type of equipment to one section of the laboratory. First, the equipment produces a high noise level that should be shielded from the surrounding area and personnel. Second, the electronic consoles used with the shaker dissipate large amounts of heat, and it is desirable to locate this equipment outside of the air conditioned portion of the laboratory. And third, the equipments perform similar functions, sometimes making it possible for auxiliary equipment to complement different shaker systems.

Acceleration. While it is not essential to group different types of centrifuges, from a functional and work flow standpoint it is a natural segregation.

Explosion Chamber. The explosion chamber should be contained in a separate air conditioned room. This room must be insulated so that noise caused by explosions is not propagated throughout the laboratory.

Research and Development Testing

Although the laboratory layout shown in Fig. 6-47 is suitable for present testing requirements, it does not allow for research and development testing. For R and D testing, as many as possible of the facilities should be movable so that in any of the cells or facilities combinations of environments can be set up. Only the heaviest facilities, such as large centrifuges, should be permanently built-in. Another requirement is that a shop be included, not only for calibration and maintenance of the facilities, but also for modification and adaptation of facilities to fit new combinations of environmental set-ups as well as improvisations and construction of new facilities. The Norair Design and the Dynamic Analyzer are ideal facilities for research and development purposes since they provide maximum combination and flexibility, which are required in studying environmental effects.

The Future of Environmental Testing Facilities

In the future, environmental testing facilities will be called upon more and more to simulate hyper environments and combined environments, as well as to increase the duration and level of many present-day tests. To be able to do this effectively and economically new materials and techniques must be developed. Improvements in existing insulators, structural materials, refrigerants, sealing and refrigerating techniques, instrumentation, etc, are needed. In addition, programmed controllers that more nearly simulate the actual expected environments are required in some areas. As various "breakthroughs" occur, they will be incorporated into existing facilities, as well as forming the foundation for entirely new ones.

TEST PROCEDURES

Environmental simulation is determined both by the facilities and test procedures used. The various types of facilities have been discussed. The remaining paragraphs of this chapter discuss the philosophy of developing test procedures under various circumstances. The factors involved in developing test procedures include:

1. The mission profile of the weapon system.

2. The operational, functional and environmental profile of the materials, equipment and subsystems within the weapon system.

3. The integration of test purposes with the test procedure.

4. The strategy and tactics of environmental testing.

5. The development of the test procedure itself.

6. Single and combined environmental tests.

7. Sequencing of environmental tests.

8. Standardization of tests (uniform duplication).

ENVIRONMENTAL TESTING GOALS

The application of scientific method to environmental testing is the foundation of sound test procedures. The purpose of the test is the starting point for analysis, defining the scope of tests to be performed, as well as their required range of validity and reliability; scientific method implies the use of the strategies and tactics that have given man unparalleled command and knowledge of his physical environment during the last 300 years. The decision to pursue a given course of environmental testing implies a decision as to the relevant variables and key parameters involved in relation to the time, facilities and resources that may be allocated to the task.

Environmental testing may be directed towards a diversity of goals:

1. The establishment of reliable performance in the mission. Obviously, this is a necessary requirement, without which all other qualities are valueless.

2. Establishment of reliable performance in the logistic environment. Almost all military equipments spend far greater periods of time in storage, transportation and in "ready-state" than they do in the mission phase, and it is evident that the equipment must be available at the point of use in a condition that permits the mission to be performed.

3. Usually neglected, but of major importance, is the maintenance environment. This includes the environments associated with the actions necessary to maintain the readiness and the performance of the system. For example, if during maintenance moisture from the hand were transferred to a piece of equipment, it could be the start of a rust spot or the cause of a fungi formation. Likewise, handling shocks during maintenance can damage equipment.

It is therefore seen that the test procedure must make provision for the induced, as well as the natural environment. Indeed, the test of one without the other verges on the meaningless.

Strategy and Tactics of Environmental Testing

The scope of environmental testing and the procedures applicable to it benefit from the fact that nature is linear over useful working ranges of the environment. That is to say: (1) components built of materials, each of which

withstand the environmental stress, have a considerable chance of working together in combination, and (2) knowledge gained on a part of a system provides guideposts to assessment of the whole system.

The sequence of environmental testing procedure goes hand-in-hand with engineering development. Order-of-magnitude results that are usable in the initial stages of research and development are followed by engineering developmental testing, in which the complete mission envelope is explored for critical areas and a precise delineation of limits. Then, the demonstration testing of the prototype is carried out, in which the object is to establish the success of the research and development. Finally, there is production testing, which demonstrates that the production items perform within the required limits.

The implementation strategy affecting the selection of the test procedure depends on the level considered. A practicable classification of these levels is as follows:

1. Materials.
2. Parts.
3. Components.
4. Subsystems.
5. Systems.

In planning environmental test groupings, it is necessary to catalog and define the materials, parts, components, equipment, subsystems and systems.

Materials. Materials are metals, their alloys and non-metals. The properties of materials establish the performance limitations of the items which they constitute. The following major classifications may be considered:

1. Metals and alloys.
2. Ceramics and graphite.
3. Plastics and elastomers.
4. Fluids (including petroleum products).
5. Composite materials.

Parts. A part is the smallest functional item.

Components. A component is an assembly of parts that has a specific function in an item of equipment.

Equipments. An equipment is an assembly of components that has a specific function in a subsystem.

Subsystem. A subsystem is an assembly of equipments that has a specific function in a system and is essential for functional completeness of the system. Examples of subsystems are: structure, engine, fuel subsystem, bombing and navigation subsystems, fire control subsystem, electrical subsystem, etc.

Systems. A system is an assembly of subsystems that has a specific function in a weapon system and is essential for the accomplishment of the weapon system design mission. Examples of systems are the flight vehicle (aircraft or missile) system and the ground servicing system.

Weapon Systems. A weapon system is an assembly of systems essential to accomplish a specific Air Force mission.

Preliminary Test Procedure Development

The strategy and tactics of test procedure development consist of the utilization of all previous knowledge to determine:

1. What factors must be considered, and the quantitative limits on such factors.
2. The value of increased accuracy and reliability of knowledge in the specific case.
3. The applicability and responsiveness of single and combined environmental tests.
4. The environments to be tested and their grouping.
5. The equipments and procedures required for the standardization of test results.
6. The number of items required.

It is obvious that a decision in any one of these areas has implications for the others. Thus, for preliminary investigations a wide range of factors may be considered, using only a single specimen in simplified tests and different equipments whose convertibility is only crudely known. Such an approach, although soundly applicable for detecting gross problem areas is not at all suitable in the succeeding stages of test procedure development in which successively higher orders of accuracy must be obtained.

Previous knowledge is the basic factor in the process of initially establishing the test procedure. In the practical case, it is seldom necessary to assume complete ignorance of materials, components or even subsystems behavior. A thorough going, critical review of available literature, previous test results, and experience is a simple, often-neglected, step that pays manyfold dividends.

The establishment of the initial test procedure does not imply rigidity, either in thinking or in procedure. Indeed, the results obtained during each group of tests must be evaluated and assessed to determine what changes are necessary in the succeeding steps of the program, and, in fact, if the program itself should be redirected.

The validity of the test procedure, and its results, is purely operational; that is, it must be judged solely in terms of its contribution to the success of the program. The succeeding sections of this chapter discuss the steps required for and considerations pertinent to the development of a test procedure, as well as the implementation of the key concepts of single and combined environments, uniform duplication of results, and selection of the number of test items.

Selection of Test Procedures

The basis for a particular test procedure is the expected operational function and environment. The scope of the test objective must be broad enough to include the data required to evaluate the design, materials and function. Hence, the designer must set the limits of information needed, and the accuracy with which it must be obtained. A check list of all the environments, such as that included at the beginning of Chapter 3, must be screened to establish: first the relevance of the environment, then the frequency and criticalness of the environmental encounter. The two, taken together, provide the envelope of environmental stresses and their quantitative limits. Certain of the environments occur in combinations, and certain are mutually inhibiting.

Considerations dealing with test chamber availability, as well as time and number of specimens available, are frequently ignored in theoretical treatments, but play an important part in all practical cases. Thus, an investigation of the apparatus required for a combined vibration, sustained acceleration and extreme temperature test chamber /9/ suggests that the tests performed reveal specimen characteristics not obtainable in any other way, and hence, that such tests are essential for a comprehensive development program. On the other hand, they were assessed as not practical for routine production testing.

It is at this point that the value of the proposed test should be studied by comparing the desired information with the cost and consequences of obtaining it. In any practical case, the number of possibilities speedily reaches astronomical proportions. For example, a relay tested under three conditions, with vibration applied along three axes, acceleration in six degrees of freedom, and with the relay in, say, 20 positions, involves a total of 1080 test set-ups and operation cycles. It is the rapid increase in the number of tests and scope of testing required that leads to the strategy of proceeding first with materials, then components, followed by equipments and subsystems.

Test requirements are approached either by simulating the environment exactly or by using a test situation that has no direct relationship to the actual environment, but from which the probability of production failures can be deduced. The possible types of tests are as follows:

1. A single environmental test is one that provides a single environment as it exists along a mission profile or accelerates it so that the total operational effect is reproduced in a very short time.

2. A mission profile environmental test is one that provides the same environmental magnitudes, durations and sequence that would be encountered in a specific mission profile of a specific aero-space vehicle.

3. A combined environmental test is an accelerated test which combines all environments that may be encountered over many missions and for several categories of mission profiles and types of equipment. The environmental magnitudes and durations do not, however, resemble the actual mission profiles and are developed on the basis of effect.

Thus, MIL Standard 210A, while not a test specification, could provide for a true simulation of the environment. "This standard indicates the probable extreme climatic conditions of the natural environment to which military equipment may be exposed and is intended to establish uniform limits not to be exceeded in normal design requirements." On the other hand, MIL-E-5272C offers a dual approach. "This specification establishes generally applicable procedures for testing....under simulation and accelerated climatic conditions." Simulated environmental conditions have the advantages of being "the real thing," but they possess the equally evident disadvantage of operating in real time; that is, the time required may readily become comparable with the service life of the weapon system. The accelerated or "hurdle" test utilizes engineering and physical knowledge to effect the necessary interpolation or extrapolation. The procedure for condensing total expected life into a reasonable test period necessarily involves a critical examination of the underlying physical phenomena to assure that the law and scaling factors used are applicable. Thus, in dynamic testing, if it can be shown that fatigue theory applies to component life, and that acceleration is proportional to stress, the S/N curve may be applied by using

$$\frac{N_v}{N_t} = \left(\frac{S_t}{S_v}\right)^n$$

say, where $\frac{N_v}{N_t}$ is the relative exposure in the device versus that in the laboratory, and where the stress ratios are measured by the accelerations. The exponent n depends on the most critical material or assembly.

The preceding approach provides a basis for establishing the necessity for tests of single environments, as well as tests of combined environments, and within each grouping, the sequencing required.

It is believed that if the development of test procedures is to become scientific rather than

analytical and arbitrary it is imperative that standard environmental test specimens be developed. These standard specimens, or sensors, are items that will react in a predictable manner to any environment or combination of environments. /4/ Further development along this line should allow duplication of common failures for various categories of equipment.

SINGLE VS COMBINED ENVIRONMENTAL TESTING

The key concept involved in selecting between single and combined tests is that of linearity and interaction. If the effect that the combined environment has is simply the addition or superposition of the separate environments, then separate environments may be used; on the other hand, if there is interaction either qualitatively or quantitatively, then single environment tests may not be performed with the confidence that they are truly representative of the physical situation encountered by the equipment.

Thus far, little has been said regarding the part played by the stage of development of the equipment or system considered. In the initial stages, there is great advantage in proceeding systematically from the known to the unknown, from "conventional environments," in which the correlation between equipment performance and test performance is known, to the hyper environments, or new environments, whose effects must be explored. Thus, in tests where the nuclear environment is involved, it is advantageous, first to perform the tests in non-nuclear environments; then, repeating in the nuclear environment those tests that are believed to interact. For a given class of materials, say, organic materials, a given environment, such as a nuclear environment, may accelerate damage by interacting with pressure, temperature, moisture and ozone./10/.

In the research and development phase involving materials, the test procedures begin with tests intended to screen desirable materials, beginning with tests in non-interacting environments having major effects and then progressing to combined environment tests on the limited number shown to be of interest. In summary, materials investigations have as their goal the establishment of performance limits and the securing of design data. Usefulness of data depends on the sound application of the scientific method, including the use of controls, adequate sample size and sound statistical procedures. In the development phase, equipment classifications given in references /11/ and /12/, discussed below, may be used.

Single Environment Tests

As previously indicated, the decision to utilize a single environment test must be based on the conclusion that either: (1) the selected environment is not interacting with other environments, (2) the interactions are small enough to be neglected, or (3) the single environment test is of such a nature (accelerated or hurdle) that it furnishes a reliable prediction of the equipment performance in the range of interaction that may be encountered. From these criteria it will be seen that the primary usefulness of single environmental tests is, first, in phases covering research and development pilot studies of materials and gross equipment performance, and second, in the qualification testing stage, in which the equipment demonstrates its performance capabilities prior to acceptance. Because of the paucity of knowledge regarding the interacting effects of accelerated, or hurdle, tests and their correlation with equipment performance in the normal environment, single tests are most frequently chosen when it is intended to utilize the accelerated stress approach. Work is underway, however, to develop a combined environment test that may be useful as a hurdle-type qualification and reliability test./12/

Single environment test specifications are available in the ASTM and MIL Standard series of publications and provide criteria for both accelerated and normal environmental test approaches. Single tests may be applied to investigate specific properties and performance, or may be utilized for all environments, as set forth in MIL-E-5272. When such a course is elected, it is necessary to establish the test sequence for each class of equipment; hence, as a first step, a suitable classification must be established, and secondly, the sequence and its exceptions must be established.

Since individual single tests are taken as non-interacting, and since the sample must last through as many test procedures as possible, it is evident that the tests be arranged so that those with the minimum tendency to damage or destroy the specimen are performed first, and those with the greater damage potential last. Damage potentials may be considered in accordance with the physical mechanisms of damage. Tests in accordance with MIL-E-5272 for aircraft and missile equipment and MIL-E-4970 for ground support equipment may be classified under the following damage groupings:

Temperature and Pressure Effects

MIL-E-5272	MIL-E-4970
High temperature	High temperature
Low temperature	Low temperature
Temperature shock	Low pressure
Altitude	Sunshine
Temperature-altitude	
Sunshine	

Corrosion Effects

MIL-E-5272	MIL-E-4970
Immersion	Rain
Rain	Humidity
Humidity	Fungus
Fungus	Salt Spray
Salt Spray	Sand and dust
Sand and dust	

MIL-E-5272	MIL-E-4970
Mechanical Effects	
Acceleration	Explosion
Explosion	Shock
Shock	Vibration
Vibration	Sand and dust
Sand and dust	

It will be noted that sand and dust appears in two categories since its effect depends on the specific type of equipment and the materials used.

Before discussing equipment classification, it must be emphasized that the design, test and environmental engineers working together have joint responsibility for making the decision best suited to their specific problem. No developed theory or body of information presently exists that permits decisions to be made on a prior basis.

Sequence Selection for Single Environmental Tests

Two types of classifications are most readily implemented in developing equipment classification for single test sequences: (1) functional classification (based on the purpose of the equipment), and (2) operational mode classification (based on the means by which the equipment operates). Functional classification can handle a wide variety of equipment, but requires a very large number of groups, while operational classification leads to groups so general that there is little specific applicability. A composite system similar in most respects to that used in the USAF Environmental Criteria Slide Rule /13/ is considered. These are as follows:

Ground Support Equipment

1. Electronic and communications equipment.
2. Aircraft and missile support equipment.
3. General base equipment.

Aircraft and Guided Missile Equipment

1. Electronic and communications equipment.
2. Autopilot, gyro and guidance equipment.
3. Power plant accessories and auxiliary power plants.
4. Instruments and sensors.
5. Armament.
6. Optical and photographic equipment.
7. Liquid and liquid-actuated equipment.
8. Gas and gas-actuated equipment.
9. Electrical equipment.
10. Mechanical equipment.

The following assignment rules are recommended:

1. The primary choice of group is based on function (i.e., Ground Support Equipment categories 1 and 2, and Aircraft and Missile equipment categories 1-6). Within the functional class, electronics takes precedence over other considerations, and any piece of equipment that contains an electronic circuit is tested with the electronics sequence.

2. If the item tested does not fall into one of the functional groups, the appropriate operational mode class is used. The selection of the operational mode class is based on the major mode of operation. Thus, a given item of equipment is classified as mechanical, or liquid and liquid-actuated, or gas and gas-actuated according to the major item, although minor elements may fit into the other groups. The decision is based on engineering analysis of the potential effects of environmental bounds on the equipment function. A more extensive set of definitions and examples is given in Appendix A.

It has already been noted that the equipment classes used are, of necessity, general, and that each item of equipment must be considered on its merits. Furthermore, the test sequences have been devised for testing a single or small sample through the entire test series. If additional test samples are available, testing time may be reduced by performing the test sequence in parallel.

The test sequence recommended for ground support equipment is set forth in Table 6-14, and that for aircraft and missile equipment in Table 6-15.

Combined Environment Tests

The concept of combined environmental testing arises from the realization that environments do not occur singly, and that in a significant portion of the cases they interact to produce results that may not be neglected. This logic serves as the basis for a test program leading to: (1) consideration of the combination of environments that must be expected, (2) consideration of the probability distribution of the joint occurrences of such combined environments, and (3) the selection of those environments that interact or combine effects. This philosophy follows directly from the operational analysis approach discussed in Chapter 4.

Combined tests tend to simulate nature better, but single environment tests pinpoint the cause of degradation of materials and equipment, thus providing for direct remedial action. Accordingly, combined environment tests are useful in evaluating combined effects during the research and development phase as well as for qualification and reliability testing.

Combined environmental encounters occur at each stage of the life history of the equipment. A useful approach is to distinguish encounters connected with the storage, logistic-transportation and maintenance phase on the one hand, and those encountered in the "use" phase of the mission on the other hand. This conception implies that the natural environment dominates

Table 6-14. Test Sequences for Ground Support Equipment

Tests (per MIL-E-4970)	Communications and electronics	Aircraft and missile support	General base
Temperature and Pressure			
Low pressure	3	1	1
High temperature	2	2	2
Low temperature	1	3	4
Sunshine	4	-	3
Corrosion			
Sand and dust	-	-	5
Rain	10	4	6
Humidity	11	5	7
Fungus	12	6	8
Salt spray	13	7	9
Mechanical			
Sand and dust	5	8	-
Explosion	6	9	-
Shock (to 15 g's)*	7	10	10
Vibration	8	11	11
Shock (over 15 g's)*	9	12	12

* If shock tests up to 15 g's can be run on the same machine and with the same set up as shock tests over 15 g's, all shock tests should be run consecutively in order of increasing severity as the last tests in the mechanical portion of the sequence.

Table 6-15. Test Sequences for Aircraft and Missile Equipment

Tests (per MIL-E-5272C)	Communications and electronics	Autopilots, gyro, guidance	Auxiliary power plants	Instruments and sensors	Armament	Optical and photographic	Liquid systems	Gas systems	Electrical systems	Mechanical systems
Temperature and Pressure										
High temperature	2	1	1	1	1	1	1	1	3	1
Low temperature	1	2	2	3	2	3	3	3	1	4
Temperature shock	5	5	3	2	4	5	5	5	5	3
Altitude	3	3	4	4	3	2	2	2	2	2
Temperature-altitude	4	4	5	5	5	4	4	4	4	5
Sunshine	-	-	-	6	-	-	-	-	-	-
Corrosion										
Sand and dust	-	-	6	7	-	9	9	11	6	-
Immersion	-	-	-	8	-	-	-	6	-	-
Rain	-	-	-	-	6	-	6	7	7	6
Humidity	12	6	7	9	7	6	7	8	8	7
Fungus	13	7	8	10	8	7	8	9	9	8
Salt spray	14	8	9	11	9	8	-	10	10	9
Mechanical										
Sand and dust	6	9	-	-	10	-	10	-	-	10
Acceleration	7	10	10	12	11	10	11	12	11	11
Explosion	8	11	11	13	12	11	-	-	12	-
Shock (to 15 g's)*	9	12	12	14	13	12	12	13	13	12
Vibration	10	13	13	15	14	13	13	14	14	13
Shock (over 15 g's)*	11	14	14	16	15	14	14	15	15	14

* See footnote on Table 6-14.

test program development up to the use phase and at that point those characteristics established by functioning in the mission are determined.

Once the spectrum of combined environmental encounters is established, it is then possible to begin the analysis of interaction at the materials, parts, components and subsystems level to determine which combined environments will mutually inhibit, and which may be neglected. This procedure permits the environmental engineer to converge rapidly on a recommended program with a quantitative indication of the trade-offs and the simplifications that must be made in the interest of utilizing available facilities.

For equipment intended for world-wide use, it is desirable to consider climates on the basis of the encounter of the natural environmental extremes by operational equipment /11/. A basic classification is given in Fig. 6-48, which distinguishes among the following use areas:

1. Ice cap.
2. Arctic.
3. Maritime.
4. Continental.
5. Desert and steppe.
6. Tropical.
7. Highland.

Environmental extremes pertinent to each location are as follows:

Ice Cap

Low temperature
Driven snow
Winds

Arctic

Low temperature
Driven snow
Winds
Temperature-condensation

Maritime

Moisture
Sunshine
Salt spray
High temperature
Temperature-condensation
Fungus

Continental

High temperature
Low temperature
Moisture
Sand and dust
Driven snow
Temperature-condensation
Fungus

Desert and Steppe

High temperature
Low temperature
Moisture
Temperature-condensation
Sand and dust
Sunshine
Driven snow

Tropical

Moisture
Temperature-condensation
Salt spray
Fungus
Sand and dust

The environmental combinations pertinent to operations in the troposphere and stratosphere include:

Aerial

High temperature
Low temperature
Temperature-shock
Temperature-condensation
Altitude
Ozone
Vibration
Acceleration
Explosion
Pressurization

Data regarding combined environments for the exosphere, space, the Moon and planets are given in Chapter 2 of this handbook. Such data should be used with caution since they contain a considerable speculative element.

Induced environmental encounters may be considered under the headings of (1) transportation and handling, (2) storage, and (3) operations.

In transportation and handling, the principal environments encountered include shock, low temperature, high temperature, moisture, temperature-condensation, and possibly sand and dust and sunshine. The environmental test procedure must be selected to reflect the operational conditions and the transportation and handling conditions. For transportation and handling, the tests are applied to the packaged equipment.

Similar considerations apply to the storage environment, which includes high temperature, low temperature, fungus, temperature-condensation, humidity, rain, blowing snow, salt spray, sunshine, sand and dust, and handling shocks. The nature and effectiveness of protection afforded by the storage facility establishes the intensity levels and combinations to be expected.

The frequency of encounters may be assessed by a step-by-step analysis of the life history of the weapon system. For manned aircraft and equipments intended for repeated use, it is apparent that environmental encounters in the

Fig. 6-48. World

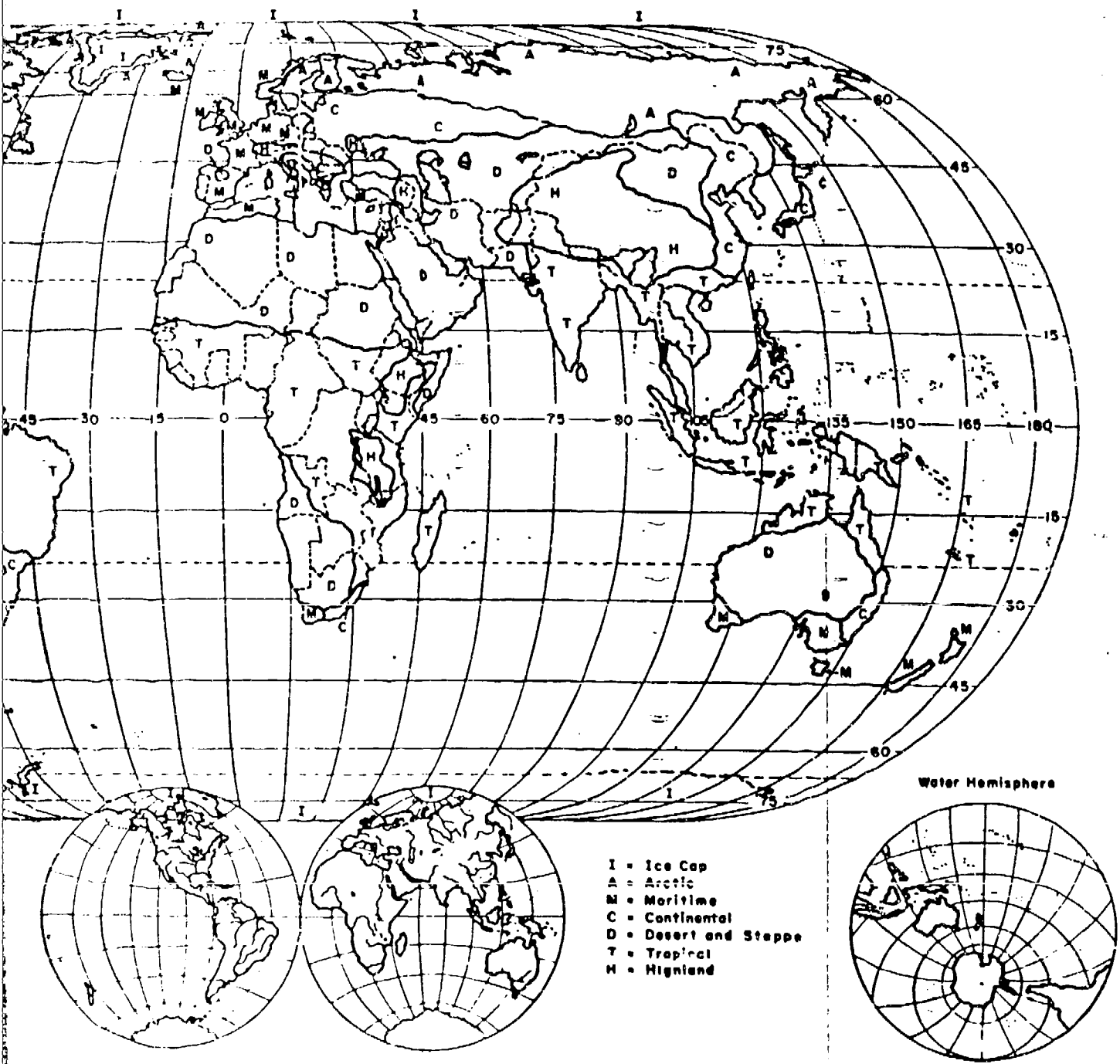


Fig. 6-48. World-wide classification of climates. /11/

first two phases of the mission profile, namely transportation and handling and storage, will be repeated less frequently than those in the other phases. Therefore, in establishing the requirements for the environmental test, the first two phases may be represented by a single series of encounters, while the rest are duplicated by repeated cycling through those environments encountered during operation.

Figure 6-49 presents a distribution of the number of encounters by typical equipments for use overseas from the point of manufacture to the point of use. This distribution is illustrative only and gives equal weight to the various end-use areas and means of transportation. The specific weapon system must be analyzed in the light of the proposed deployment, utilization and structure of use.

Encounters during ground standby are obviously a function of the location as modified by local measures. Realistic combinations typical of ground standby in each climate are as follows:

Ice cap and Arctic	-65 F (-54 C) outside air temperature (OAT); plus blowing snow at 15 mph and higher (4-hour duration).
Desert	125 F (52C) OAT, plus 120 watts per square foot (A effect-- compartment temperature up to 160 F (71 C)--4-hour duration).
	100 F (38 C) OAT, plus 120 watts per square foot (A effect) (4-hour duration).
Tropic	75 to 95 F (24 to 35 C) OAT, plus 4 inches of rain per hour (2-hour duration).
	75 to 95 F (24 to 35 C) OAT, plus salt spray (4-hour duration).
	95 F (35 C) OAT, plus 120 watts per square foot (A effect) (4-hour duration).
	75 to 90 F (24 to 32 C) OAT, plus 95% relative humidity (4-hour duration).
Maritime	68 F (20 C) OAT, plus fog (moisture) (4-hour duration).
	80 F (27 C) OAT, plus 90% relative humidity (4-hour duration).
	70 F (21 C) OAT, plus salt spray (4-hour duration).
	75 F (24 C) OAT, plus rain at 4 inches per hour (2-hour duration).
Continental	90 F (32 C) OAT, plus 120 watts per square foot (A effect) (4-hour duration).
	80 F (27 C) OAT, plus sand and dust (4-hour duration).
	90 F (32 C) OAT, plus 95% relative humidity (4-hour duration).
	20 F (-7 C) OAT, plus blowing snow 40 mph and higher (4-hour duration).

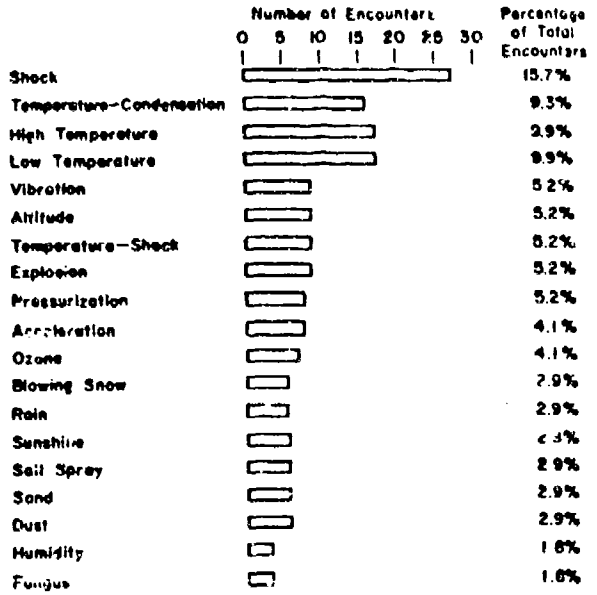


Fig. 6-49. Environment encountered from point of manufacture to point of use.

The mission profile encounters are also determined by operational analysis. Typical combinations /11/ indicative of the factors to be considered may be listed for a hypothetical cargo aircraft and a missile as follows:

Cargo Aircraft (Basic Mission)

Takeoff and climb	Standby conditions to vibration (to 2000 cps), plus 1013 mb to 572 mb (at 15,000 feet), plus to 10 F (-12 C) ram air temperature.

Initial cruise, 340 minutes	572 mb to 376 mb (at 25,000 feet), plus 500 cps, plus -39 F (-34 C) ram air temperature.
Descent, 30 minutes	Cruise condition to sea level in various climates, plus shock.
Unload, 60 minutes	Standby conditions in various climates.
Take-off and climb, 30 minutes	Unload conditions to vibration (to 2000 cps), plus 1013 mb to 301 mb (at 30,000 feet), plus to -24F (-31 C) ram air temperature.
Final cruise, 490 minutes	-30 F (34 C) ram air temperature, plus 239 mb, plus 500 cps.
To touchdown, 30 minutes	To standby conditions, plus to 1013 mb, plus to 500 cps, plus 30 g's for 0.012 second.

NOTE

Ground-standby conditions at take-off and at touchdown for all long-range aircraft may reflect a change from one climate to another.

Missile

Launch	to 50,000 feet in 150 seconds, acceleration (15 g's for 3 seconds), plus 160 F (71 C)*, plus 1013 mb to 116 mb, plus 2000 cps.
Climb	50,000 to 80,000 feet in 10 seconds, plus 160 F (71 C)* plus 116 mb to 27 mb, plus to 2000 cps, plus ozone (0.007 to 0.029 cm per km at 65,000 feet), plus cosmic radiation.
Initial cruise	85,000 feet (22 mb), plus 160 F (71 C)*, plus 2000 cps.
Final cruise, 5 minutes	to 100,000 feet (11 mb), plus 160 F (71 C)*, plus to 2000 cps, plus ozone.

NOTE

*Ram air temperature effects insulated and/or refrigerated to this temperature.

In terminal dive, the missile is a true ballistic projectile and warhead function is the sole critical consideration.

The definition of the combined environments to be encountered is logically followed by a determination of the interaction environments; that is, those environments that will be encountered at any point in the life history of the weapon system and which interact. This is approached by considering the effects of the various environments on the materials and parts determining the mechanism of damage and interaction.

Standardization of Environmental Testing

The standardization of environmental testing is an obvious, but frequently neglected, point of scientific method. A standardized test is a test that can be duplicated, and hence verified. The word "duplication" implies that the tests shall be reproducible with the differences in test results due only to random causes of variation, which must be small in comparison with the results measured. /14, 15/

The goal of standardized testing is not necessarily that tests and test procedures be uniform, but rather that they be standardized; that is, that it shall be possible to translate the results of tests performed in one facility according to a given procedure into a prediction of results that would be obtained in another facility, and that both of these be accurate predictors of results to be obtained in the field.

There are two major problems involved in the standardization of environmental tests. The first is the writing of good specifications for the tests that must be carried out. These specifications must not only be clear and detailed, but they must specify procedures and conditions that are attainable in the test laboratory. The second problem is one of obtaining compliance with the specification on the part of the agencies performing the tests.

Environmental Test Specifications. The problem of obtaining good environmental test specifications is chiefly one of clear, unambiguous presentation. Such specifications as MIL-E-5272, MIL-E-4970, etc., should be regarded as guides to the writing of environmental specifications rather than the end product themselves. The details of the environmental test required for any item should be written into the specifications for that item, with MIL-E-5272 and MIL-E-4970 used for the guidance of the specification writer, rather than as convenient all-inclusive authorities that may be referenced to save the specifications writer the trouble of detailing the tests he wants.

In order for the specification writer to perform his task adequately, (1) he must have access to thorough, basic information on environmental testing, (2) he must be familiar with the equipment to be tested, (3) he must be familiar with the test equipment that will be required to perform the environmental tests, (4) he must be very familiar with all environmental test procedures required, and (5) he must be familiar with all environmental effects.

In order to insure uniform duplication of results, it is generally advisable for the specification writer to discuss the desired sequencing of tests in the specification. If his previous experience indicates that a specific sequence of tests is desirable, he should specify such a sequence. If he feels that only one or two tests should be done in a specific sequence, with the remainder of the sequencing optional, he should so state. Even if it is felt that no specific sequence should be required, a comment to this effect should be made in the specification. It is only in this manner that the test engineer will be provided with the guidance that will allow him to conduct a properly designed environmental test program.

Should the specification writer desire combined environment testing, he must spell out in great detail exactly how the tests shall be conducted, what types of equipment shall be used, what the limits or conditions shall be, and how the tests shall be interpreted. In any case, whether combined environment testing or single environment testing is used, standards for the interpretation of test results must be supplied in order to allow the test engineer to determine whether his equipment passes or fails the test.

An Air Force sponsored study of the uniform duplication of environmental test results /16/ has made the following recommendations with respect to specifications for environmental testing:

1. The detailed equipment specifications should specify the number of equipments that must be subjected to the test program, the test sequence for accommodation of each test item, and the applicable procedure for each test.

2. The detailed equipment specification should specify the physical and electrical measurement (including detailed test procedures for accomplishing them when applicable) to be performed initially, during, and/or after environmental exposure. Included also should be the requirements that will insure satisfactory performance of the test equipment.

3. The detailed equipment specification should specify any modification of test or requirement of the general specification, particularly with regard to test period, duration, severity of environmental exposure, environmental and instrumentation tolerances, standard test conditions, etc.

4. The detailed equipment specification should specify in detail any special considerations due to the particular test equipment, such as mounting method, orientation, etc.

Compliance with Test Specifications. Obtaining compliance with all the requirements of the specification is a problem of educating the agency doing the testing, and insuring that adequate test equipment and test facilities are available. The reliance on the presence of a government inspector at the test agency is not enough to insure complete compliance on the part of the organization doing the testing. No matter how much detail is written into an environmental specification, it is difficult to obtain consistent interpretation on the part of many inspectors.

The key to the operation of a successful test program is the education of the test engineer. He must understand completely the operation and characteristics of the equipment he is testing, as well as the tests that are to be performed and the test equipment that is to be used. In this respect, reference /16/ draws the following conclusions:

1. In general, to insure the uniformity of environmental test conditions, consideration must be given to the following:

a. All test parameters must be controlled to the extent that, within the range of test tolerances, the test conditions do not permit variations in test results.

b. All other environmental parameters, not just those under test, that could influence the results of the test must be specified and controlled to whatever extent is necessary to prevent variations in results.

c. The environmental test must be clearly specified in such a manner as to preclude variations in interpretation by the test engineers.

d. All chambers and associated instruments must be capable of controlling the environments in the manner specified and within the accuracy required.

e. The personnel performing the tests must be sufficiently trained and capable of performing the test in the specified manner.

2. In general, to insure uniformity and repeatability of environmental test results, consideration must be given to:

a. The operation and electrical tests (or other types of tests) to be performed on the equipment must be clearly specified, including the required measurement accuracies.

b. The applicable environmental tests, conditions of tests, sequence of tests and number of equipments to be tested must be clearly specified, with proper emphasis on any modification or special consideration not covered in the general specification.

c. The tests must be performed in a careful and precise manner, with attention given to the limitations of the test equipment and instrumentation. All data must be recorded and reported accurately and legibly to preclude any possible variation in test results.

In order to achieve uniformity in environmental test results, standards for environmental test chambers must be set up in a clear

and unambiguous manner and must be enforced. The Air Force study of environmental test duplication /16/ indicates that a wide variety of chambers are in use. Those vary so widely in design, construction details and methods of operation that obtaining compliance with specifications is often difficult, if not impossible.

There are two ways to insure duplicable environmental results. One is to develop detailed specifications for standardized test facilities and test procedures for various categories of equipment, and the other is to police test organizations to assure that testing is accomplished in adequate facilities using satisfactory test procedures. Probably the best method is one where the best in specifications are developed both for test procedures and facilities, and where a spot check inspection is made of testing accomplished. The inspection action would be most effective if carried out by the environmental test industry itself.

REFERENCES

1. Cockrell, William D., Industrial Electronics, McGraw-Hill Book Company, Inc., 1958.

2. Stuhlinger, Ernst, Instrumentation for Space Research, Research Projects Laboratory, Development Operations Division, Army Ballistic Missile Agency, Redstone Arsenal, Alabama, 19 March 1959.

3. Environmental Test Sequencing and Number of Test Items, WADC TR 59-490, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1959.

4. McGee, John and Chester Polak, The Development of Standard Environmental Test Specimens, WADC TR 59-697, Inland Testing Laboratories, Contract No. AF 33(616)-6116, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, October 1959.

5. Rocket Sled Design Handbook, Report No. ISTRACON 60-1, Contract No. AF 29 (600) 2000, Air Research and Development Command, U. S. Air Force, January 1960.

6. Kircher, J. F., Survey of Irradiation Facilities, REIC Report No. 11, The Radiation Effects Information Center, Battelle Memorial Institute, Columbus 1, Ohio, 30 April 1960.

7. Minzner, R. A., K. S. W. Champion and H. L. Pond, The ARDC Model Atmosphere, 1959, AFCRC-TR-59-267, Air Force Surveys in Geophysics No. 115, Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command, Bedford, Massachusetts, August 1959.

8. Schueller, Otto, Space Environment Facility for Life Support Systems, Aerospace Medical Laboratory, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, January 1960.

9. Simulated Combined Vibration, Sustained Acceleration, and Extreme Temperature Environments, WADC TN 58-541, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1959.

10. Brown, C. D., et al, Determination of a General Test Philosophy for ANP Weapon System, WADC TN 57-323, ASTIA Document No. AD 131045, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, July 1957.

11. Feasibility of Combined Environment Testing, WADC TR 56-546, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, 1956.

12. Development of Combined Qualifications Test Programs for the Air Force, WADD TR 60-440, U. S. Air Force, ASD, U. S. Air Force, Wright-Patterson Air Force Base, Ohio, July 1960.

13. Englehardt, R. E., Development of Air Force Environmental Criteria Slide Rule, WADC TR 57-286, ASTIA Document No. AD118296, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, July 1957.

14. Deming, W. E., and Birge, R. T., On the Statistical Theory of Errors, Graduate School, U. S. Department of Agriculture, Washington, D. C., 1934.

15. Shewart, Walter A., Statistical Method from the Viewpoint of Quality Control, Graduate School, U. S. Department of Agriculture, Washington D. C., 1939.

16. Uniform Duplication of Environmental Test Results, Part I, Part II and Part III, WADC TR 58-613, U. S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio, November 1958.

BIBLIOGRAPHY

Abernathy, A. H., Combined Environments in Large Test Chambers, presented at the Insitute of Environmental Engineers Annual Meeting Chicago, April 1958.

Anderson F. G., "AN/AKT-14 Telemetry System, Part VI, PWM and FM/FM Automatic Data Reduction with AKT-14 Telemetering Components," IRE Professional Group Transactions, TRC-2, March 1956.

Anderson, Merwin T., and Leonard L. Robinson, "Laboratory Simulation of Rocket Engine Noise," Environmental Quarterly, 4th Quarter, 1958.

Ankeney, D. F., R. W. Murphy and D. M. Nelson, "The NOTS Controlled Vibration Track Test Vehicle," Shock and Vibration Bulletin, Part III, No. 27, June 1959.

"Atmosphere Simulator," Fortune, April 1959.

Bone, A. G. and R. G. Anderson, Installation Testing Air Mileage Unit, Mk. 4, ASTIA Document No. AD 115383.

Brown, Ralph, E., "A Precision Centrifuge Machine for the Evaluation and Calibration of Inertial Guidance Accelerometers," Proceedings of Institute of Environmental Engineers, 1959.

Burgess, J. C., "The Vibration Environment of Supersonic Track Sleds," Shock and Vibration Bulletin, Part III, No. 27, June 1959.

Burrus, Walter R., Standard Instrumentation Technique for Nuclear Environmental Testing, ASTIA Document No. AD 142179.

Cammarata, John, "Review of Environmental Test Equipment," Electrical Manufacturing, May 1957.

"Chamber Simulates Space Environment," Aviation Week, 13 April 1959.

Cool, William P., "Criterion for Chamber Specification," Environmental Quarterly, April 1959.

Crandall, S. H., "Random Vibration," The Technology Press of the Massachusetts Institute of Technology, 1948.

Crede, C. E. and E. J. Lunney, Establishment of Vibration and Shock Tests for Missile Electronics as Derived from the Measured Environment, ASTIA Document No. AD 118133.

Davis, L. I., "Missile Component Testing on Rocket Sleds at the Air Force Missile Development Center," Shock and Vibration Bulletin, Part III, No. 27, June 1959.

DiTaranto, R. A. and J. J. Lamb, Preliminary Investigation of Hyper Environments and Methods of Simulation, Part II, Simulation Methods, WADC TR 57-456, ASTIA Document No. AD 142617, U.S. Air Force, ASD, Wright-Patterson Air Force Base, Ohio.

DiTaranto, R. A. and J. J. Lamb, Preliminary Investigation of Hyper Environments and Methods of Simulation, Part III, Proposed Hyper Environmental Facility, WADC TR 57-456, ASTIA Document No. AD 142338, U. S. Air Force ASD, Wright-Patterson Air Force Base, Ohio.

Dryden, Warren, "Simulation Vibration for Helicopters," Vibration Notebook, August 1959.

Dumond, Jesse W. M., Improvements in the Precision of Beta-Ray Spectroscopy, ASTIA Document No. AD 8368.

Elizalde, J. C., H. T. Ida, R. T. Hartung, et al, Feasibility Study for A Space Environment Simulator Capable of Duplicating An Accurate Space Vehicle Temperature History, Report No. ERR-AN-018, Convair Astronautics, Division of General Dynamics Corporation, 30 August 1960.

Flight Test Instrumentation Group, Temperature Measuring Systems Used on Navaho Missiles, ASTIA Document No. AD 147945.

Fundamentals of Guided Missile Packaging, Chapter 5, ASTIA Document No. AD 210000.

Gerlach, A. A., "FM Recording in Guided Missiles," Electronics, 26 January 1953.

Granick, N., "Response of Structures Under Random Vibration," Environmental Engineering, Vol. No. 1, February 1959.

Granick, N., Status Report on Random Vibration Simulation, ASTIA Document No. AD 203125.

Haase, R. J., Acoustical Sound Recorders, Reproducers and Analyzers, Evaluation of, ASTIA Document No. AD 157648.

Hancock, Warren D., "In-Flight Vibration Measurement," Test Engineering, July 1959.

Handbook of Acoustic Noise Control, WADC TR 52-204, Volume I, "Physical Acoustics," by Lukasic and Noble, June 1953, and Volume VI, "Noise and Man," by Walter A. Rosenblith, Kenneth N. Stevens, and the staff of Bolt, Branek, and Newman, April 1955.

Handbook of Noise Control, edited by Cyril M., Harris, McGraw-Hill Book Company, Inc., 1957.

Harris, C. M. Handbook of Noise Control, McGraw-Hill Book Co., 1957.

Hecht, Bernard, Prediction of Failure Rate with Accelerated Life Tests, Sprague Technical Paper 58-1.

Hermann, Fred, Basic Instrumentation and Control Theory as Applied to Environmental Test Chambers.

"High Speed Track Facility," Fortune, April 1959.

Howard, Darnley M., Development of a Fatigue Damage Indicator, ASTIA Document No. AD, 27588.

Hubbard, A. L., "Syetem Testing on Dynamic Restraints at Lockheed SCTB, "Shock and Vibration Bulletin, Part III, No. 27, June 1959.

Instrumentation Installation for Climatic Test of Aircraft, General Specification for, MIL-I-5289B(ASG) Navy Bureau of Aeronautics.

Kamperman, George W., Design of the High Intensity Noise Test Facility, ASTIA Document No. AD 202561.

Kennard, D. C., Jr. and C. E. Thomas, Data Reduction Techniques for Flight Vibration Measurements, ASTIA Document No. AD 210478.

Laesch, William E. and Warren W. Smith, Correlation of Natural Weathering and Sheltered Storage Exposure Tests with Simulated Environmental Laboratory Tests, ASTIA Document No. AD 76798.

Launching of Free Flight Models at High Velocity, ASTIA Document No. AD 146103.

Linschitz, Henry, Non-Electronic Dose Rate Indicating Systems, ASTIA Document No. AD 41810.

Lowe, R., "Correlation of Shock Spectra and Pulse Shape with Shock Environments," Environmental Engineering, Vol. No. 1, February 1959.

"Manual of Nuclear Instrumentation," Nucleonics, McGraw-Hill Publishing Co., N.Y.

McIntee, F. P,. "Low-Temperature Pneumatics in the Environmental Chamber," Proceedings of Institute of Environmental Engineers, 1959.

Mershon, H. E., Explosion-Proof Test Criteria for Reconnaissance Equipment, Part III, Surge Generator, ASTIA Document No. AD 207523.

Mills, Charles, "Value of Environmental Simulation in System Testing Program," Test Engineering, July 1959.

Monroe, J. P., Practical Considerations of Random Vibration Testing, Lear Publication LTL-1006.

Montgomery, C. D. and B. D. Sissom, "U. S. Army Ordnance Automotive Environmental Testing Facilities," Shock and Vibration Bulletin, Part II, No. 26, December 1958.

Morrow, C. T., "Shock Spectrum as a Criterion of Severity of Shock Impulses," Journal of Acoustical Society of America, Vol. 29, No. 5, 1957.

Morrow, C. T. and H. I. Sargent, "Sawtooth Shock as a Component Test," Journal of Acoustical Society of America, Vol. 28, p. 959, 1956.

Morrow, C. T. and R. B. Mershmore, "Shortcomings of Present Methods of Measuring and Simulating Vibrational Environments," Journal of Applied Mechanics, 22 September 1956.

Nichols, M. H. and L. L. Rauch, Radio Telemetry, 2nd Edition, John Wiley and Sons, 1956.

Noise Measurement Techniques, National Physics Laboratory, ASTIA Document No. AD 144133.

Pleuthner, Richard L., and James P. Welsh, Manual of Standard Temperature Measuring Techniques, Units, and Terminology for Miniaturized Electronic Equipment, ASTIA Document No. AD 49485.

Pride, A. M., and A. T. Decker, Noise Level Analyzer, ASTIA Document No. AD 21797.

Radar Guidance Group, Design of Instrumentation Mounting Platforms, ASTIA Document No. AD 151694.

Redfield, Alfred G., Nuclear Induction Spectrometer for Use at High RF Intensities and Low Temperatures, ASTIA Document No. AD 101010.

Remaley, Charles W., General Discussion of Methods to Simulate Aircraft and Missile Acoustical Environment for Test Purposes, ASTIA Document No. AD 130012.

Schauch, Wm. J. and W. J. Bell, A High Temperature Recirculating Air Oven (1300 F) for Physical Property and Structural Component Testing, ASTIA Document No. AD 9527.

Schnee, M. and R. Wohl, Study of Fatigue Evaluation Procedures for Electron Tubes, Research and Development Report, Material Laboratory, N. Y. Naval Shipyard, 13 February 1956.

Schock, R. and R. F. Lander, "Flight Testing Spacecraft," Electronics, 27 March 1959.

Schulman, James H., "Glass Dosimeters for Radiation Measurement," The Industrial Atom, TID-8006.

Seiff, Alvin, The Use of Gun-Launched Models for Experimental Research at Hypersonic Speeds, ASTIA Document No. AD 150315.

BIBLIOGRAPHY (continued)

"Solving Reentry Problems," Electronics, Business Issue, 5 September 1958.

"Space Technology Laboratories," Aviation Week, 18 May 1959.

Stollenwer, E. J. and R. W. Perry, Preliminary Planning for a Hyper Velocity Aeroballistic Range at AEDC, ASTIA Document No. AD 157144.

Sumnicht, H. I., A Method for Measuring Effective Energy from Radiation Sources, ASTIA Document No. AD 157082.

"The First Simulated Trips to Venus and Mars," Design News, 18 August 1959.

Tomaino, Michael F., "Environmental Testing of Electronic Equipment," Electronics, 28 March 1958.

Yarcho, Wayne, B., Environmental Test Facilities of Wright Air Development Center, ASTIA Document No. AD 110740.

Young, Robert W., A Brief Guide to Noise Measurement and Analysis, ASTIA Document No. AD 66666.

APPENDIX A

EQUIPMENT CLASS DEFINITIONS AND EXAMPLES

1. GROUND SUPPORT EQUIPMENT, ELECTRONIC AND COMMUNICATIONS

Communications and electronic equipment of all types. Class includes all equipment with electronic circuits as components.

1. Ground radio equipment.
2. Ground radar equipment.
3. Electronic test equipment.
4. Wired communications equipment.
   a. Telephone.
   b. Telegraph.
   c. Teletype.
   d. Facsimile.
   e. Wired audio, including public address, motion picture sound systems, sound recorders, and reproducers, etc.
5. Electronic computers.
6. Electronic office machines.

2. GROUND SUPPORT EQUIPMENT, AIRCRAFT AND MISSILE SUPPORT

Equipment used outdoors on airfields and missile launching pads for servicing, maintenance, checkout, support, etc. Electronic equipment is not included.

1. Air conditioning, heating and ventilating equipment.
2. Test and checkout equipment (except electronic).
3. Crash, fire and other emergency equipment.
4. Electrical support equipment.
5. Fuel and oil handling equipment.
6. Maintenance equipment.
7. Materials handling equipment.
8. Pneumatic support equipment.
9. Airfield lighting equipment.

3. GROUND SUPPORT EQUIPMENT, GENERAL BASE

All ground support equipment not included in electronics and communications or aircraft and missile support classes.

1. Office equipment (except electronic).
2. Printing and reproducing equipment.
3. Commercial-type electrical equipment.
4. Air conditioning and refrigeration equipment.
5. Heating and ventilating equipment.
6. Plumbing equipment.
7. Laboratory apparatus and equipment.
8. Meteorological equipment.
9. Photographic and optical equipment.
10. Shop machinery and maintenance equipment.
11. Timekeeping equipment.
12. Construction equipment.
13. Vehicular equipment.
14. Materials handling equipment (not flightline).

4. AIRCRAFT AND MISSILE EQUIPMENT, ELECTRONIC AND COMMUNICATIONS

All airborne and missile-borne electronic and communications equipment. Class includes all equipment containing electronic circuits.

1. Facsimile equipment.
2. Sound recording equipment.
3. Visible and invisible light communications equipment.
4. Radio and television receivers and transmitters.
5. Radar equipment.
6. Wired audio equipment.
7. Communications equipment accessories.
8. Electronic computers.
9. Telemetering equipment (airborne positions).
10. ECM equipment.

5. AIRCRAFT AND MISSILE EQUIPMENT, AUTOPILOT, GYRO AND GUIDANCE

Autopilots and gyro systems, missile guidance and control equipment, and essential accessories, except electronic equipment.

1. Control assemblies.
2. Pressure gages.
3. Pressure regulators.
4. Servos.
5. Hydraulic sumps.
6. Speed control valves.

7. Hydraulic regulators.
8. Solenoids.
9. Gyroscopes.
10. Navigation equipment.
    a. Astral.
    b. Inertial.
    c. Infrared homing.
    d. Radar controlled.

6. AIRCRAFT AND MISSILE EQUIPMENT, POWER PLANT ACCESSORIES AND AUXILIARY POWER PLANTS

All aircraft and missile power plant accessories and auxiliary power plants. Does not include primary power plant.

1. Auxiliary power plants.
2. Boosters and takeoff assist units.
3. Ignition and electrical components.
4. Propeller components.
5. Aircraft engine accessories.
    a. Carburetors.
    b. Fuel injection pumps.
    c. Regulator assemblies.
    d. Valve assemblies.
    e. Engine controls.
    f. Starters.
    g. Air intake filters.
6. Missile power plant accessories.
    a. Engine controls.
    b. Electrical components.
        (1) Generators.
        (2) Ignition systems.
        (3) Primer assemblies.
        (4) Regulators.
    c. Governor assemblies.
    d. Pump assemblies.
    e. Fuel regulator assemblies.
    f. Starters.
    g. Valve assemblies.

7. AIRCRAFT AND MISSILE EQUIPMENT, INSTRUMENTS AND SENSORS

Instruments, indicators and electric meters; sensing units and signal assemblies that transmit information to other units. Electronic equipment is not included.

1. Power plant.
    a. Fuel and oil pressure signal assemblies.
    b. Tachometers and flexible shaft adapters.
    c. Gage units.
    d. Engine instrument transmitters.
    e. Signal assemblies.
2. Flight instruments.
    a. Accelerometers.
    b. Altimeters (except electronic).
    c. Load adjuster computers.
    d. Signal assemblies.
    e. Gages.
    f. Pitot-static tubes.
    g. Indicators.
    h. Venturi tubes.
    i. Warning signal assemblies.
    j. Inclinometers.
3. Navigation instruments.
    a. Compass caging units.
    b. Chronometers and clocks.
    c. Compasses.
    d. Navigational and guidance system computers (except electronic).
    e. Driftmeters.
    f. Navigation instrument transmitters.
    g. Sextants.
4. Electrical meters.

8. AIRCRAFT AND GUIDED MISSILE EQUIPMENT, ARMAMENT

All aircraft gun, bombing, and rocket equipment, plus accessories and parts; guided missile warheads and accessories. Does not include automatic flight control equipment and electronic components.

1. Mechanical equipment.
    a. Gun adapters.
    b. Bombsights.
    c. Gun chargers.
    d. Aircraft guns.
    e. Gun and bombsight mounts.
    f. Bomb, rocket, flare and torpedo racks.
    g. Bomb shackles.
2. Electrical equipment.
    a. Gun chargers.
    b. Gun heaters.
    c. Bomb, gun and rocket solenoids.
    d. Bombing, navigational and fixed fire control computers (except electronic).
    e. Intervalometers.
    f. Servos.
    g. Solenoids, turret.
3. Warhead equipment and accessories.
    a. Arming devices.
    b. Fuzes and initiators.
    c. Safety devices.
    d. Self-destruction units.

9. AIRCRAFT AND MISSILE EQUIPMENT, OPTICAL AND PHOTOGRAPHIC

All airborne and missile-borne still and motion picture camera and other optical equipment not part of specific functional equipment in other classes.

1. Cameras.
2. Mechanical camera accessories.

3. Electrical camera accessories.
4. Other optical devices and accessories.

10. AIRCRAFT AND MISSILE EQUIPMENT, LIQUID AND LIQUID ACTUATED

Liquid-carrying or hydraulic-actuated equipment that cannot readily be placed in one of the functional categories. If system has both major electrical and liquid components, it should be classed with electrical systems.

1. Hydraulic struts and actuating cylinders.
2. Hydraulic brakes.
3. Accumulators.
4. Aftercoolers.
5. Compressors.
6. Coolers.
7. Dehydrators.
8. Filters and strainers.
9. Fire extinguishers (liquid-filled).
10. In-flight refueling equipment.
11. Pumps.
12. Coolant radiators.
13. Valves.
14. Windshield wipers (hydraulic).
15. Vents.

11. AIRCRAFT AND MISSILE EQUIPMENT, GAS AND GAS ACTUATED

Gas-carrying or gas-actuated equipment that cannot be placed in one of the functional categories. Electro-pneumatic systems should be classed with electrical systems.

1. Accumulators.
2. Oxygen breathing equipment.
3. Canopy removers, explosive.
4. Compressors.
5. Pneumatic actuating cylinders.
6. Dehydrators.
7. Ejection seats, propellant actuated.
8. Fire fighting equipment (gas type).
9. Pumps.
10. Gas pressure regulators.
11. Valves.
12. Propellant actuated guillotine.

12. AIRCRAFT AND MISSILE EQUIPMENT, ELECTRICAL

Electrical (but not electronic) equipment in aircraft and missiles. Includes all electro-hydraulic, electro-pneumatic and electro-mechanical equipment that cannot be placed in one of the functional classifications.

1. Actuators (linear, rotary, switch).
2. Phase adapters.
3. Alarm devices.
4. Alternators.
5. Junction boxes.
6. Booster coils.
7. Generators.
8. Electric heaters.
9. Inverters.
10. Light assemblies.
11. Electric motors.
12. Electric control panels.
13. Electrical fire fighting and detecting system parts.
14. Voltage regulators.
15. Screw jacks.
16. Timers.
17. Induction vibrators.
18. Food warmers.
19. Electric windshield wipers.
20. External power receptacles.
21. Power converters.

13. AIRCRAFT AND MISSILE EQUIPMENT, MECHANICAL

Aircraft and missile equipment that has only mechanical-operating parts.

1. Glider towing and pick-up assemblies.
2. Controls (manual).
3. Gear boxes.
4. Cargo tie-down equipment.
5. Cargo hoists.
6. Mail pick-ups.
7. Seat assemblies.
8. Bearings.
9. Jettisoning equipment.
10. Parachute recovery equipment.
11. Pulleys.
12. Universal joints.

APPENDIX B

UNITS AND TERMS

Unit or term	Symbol	Definition or equivalents
Absorptivity		Ratio of absorbed radiant energy to incident radiant energy.
Acceleration due to gravity (Earth)	g	980.665 cm/sec^2; 32.17 ft/sec^2 (sea level value at 45.544° latitude).
Albedo		Ratio of reflected light to incident sunlight.
Angstrom	Å or A	10^{-8} cm; 3.94×10^{-9} inch.
Aphelion		Point of planet's (or comet's) orbit most distant from Sun.
Apogee		Point of satellite's orbit most distant from Earth.
Astronomical unit	AU	Mean distance from Earth to Sun: 149.8×10^6 km; 92.9×10^6 mi.
Atomic number	Z	Number of protons in nucleous of atom (thus, also number of electrons).
Bar		10^6 dynes/cm^2; 14.50 psi; 750.06 mm of Hg.
Dissociated atom		Free atom that separated from molecular combination by absorption of energy.
Dyne		Force required to accelerate a one-gram mass 1 cm/sec^2; 1 gm - cm/sec^2; 2.248×10^{-6} lbs - force.
Ecliptic		Apparent path, or great circle on celestial sphere, of the Sun as seen from Earth. Plane of Earth's orbit is coincident with ecliptic plane.
Electron volt	ev	Kinetic energy of particle of electronic charge when particle has fallen free through potential drop of 1 volt: 1.602×10^{-12} ergs; 1.602×10^{-19} joules; 1.52×10^{-22} Btu.
Electrostatic unit	esu	Charge of electron; 1.603×10^{-19} coulomb.
Emissivity	ε	Ratio of radiant emittance of an actual body to radiant emittance of black body at same temperature.
Erg		1 dyne - cm; 7.368×10^{-8} foot-lbs; 10^{-7} joules.
Gamma		10^{-5} gauss; 10^{-5} oersted.
Gauss		1 magnetic force line /cm^2; 1 maxwell/cm^2; 6.452 lines/in^2.
Geopotential altitudes		Height (km, ft, etc.) of altitude expressed in equal increments of potential energy based on sea level value. Becomes numerically smaller than geometric (standard) altitude with increasing height.

APPENDIX B (continued)

Unit or term	Symbol	Definition or equivalents
Gram calorie		4.18 joules; 4.18 x 10 ergs.
Ionized atom		A neutral atom that has lost or gained one or more electrons by the absorption of energy, and thus becomes charged.
Joule		1 watt-sec; 10^7 ergs; 9.48 x 10^{-4} Btu.
Kelvin, degrees K		Absolute temperature scale; zero K equals -273.16 C or -459.69 F.
Light year		Approx. 9.5 x 10^{12} km; 5.9 x 10^{12} mi.
Lumen	ϕ	Radiant power evaluated in terms of eye's response; 1 lumen= 1/680 watt at 0.554 micron.
Mass number	A	Total number of protons and neutrons in nucleus gives approx. measure of nuclear mass.
Mean free path	MFP	Average distance traveled by atom or molecule between two consecutive collisions with atoms or molecules.
Micron	μ	10^4 angstroms; 10^{-4} cm; 3.94 x 10^{-5} inches.
Millibar		10^3 dynes/cm^2; 0.0145 psi.
Normal temperature and pressure	NTP	-0 C and 760 mm of Hg.
Number density	n	Number of particles (atoms, electrons, etc.) per cubic centimeter.
Perigee		Point of satellite's orbit closest to Earth.
Perihelion		Point of planet's (or comet's) orbit closest to Sun.
Planck's constant	h	6.624 x 10^{-27} erg-sec; 6.624 x 10^{-34} joule-sec.
Radiant emittance	w	Radiant power per unit area emitted from a surface (watts/cm^2).
Radiant power (flux)	P	Rate of transfer of radiant energy (watts).
Reflectivity		Ratio of reflected energy to incident energy.
Solar constant at 1 astronomical unit		1400 watts/m^2; 2.00 cal/cm^2 - min; 130 watts/ft^2; 443 Btu/ft^2-hr.
Standard temperature and pressure	STP	-15 C and 760 mm of Hg.
Universal gravitational constant		6.67 x 10^{-8} dyne - cm^2/gm^2.
Velocity of light (in vacuum)	c	2.9977 x 10^{10} cm/sec; 186,278 miles/sec.
Weber		10^8 maxwells; 1 volt - sec.

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