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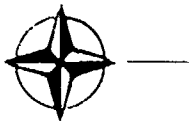
VERTICAL INSTRUMENTS

by

J. H. KEARNS and E. WARREN

JULY 1962

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NORTH ATLANTIC TREATY ORGANIZATION

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J.H. Kearns and E. Warren

This Report was presented at the Twenty-First Meeting of the Flight Mechanics Panel
of AGARD, held in Paris, 6-10 July, 1962

SUMMARY

This Report is a discussion of Vertical Scale Instruments covering the historical facts which lead to their design through to their application. The point is made that Vertical Instruments represent the foundation of a new approach to the creation, design and development of displays. This was our first attempt to deliberately design displays so that they would be suited to the total system job and the needs of the pilot. These instruments are now in use in over twelve squadrons and both pilot acceptance and reliability have been very good. Work is continuing on several parts of the Air Force Control-Display Program of which the effort on vertical instruments is a part. Work is being done on improved mechanization techniques, more comprehensive analysis methods for determining information requirements for human operators performing complex control tasks and advanced display designs to meet these requirements.

SOMMAIRE

Ce rapport traite des appareils de mesure à échelle verticale, avec un exposé des faits historiques ayant amené à leur conception et à leur application. Après avoir rappelé que les appareils à échelle verticale représentent la base d'une nouvelle manière d'aborder la question de la création, de l'étude et de la réalisation d'indicateurs, l'auteur signale le fait que c'est la première fois que l'on s'est efforcé d'étudier des indicateurs expressément pour qu'ils conviennent au fonctionnement du système dans son entier et aux besoins du pilote. Ces instruments sont maintenant en service auprès de plus de 12 escadrilles, et ont donné des résultats très satisfaisants aussi bien du point de vue de leur acceptation par les pilotes que du point de vue de leur sûreté de fonctionnement. Des travaux se poursuivent au titre du Programme d'indicateurs de l'Armée de l'Air Américaine, et dont ceux sur les instruments à échelle verticale font partie. Des études en cours portent sur des techniques de mécanisation améliorées, sur des méthodes de dépouillement plus complètes permettant de définir les indications nécessaires à l'opérateur humain dans l'exécution de manoeuvres de commande complexes, et sur des modèles d'indicateurs d'avant-garde destinés à répondre à ces besoins.

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CONTENTS

	Page
SUMMARY	ii
SOMMAIRE	ii
LIST OF FIGURES	iv
1. INTRODUCTION	1
2. BACKGROUND	1
3. TESTS	3
4. THE FUTURE	4
BIBLIOGRAPHY	8
FIGURES	14
DISTRIBUTION	

LIST OF FIGURES

	Page
Fig. 1 Air Force advanced instrument system	14
Fig. 2 Air Force advanced instruments	15
Fig. 3 Advanced instrument installations	16
Fig. 4 Mechanism comparisons - old & new	17
Fig. 5 Samples of vertical scale designs	18
Fig. 5(a) 'Phase III' altimeter	19
Fig. 6 Test panels	20
Fig. 7 'Phase III' airspeed	21
Fig. 8 A fuel management indicator	22
Fig. 9 Vertical scale with variable scale factor	23
Fig. 10 A flight control system	24
Fig. 11 The Mark IV space ship cockpit (experimental)	25

VERTICAL INSTRUMENTS

J. H. Kearns* and E. Warren*

1. INTRODUCTION

A review of vertical instruments is a very appropriate subject for many reasons. First of all, a prior paper by Major Brown, in May 1959, announced and introduced the new instruments to this committee and it is therefore proper to report on our experience with these instruments. But perhaps a more significant reason for discussing vertical instruments and, in particular, the Air Force Advanced Instrument System is that they were a party to, in fact an essential part of, what we might call the new age or the scientific age of display design. Instruments and displays are certainly not a new subject but, at about the same time that the Air Force introduced their new vertical instruments, displays began to be recognized as an engineering problem in their own right. The vertical instruments represent the foundation of this new approach to the creation, design and development of displays. This was our first attempt to deliberately design displays so that they would be suited to the total system job and to the needs of the pilot. Furthermore, this was the first attempt to design a set or group of instruments to fit together in-so-far as the display is concerned. The Air Force Advanced Instrument System consists of four instruments which present the essential information parameters as attitude and heading - navigational relations - on one part, augmented by an altitude group and a speed group which are both vertical tape instruments. Since the two tape instruments look appreciably different the System has become known as the Air Force Vertical Instrument Program. That is unfortunate because the vertical characteristics are only of minor significance and occur in only two instruments.

Four displays, independent yet designed to harmonize and to work in a cooperative manner, marked the beginning of the development and application of systems design procedures to the instrument display area. Systems design and systems engineering are not new and were not new at that time, but systems design of the instrument displays *per se* was new and so it is appropriate to look back upon these instruments, to review the progress, and to consider the present status not only for the purpose of looking back and evaluating the instruments but also as a means of reviewing progress in the development of control-display as a science. Thus I would like to report our experiences with vertical instruments and our plans for them, and correlate these with the progress made in our infant science, Control-Display.

2. BACKGROUND

It is a little difficult to pinpoint the exact moment of conception of this new approach to display design, but certainly there was a long gestation period for the essentials of the idea to take form. The preliminary design of the Air Force Instrument System was done by Siegfried Knemeyer. Mr. Knemeyer is the originator of the modern flight director, which presents flight information divided into two displays, the attitude director and the horizontal situation display. Variations of this basic

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design are being produced by the major instrument manufacturers and this concept is almost universally accepted in international transport aviation. It was some time during the latter part of 1955 that directed effort got under way which resulted in the ultimate development and production of what we now call the Advanced Instrument System, of which the vertical scales are a part. The significant thing about this program and the way it began was that the question posed was not how a particular single parameter (e.g. altitude, airspeed, or attitude) should be displayed, but rather, as it was most appropriately phrased, "What must the pilot know; what must he see to control an aircraft during normal flight?" Note that this question did not constrain us to the design of a single instrument, nor did it presuppose any specific information requirements. The solution to the question had to be based, by its nature, on mission performance requirements. Contributing to the solution was an enormous wealth of background knowledge and experience in flying, piloting all kinds of vehicles under all conditions, and an intimate familiarity with the instrument systems and operational procedures. Many decisions were made intuitively against this tremendous background of knowledge and experience. In retrospect we can observe that this became the philosophy and the 'corner stone' for the new science which we call 'Control-Display.' We were indeed fortunate to be present when this unusual event occurred. The particular combinations of skills, experiences and circumstances combined to start us out on a new and promising line of endeavor.

In our initial endeavor we limited the scope to that degree which seemed to us to be within our capacity to handle and produce useable results within a reasonable period of time. Our standards were reasonable also, since we hoped not for the best, but were aiming at producing a product that was suitable for the job. The program was not begun with the intent of developing vertical-scale instruments as an end in itself. This should be clearly understood. The requirement for vertical scales and ultimate development of them came about as a result of needs recognized as the program progressed.

The attitude indicator was selected as being the central instrument fundamental to instrument flight. It was the foundation and we attempted to construct upon and around it displays which would enhance and work in harmony with this attitude indicator eliminating as much as possible those inconsistencies so prevalent among the independently designed displays. Building out from the attitude indicator was to be all the information which was pertinent to the control of attitude and flight. Our philosophy was simple: present all the parameters that are related to the pitch of the aircraft and all those that are related to the yaw and do so in a manner such that there would be consistent cues of motion and response between the display, the controls, the external visual world and the kinesthetic senses. This resulted in what is well known now as the T-scan and produced a set of instruments known as the Phase II instruments. More formally they are called the Advanced Instrument System (see Figs. 1 and 2). These instruments have been a production installation in our F-106 and F-105 airplanes for some time now (Fig. 3).

As is well known, it would not be possible to introduce anything as extensive as this into a cockpit without many problems and much concern, and rightfully so. The changes represented here are not only changes in display, which are certainly of concern, but also changes in the mechanization. Fairly conventional servo techniques were used, but the mere introduction of servo instruments into primary flight instruments was a truly significant change (Fig. 4.). In place of the altimeter with its bellows and mechanical linkages we now have an instrument with not only the

mechanical linkages replaced with a servo, but with five servo loops. This is an instrument with about one thousand parts and a volumetric efficiency almost twice that of any preceding instrument. Naturally, questions were raised about such things as producibility, cost, maintainability, and reliability. In addition, these instruments looked different, which was perhaps the greatest obstacle to their introduction. There were tests and still more tests. Each new group had to run tests. Each group inspecting the instruments were concerned about cost, reliability and utility.

3. TESTS

What was the outcome? How were they accepted? Were there problems in usage? How reliable and maintainable are they as looked at from the vantage point of hindsight? Summing up the experience, comments and test reports I think we can conservatively say that they were amazingly successful, particularly when it is considered that only four years elapsed between their inception and their production, compared with a normal time of seven years. A bibliography and various test reports with regard to these instruments, or vertical instruments in general, are appended to this Report. I would like to review briefly some extracts from these documents and experiences.

WADC TR 58-431 is a report on these instruments covering developmental work and extensive flight testing performed by the Air Force at Wright Field, Ohio. Many critical comments were obtained regarding such things as scale factors, reflection, sticking and switching. However, a most significant point to note is the universal acceptance of the instruments; the criticisms were generally constructive and pertained to mechanization aspects. Reliability was a concern and a considerable amount of data was obtained which was useful in improving the mechanization.

One of the most recent reports, dated March 1962, has been issued by the USAF Instrument Pilot Instructor School of Randolph Air Force Base, Texas. The School had performed an operational test and evaluation of the Integrated Flight Instrument System. The purpose of the test was to determine the suitability of this system for transport-type aircraft and to determine how pilot performance would be affected by loss of various components of the system. Installation was in a T-29. Ten pilots from the School were subjects. In addition, twenty six pilots from MATS, FAA, and the C-141 Program Office flew orientation flights on the system. Information was obtained by means of questionnaires. The report comments "...generally the integrated flight instrument system was enthusiastically received... The average transition time to attain proficiency on the new system varied between four and six hours flying time... All subject pilots connected with the project universally agreed that the integrated flight instrument system was suitable for use on jet transport-type aircraft... It may be stated that the integrated flight instrument system provides the pilot with a complete and satisfactory instrument panel which makes it highly suitable for use in high-performance aircraft".

Naturally deficiencies were pointed out, with recommendations for improvement. For example, the minus values on the altimeters should be depicted in red. White lighting should be incorporated. A tail or reciprocal bearing indicator should be added to the bearing pointer of the HSI. However, all the recommendations concerned details; none was critical of the theme or general scheme.

Over twelve squadrons are now using these instruments in operational aircraft and ...

excess of 2500 instruments have been produced. There has been a continuing program to follow up on operational experience for purposes of checking maintenance reliability experience and accomplishing improvements in the design. These changes have involved such things as teflon coating for rollers and brakes, reducing reflective characteristics of cover glass, even lighting over the whole surface, circuit improvements, mechanical changes to improve strength, clearances and weight. Pilot acceptance has been good. Performance and maintenance have also been good.

4. THE FUTURE

What does the future hold for these instruments? What are possible future instruments? What does the future look like for the control-display area?

In order to discuss these questions in a meaningful manner it is necessary first to consider the philosophy or attitude of the Air Force. The Air Force desires to 'Get the job done' and to do it in the most effective and expeditious manner, without expensive frills and embellishments. In the case of the cockpit it is desired to put into it those instruments and displays which are necessary for satisfactory and effective use of the vehicle; everything else is secondary. Advances in vehicle performance have made this job more difficult. The demands upon displays have become more stringent, which has resulted in the increased attention and effort necessary to achieve satisfactory systems performance.

This situation does not allow us to rely only on the intuitive judgement of a few people. The demands of the mission, the vehicle, and other sub-system diversions have forced us to develop special control-display engineers in order to cope with the problem of designing an adequate system.

It was necessary to establish a special program to provide these required capabilities. This is now called the Air Force Control-Display Program. Note, however, that the attitude is still the same. The job must be done satisfactorily, efficiently, and economically.

At this point it is again appropriate to correct the misunderstanding mentioned earlier. The Air Force Control-Display Program produced the Advanced Instrument System. A distinctive feature of this system is the vertical shape of two instruments. Since then people have talked of the Air Force Vertical Instrument Program. Apparently this, in turn, led to the generalization that the Air Force wants vertical instruments. However, this is not the case. What is wanted is the most suitable design for the job, whether it be straight, round, or spiral.

As to the future of these instruments, we can most conveniently think in terms of the immediate future and then what might come thereafter. For the immediate future, as might be expected, things probably will not change radically. As we move into the next period greater changes will emerge. These will be evolutionary in nature, rather than revolutionary. Beyond that we can expect considerable changes not only as the result of learning more about how to get information to the man visually, but also as a result of some of the very different kind of generation techniques which are just in their formative research stages at the moment.

The Advanced Instrument System was not intended to deal with the problem totally, but it was to be a start upon which we could build. One of the essential requirements imposed was that it should have growth potential. Our family name for this system, the Phase II Instruments, reflects this. There had already been a set called the Phase I Instruments and we anticipated a Phase III. We are now in the process of working on the Phase III Instruments. They will not be radically different in appearance. However, their development process does reflect the continual advances being made in this new science.

The Phase II Instruments were designed for general flight conditions, with some special provision for the interceptor mission. Their design did not provide for certain problem phases of flight. One of these is the Approach and Landing Phase. Instrument flight to touch-down under zero-zero conditions does not yet have a routine solution. This phase is our particular concern now. We are pursuing a program which we hope will provide a practical solution for control of a manned vehicle under IFR during approach and landing. Note that the problem is one of control. Both displays and man are essential ingredients or components of the total control system. A feasible concept of solution must be devised for the total problem before anything useful can be done in developing a component. In the past the solution required consideration of the physics of the problem. System synthesis was useful as an adjunct to conceptualizing possible system solutions. Permissible variables included sensing devices, computers, displays and modifications to the airframe and piloting technique. This effort on a problem and the conceptualizing of a system solution led us to the point where we could begin to identify more specifically the demands for information requirements to be imposed upon the display system. This involved taking the Phase II displays and augmenting them with the necessary display of additional information needed. The first important item is vertical path angle information. The pilot controls attitude, but his objective is control of the flight path of his vehicle. It was thought necessary to display path angle in combination with pitch angle on the attitude indicator. The second important item, a most critical one, is absolute altitude or remaining altitude over touch-down. That is, a direct measurement of the height of the aircraft above the runway. When synthesizing a solution many assumptions may be made which very much simplify the problem, at least in totally conceiving and describing the required solution. Thus, in this case, we assumed that there was a completely adequate system for measuring the distance between the aircraft and the ground. (An outcome of this approach is a detailing of the requirements such a system must satisfy.) Pursuing this assumption further, in-so-far as the display is concerned, we found that we not only need to have absolute altitude information, but that we must have it in order to make meaningful decisions about the rate of descent of the aircraft. Therefore, these two particular pieces of information must be related in the display. It also appeared that altitude need be known only in the detail that is necessary to allow proper and adequate judgement in controlling the rate of descent. Consequently, we took our Phase II altimeter and added to it a tape indication which moved proportionally to the absolute altitude over the vertical velocity scale. When making judgements about his rate of descent the pilot needs only a qualitative indication, a judgement of the absolute altitude information. This was only the initial step in the design of the display. The dynamics are another problem which, from the practical viewpoint, can only be solved through synthesis. It is impractical to attempt the variations in the dynamics and provide for the control required in an aircraft flight test program. This must be done initially in a simulator. Only after the initial difficulties have been eliminated should the installation be made in the aircraft. Our initial efforts were in trying variations of this tape in combination with the rate of climb. We tried linear and non-linear scale

functions, logarithmic and broken scale, and, of course, we varied the scale factor, damping, range, and pilot technique; and it is most important to remember that pilot technique is a variable.

While we are interested in military missions this problem of IFR approach and landing is not peculiar to military missions. The Federal Aviation Agency is concerned with the landing problem as it pertains to civilian aircraft. As a result of this common interest in all-weather landing there was established a joint effort specifically related to the altitude instrument necessary for landing. In this effort we conducted a test program on three different instruments, each of which provided absolute altitude information. In each design the scale factors, damping and response rate were the result of prior design effort to optimize each version. Other versions had been previously considered (see Figs. 5 and 6). Instrument delivery problems required us to use a Phase IIA instrument modified to conform in the essentials to the Phase III instrument characteristics. A 1-inch wide module instrument and a circular scale instrument were the other two tested. The three instruments in their panel arrangement are shown with a standard practice panel in Figure 7.

This program has just been concluded last month and a report has not yet been published. However, the conclusions indicate, without reservation, that absolute altitude is indeed, an essential ingredient. Furthermore, while there were differences between the instruments they all produced an improvement compared with the condition in which this information was utterly lacking. It should be noted that here we were attempting to display the needed information in the most suitable manner. The results indicate that such information may be displayed vertically or on a circular scale, with the choice of vertical or circular scale being dependent upon other factors. Therefore a test on performance would not permit a generalized conclusion as to which is the better scale. Among the most important of these other factors are the specific problems of installation encountered in tailoring the instrument to a given vehicle. Certainly costs are a consideration as well. Again, I would like to emphasize that we do not have a vertical-instrument program. We have an instrument program which is not biased against vertical instruments or against any other type of instruments. Note also that in correlating this to our scientific advancement we are dealing with the problem in more of an engineering manner, getting such things as systems synthesis and information requirements arranged in their proper sequence.

The third item which we added to the information to be displayed is distance to touchdown. This information we tentatively integrated on the horizontal situation display.

All these display items which I have just discussed as being part of our Phase III endeavor are in the process of installation in aircraft and will be subjected, during the coming months, to a very broad flight verification by a cross-section of the most expert military and airline pilots in the United States. We have, already, experimental evidence that this line of endeavor is on the right track and will produce very significant results. It should be noted that in this endeavor not only are the essential display aspects under evaluation, but also that they are intimately integrated with different schemes of automaticity in the control of the aircraft. This is done in such a manner that the pilot is oriented as the most reliable element in the control loop, that is as an active control element himself. This new Air Force concept of total integration of manual and automatic flight with the necessary display of essential flight

information, for the entire range from direct manual control to all degrees of automatic control, is, in our opinion, the only way to arrive at the total solution. As has been mentioned earlier, displays singularly or within the wider context of a display system cannot be treated separately. They must be considered intimately with the total control problem, be it manual or automatic.

The Phase III airspeed, an advancement over the Phase II airspeed, is now being studied, but is not nearly as far advanced as the Phase III altimeter. We have not, as yet, done much directly on the speed instrument, although the system synthesis has implications bearing upon the requirements or characteristics desired of the Phase III airspeed. We are now building an instrument, a sketch of which is shown in Figure 8, but we have no data on it yet.

It is interesting to note that we seem to have provided a release of inhibitions as far as vertical scales, or more properly, linear straight scales, are concerned. They are now being considered for very many applications, such as engine instruments, 'time to go' information and fuel-distance relationship. In addition they are not only being used for displaying primary information, but also for drawing comparisons between different kinds of information where the comparison itself is the meaningful information, as in the fuel management indicator (Fig. 9). There have been a number of interesting innovations proposed for these scales; see, for example, the sketch in Figure 10, which is a vertical scale with a variable graduation or variable scale factor capability. Another interesting facet of the new look in the instrument field is the fact that the instrumentation or mechanization is following the display, rather than, as in the past, the display having to suit itself to mechanization capabilities. For example, we have had new developments in high-speed counters, miniature counters, and electroluminescence, tailored to the needs of displaying information in various forms. There are new capabilities in the tape and tape drives and miniature magnetic clutches and a renewed interest in investigating and advancing other means of generating displays, even such exotic ideas as true volumetric three-dimensional displays and instruments which accept digital input and provide an analog display, although they have no moving parts.

Finally, I would like to mention work in progress aimed at developing a complete control-display system. This program has pursued analytical treatment for deriving information requirements, is making use of the latest advances in all aspects of flight control, and is applicable to a multi-orbit vehicle. Figure 11 gives a generalized diagram of the system and Figure 12 shows the panel layout.

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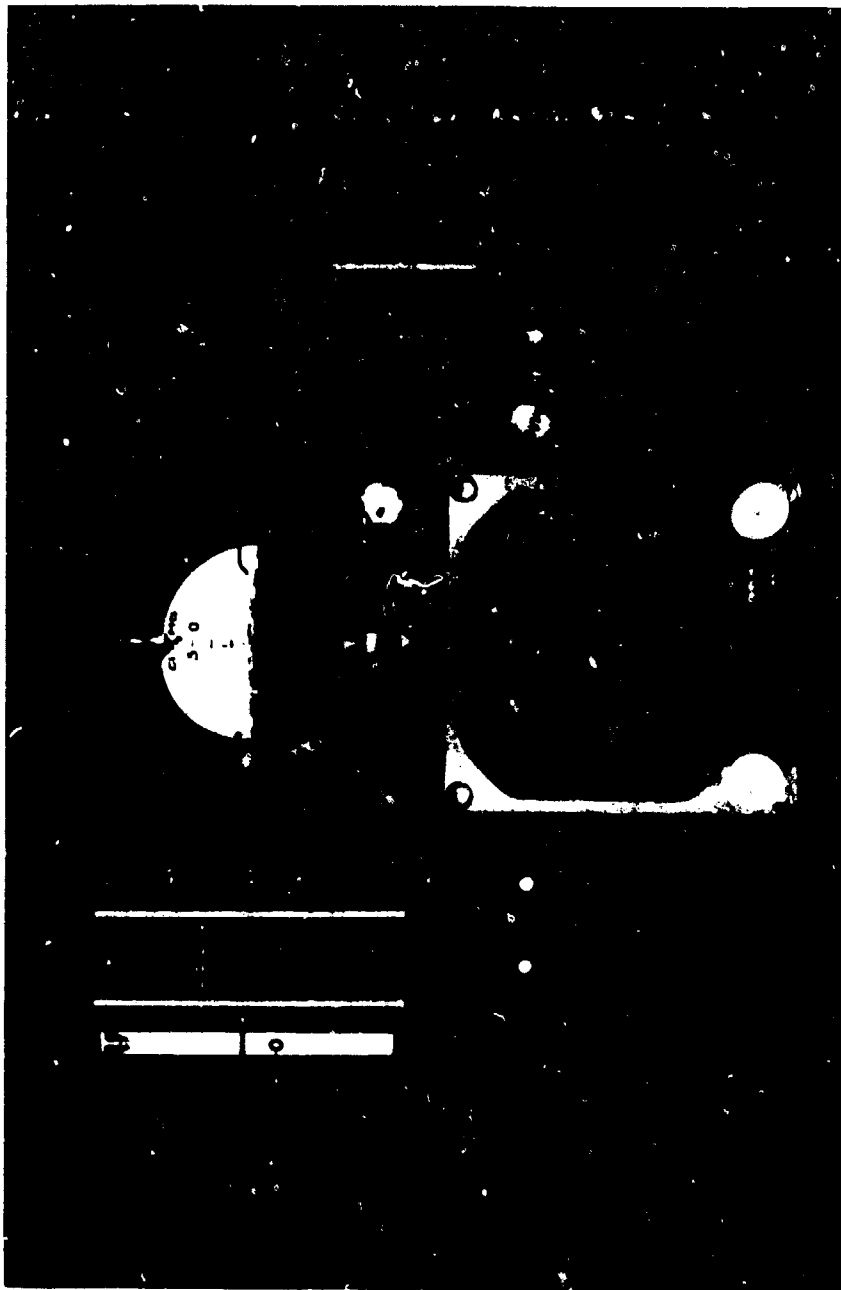


Fig. 1 Air Force advanced instrument system

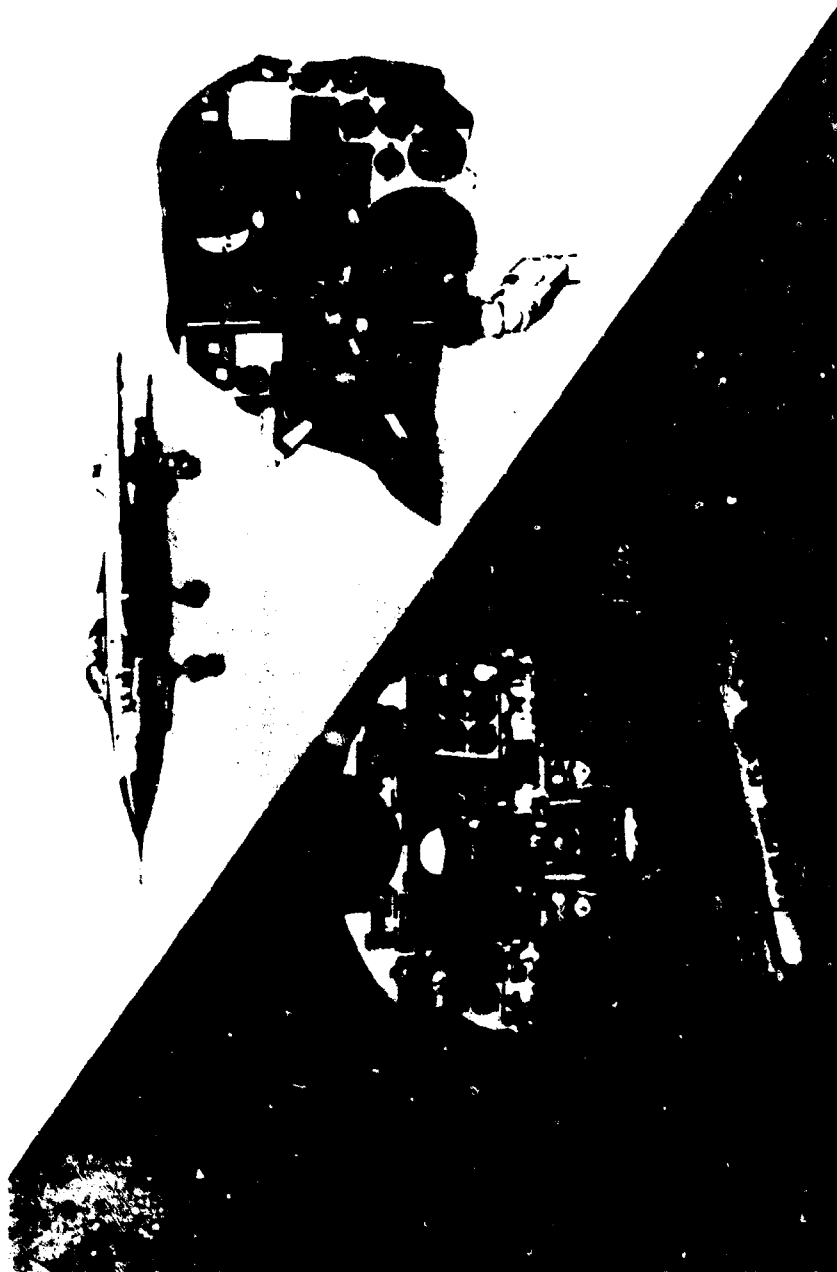


Fig. 3 Advanced instrument installations



Fig. 4 Mechanism comparisons - old & new



Fig. 5 Samples of vertical scale designs

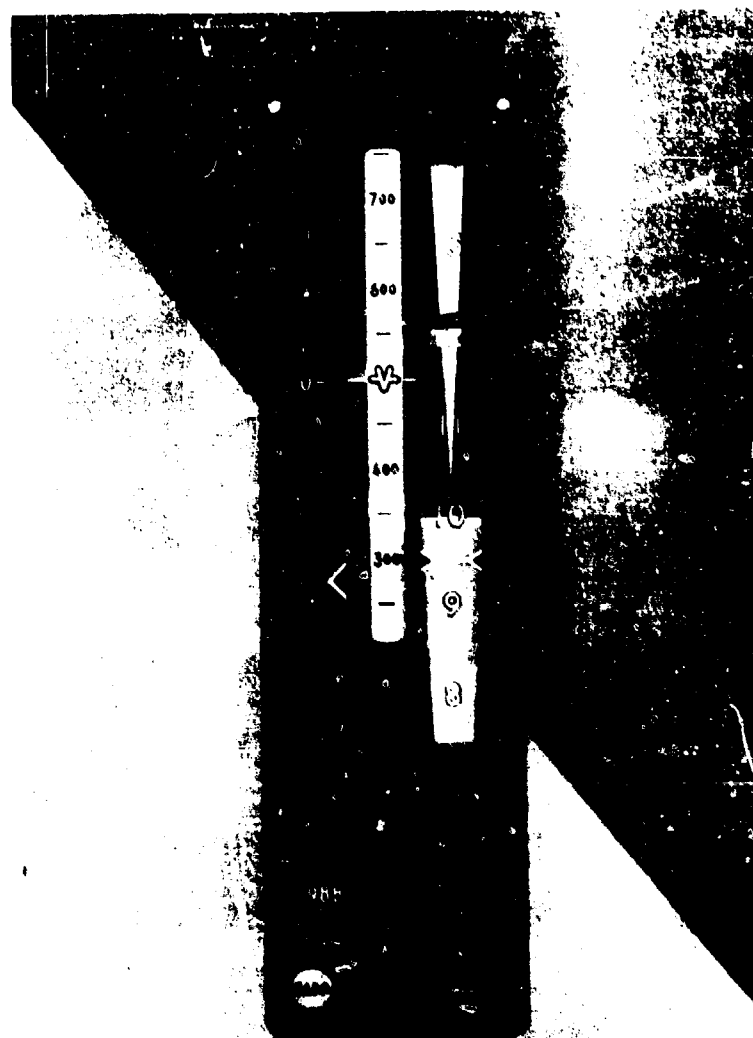


Fig. 5(a) 'Phase III' altimeter

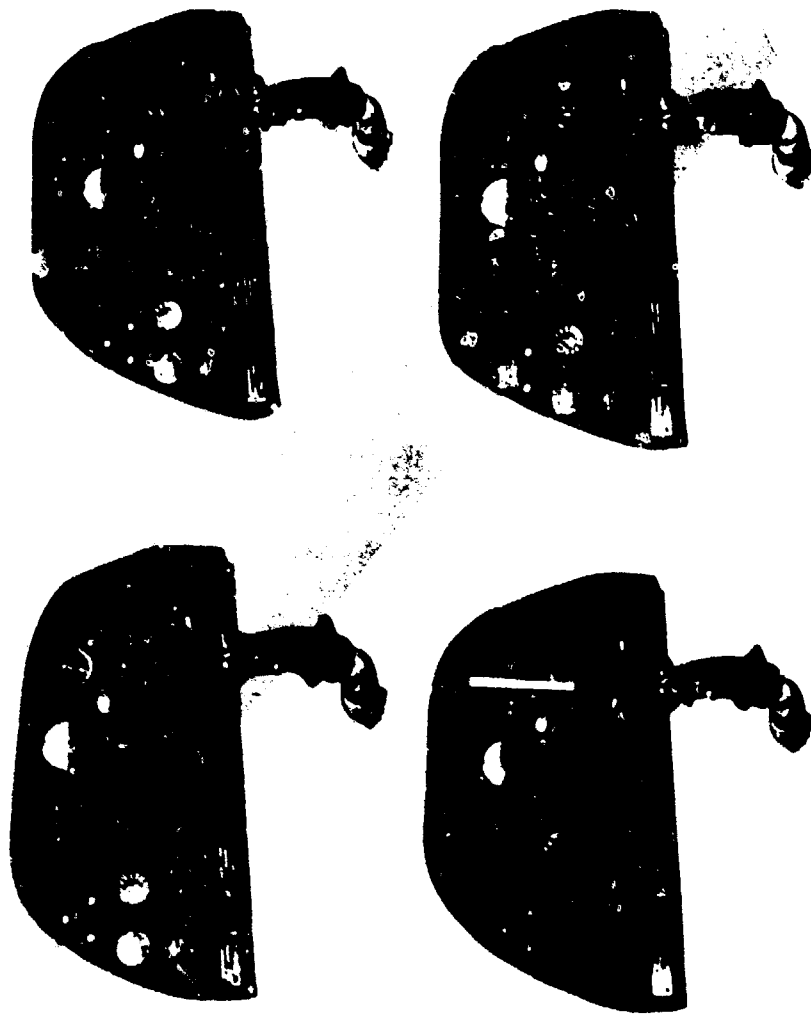


Fig. 6 Test panels

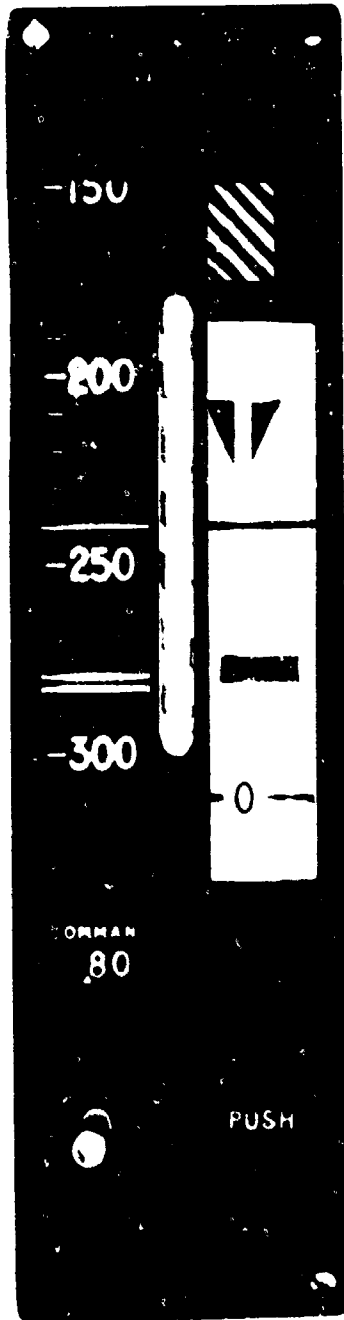


Fig. 7 'Phase III' airspeed

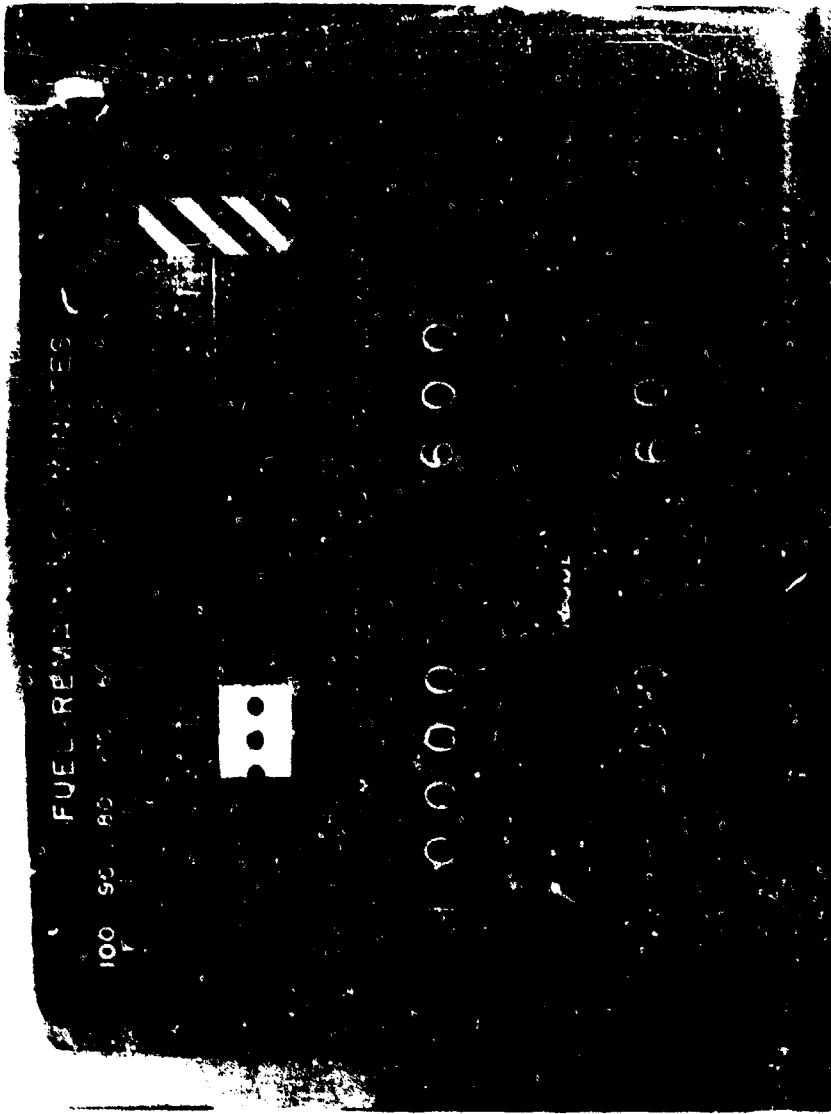


Fig 2 A fuel management indicator

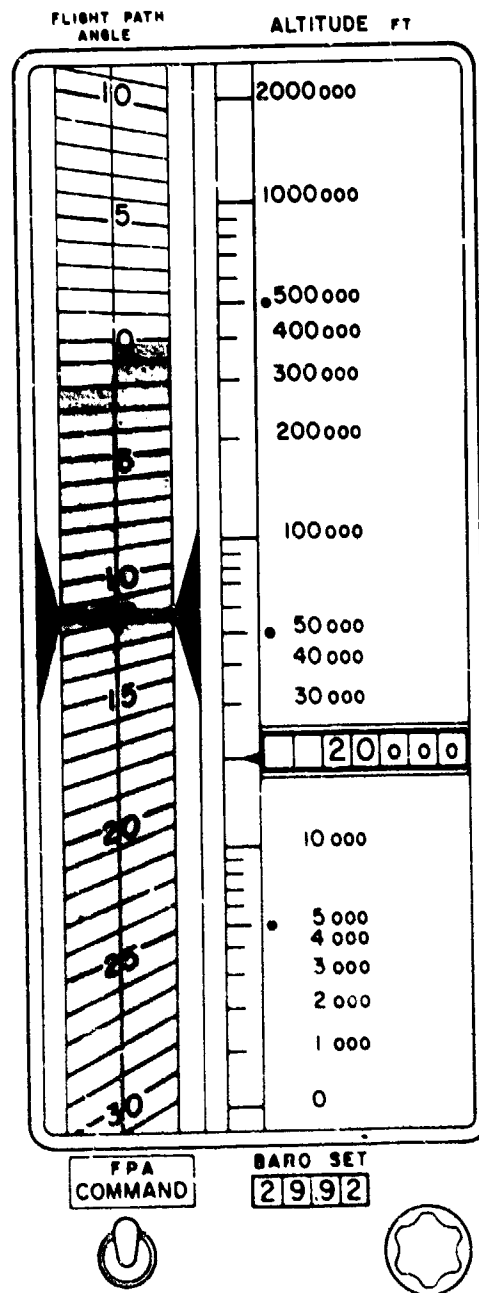


Fig. 9 Vertical scale with variable scale factor



Fig. 10 A flight control system



Fig. 11 The Mark IV space ship cockpit (experimental)

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