STUDIES OF PILOT CONTROL DURING LAUNCHING AND REENTRY OF SPACE VEHICLES, UTILIZING THE HUMAN CENTRIFUGE

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For Presentation at the Twenty-Seventh Annual Meeting of the
Institute of the Aeronautical Sciences

New York, New York
January 26-29, 1959

STUDIES OF PILOT CONTROL DURING LAUNCHING AND REENTRY OF SPACE VEHICLES, UTILIZING THE HUMAN CENTRIFUGE

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INTRODUCTION

With the ever increasing complexity of airplanes and the nearness to reality of manned space vehicles the use of pilot-controlled flight simulators has become imperative. The state of the art in flight simulation has progressed well with the demand. Pilot-controlled flight simulators are finding increasing uses in aeromedical research, airplane and airplane systems design, and preflight training. At the present many flight simulators are in existence with various degrees of sophistication and sundry purposes. These vary from fixed base simulators where the pilot applies control inputs according to visual cues presented to him on an instrument display to moving base simulators where various combinations of angular and linear motions are added in an attempt to improve the flight simulation.

In the flight simulation of space vehicles one of the major environmental factors to be considered is the high and sometimes oscillatory accelerations that the pilot will be subjected to during the launch and reentry phases of the flight. Based on past flight experience and somewhat meager knowledge of the effect of dynamic flight loads on the pilot

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and on pilot control, an examination of the required accelerations predicted for launching and reentry indicates some probable problem areas. Areas requiring special consideration include, pilot physiological tolerance to accelerations, associated body support and restraint required and pilot-vehicle control in the acceleration environment. The human centrifuge at the U. S. Naval Air Development Center, Johnsville, Pa., by means of a controlled two-gimbal system can provide an accurate reproduction of the linear accelerations of flight along all three axes. This facility, therefore, provides a means to investigate problems such as those mentioned above. The purpose of this paper is to describe the centrifuge and its operation and to discuss use of the centrifuge in pilot-controlled flight simulation and other work pertinent to space studies.

CENTRIFUGE DESCRIPTION

The Johnsville human centrifuge, shown in figure 1, is in the Aviation Medical Acceleration Laboratory at the Naval Air Development Center, Johnsville, Pa. This centrifuge has an arm of 50-foot radius directly mounted on the armature shaft of a 4,000-horsepower d-c motor. A peak value of 40G radial acceleration can be obtained in 7 seconds. At the end of the centrifuge arm is a gondola within a power-driven double-gimbal system. The outer gimbal which rotates about a horizontal axis perpendicular to the arm may rotate to 90°. The inner gimbal which rotates about an axis in the plane of the outer gimbal, may rotate through 360°. This gimbal has been limited in deflection to about ±100° in past programs to prevent exposure of the pilot to large negative accelerations. The angular velocities of the gimbals can reach 2.8 radians/sec and the angular accelerations can reach 10 radians/sec^2. When radial accelerations do not exceed 20G, the gimbals may be driven with gondola loads up to 600 pounds. Additional details of the centrifuge operation and capabilities are given in references 1 and 2.

The total acceleration force at the center of the gondola when the arm is set in motion is comprised of three components as shown in figure 2. The radial force, A_R, is proportional to ω^2 where ω is the angular velocity of the arm. The tangential force, A_T, is proportional to $\dot{\omega}$, the angular acceleration of the arm, and A_V is the component due to gravity. The controlled gimbals can operate singly or in combination and allow continuous positioning of the gondola with respect to the total resultant acceleration force. It is this gimbal system that makes this centrifuge unique. By proper and continuous control of the gimbals in combination with the rotation of the arm, an accurate reproduction of the linear accelerations of flight along all three axes can be obtained.* It should be noted at this point that the orientation and rates of orientation of the gimbals are purely determined by the three components of linear accelerations to be reproduced. This is to say that accurate reproduction of the three linear accelerations of flight will result in angular motions of the gondola which may be unlike the angular motions experienced in flight. The significance of these motions relative to pilot-controlled flight simulation will be discussed in a subsequent part of the paper.

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*Only accelerations with a resultant magnitude of 1G or greater can be obtained; for accelerations less than 1G the centrifuge remains at rest.

PILOT TOLERANCE STUDIES

Several investigations have been made recently on the centrifuge to determine mainly pilot physiological tolerance to acceleration considering several body support techniques. One such study considered pilot tolerance and performance under linear accelerations typical of those calculated for a high-drag vehicle reentering from orbit. (Ref. 3.) One of the main purposes of this experiment was to determine if an NASA designed contour couch, shown in figure 3, would provide adequate support for high G exposure. The subjects rode in this semi-supine position and were oriented such that the direction of the "G" force was principally from chest to back. The purposes of contouring the couch about the subject's body were to minimize the body pressure points by proper distribution of the weight and to minimize jostling effects due to oscillatory accelerations. Pilot performance was evaluated by assigning the pilot an arbitrary visual tracking task. The centrifuge in this program was operated by open-loop control, that is, the accelerations that the pilots were subjected to were programed and unaffected by any pilot control motions. The type of acceleration patterns that the pilots were subjected to are shown in figure 4. For the vehicle characteristics assumed the acceleration profiles shown were calculated for entry angles of -1.5°, -4.75°, and -7.5°. Tests were also made when the pilots were subjected to oscillatory patterns simulating reentry oscillations. Three subjects were used, one an NASA test pilot. All subjects wore standard Navy Z-2 G-suits. An important factor in increasing the tolerance level during the runs was the technique with which the subject strained, as if he were trying to support someone standing on his chest. No chest pain was reported as long as proper straining was maintained, although breathing became difficult around the 12G level. Blurring of vision was reported by some subjects at levels of G near 16. Subjects were able to operate a small, right-hand control stick under accelerations as high as 25G. A thumb-operated switch was also used effectively. Although conclusive objective data were not obtained, performance of the tracking task showed deterioration with increasing acceleration but improved with experience. It was felt that the contoured type couch offered a satisfactory means of support for entry accelerations as high as 25G for a trained subject.

Another investigation, undertaken by R. Flannagan Gray of AMAL, to determine pilot tolerance to high G exposure is a study of G protection afforded by submersion of the subject in water. The Gray-G capsule, shown in figure 5, has been constructed to carry out this work. It is known that it is not the absolute forces generated by high accelerations which do damage but rather the body distortions produced by differential forces. Gray reasoned that if body distortions could be minimized, much higher acceleration tolerance could be achieved. By maximally filling the lungs and being immersed in water over the head, Gray has withstood 16G, head to seat, with a one minus cosine wave form of 25-second period, without greyout. Without protection, a subject greys out under positive accelerations at about 3G. The water during acceleration compressed the air in the lungs. This compressed air in the lungs reduced the pooling of blood in the lungs and so helped maintain circulation to the brain. Tolerance to back-to-chest acceleration, forcing the heart forward in the chest, is limited for the unprotected subject by breathing difficulties and chest pain. Centrifuge accelerations above 15G, back to chest, had not been tolerated by humans. But in the Gray G capsule back-to-chest accelerations of 31G have been reached, with a one minus cosine wave form of 25-second period and with the peak being held for 5 seconds, without reaching tolerance limits. This work is continuing and a modified plastic form of the capsule, with minimum water volume and minimum weight is being designed.

PILOT CONTROL STUDIES UTILIZING CENTRIFUGE

CLOSED-LOOP CONTROL

Some 20 months ago, the Navy developed a technique of "tying in" the centrifuge with an electronic analog computer to be used as a pilot-controlled flight simulator. This technique is illustrated in figure 6. The simulator consists primarily of two facilities - the centrifuge and the Typhoon electronic analog computer. These two facilities are located approximately 3/4 of a mile apart and are tied together operationally by telephone lines. The pilot is situated inside the gondola and provided with necessary controls, display instrumentation, and restraint. The Typhoon computer provides the aerodynamic simulation of the aircraft or vehicle under consideration. The control loop is accomplished by feeding the three linear accelerations of the pilot as computed by the analog from the equations of motion of the airplane to a so-called coordinate converter. This is an electronic analog setup which determines from the accelerations the required velocity and acceleration of the centrifuge arm and the proper gimbal angles to be fed to the centrifuge as commands. The drive signals then cause the centrifuge to move in such a manner to produce the desired accelerations on the pilot. While undergoing these accelerations, the pilot observes necessary display quantities from the computer, and applies control motions which are fed back as input signals to the computer. So the loop is closed as the pilot actually controls the motions of the centrifuge and the accelerations that he is subjected to.

In general, the correlation between the desired or commanded accelerations and those actually produced by the centrifuge under closed-loop control was good. The reentry accelerations for one of the most critical cases encountered in the study to be discussed, are shown in figure 7 and represent probably the poorest correlation obtained. Here the accelerations computed during a reentry are compared with the accelerations measured in the centrifuge gondola. As a_Z reaches a high level of G and becomes oscillatory a serious inaccuracy is noted in the a_X component. As was noted previously the angular motions experienced by the pilot during such a run are not entirely comparable to those he would experience in the airplane. However, it was found that under the high linear accelerations, such as shown here, the pilots were not significantly disoriented or distracted by these wrong angular motions.

Utilizing the capabilities of this flight simulator to produce high and rapidly varying accelerations, typical of those that will have to be considered for the launching and reentry of space vehicles, various aspects of pilot-vehicle control have been investigated. Some of the problems considered were: effects of accelerations on desirable pilot control techniques and choice of control and display configuration, pilot tolerance to high oscillatory accelerations and advantages of various restraint devices. Although some assessment of the problems of pilot tolerance and restraint can be made with open-loop centrifuge control, the total and ultimate effects of acceleration on pilot control, as indirectly due to pilot tolerance and restraint, can more completely be determined by a closed-loop study. The simulated flights that were used for the closed-loop study considered a single-stage boost, coast to high altitude and reentry. The mission was typical of those that may be flown by the X-15 research airplane. Before discussing some of the problem areas investigated in the closed-loop studies it is worth noting some of the operational procedures followed on the centrifuge to insure pilot safety.

During simulated flights, the centrifuge was viewed by the project officer, who coordinated the conditions for the run, the centrifuge operator, whose primary function was to synchronize the centrifuge with the computer and the medical officer, who viewed the pilot's electrocardiogram and control motions on a recorder. All stations were in an open communication system and the centrifuge could be rapidly brought to rest from each station, as well as by the pilot himself. Also safety stops were included in the simulator which would automatically terminate the run if the commanded accelerations exceeded specific values.

A simulated trajectory on the centrifuge starts with the boost. During the boost phase the thrust acceleration gradually builds up to the order of 5G and the pilot is forced back against the seat. Thrust misalinement was simulated so that during the power-on part of the exit, the pilot has to apply corrective controls with the rudder pedals and a side-arm console stick. A side-arm stick was included in the centrifuge studies to provide a controller that could be operated under high dynamic loads with a minimum of involuntary pilot control inputs. At this G level, it was found that the pilot can keep his feet on the rudder pedals, but this requires some effort. He can still reach the instrument panel to operate switches if required. At the termination of thrust, oscillations start as the pilot quickly recenters the controls. As the airplane coasts to higher altitude, the decreasing dynamic pressure causes a decrease in aerodynamic control effectiveness. Thus, any residual oscillations must be damped by the use of reaction control. Reaction control must also be used at the high altitudes to maintain proper attitude and orient the airplane for reentry. In actual flight, the pilot would be at 0-G during this portion of the trajectory. The centrifuge, unable to simulate this condition, remains at rest.

Considerable effort of the closed-loop investigation was devoted to the ability of the pilot to control the airplane during reentry. To avoid serious aerodynamic heating problems and excessive load factors which might overstress the airplane, it was necessary that the airplane enter the atmosphere at relatively high angles of attack. The coupling of the airplane motions at high angles of attack, combined with the rapid increase in airplane frequency, control response and dynamic loads upon entering the atmosphere, presents a new and somewhat difficult control problem to the pilot. A factor of primary importance is the amount of stability augmentation provided for the airplane during reentry. Without any stability augmentation (only the inherent damping of the airplane) certain prescribed procedures are necessary for successful reentries. These procedures, generally, are for the pilot to establish an angle of attack at high altitude, trim the airplane at this angle and then to concentrate on holding the wings level until the pullout is accomplished. Little or no pitch control is applied after the trim is established in order to minimize the possibility of disturbing the airplane and starting an oscillation. Proper setup of the desired trim condition for reentry while the airplane is still at high altitudes is important for successful recoveries. After trimming in the reentry angle of attack, the pilot must damp out small oscillations before the airplane enters the more dense atmosphere. If oscillations are excited subsequently during the reentry, the pilot does not attempt to correct for each oscillation but to control only the mean values of angle of attack or normal load. Also critical in the reentry is not to establish a roll angle, thereby losing a portion of the aerodynamic lift, which makes the pullout of longer duration and higher dynamic pressure. The importance of a well-fitted arm and elbow rest for a side-arm controller, careful dynamic balancing and optimization of the breakout and friction forces of controls, were greatly emphasized by this phase of the investigation.

Addition of stability augmentation about all three axes greatly improves the controllability of airplane and offers to the pilot a wider choice of reentry conditions that may be used for acceptable recoveries.

With proper restraint and proper operation of the antiblackout protective equipment, it was found that the pilots could tolerate the reentry accelerations, including oscillatory accelerations which might occur during reentries without stability augmentation. Proper body and head restraint were found desirable in minimizing loss of orientation and distractions from being jostled about.

One extreme reentry condition involved normal acceleration of 7G and longitudinal deceleration of 4G which lasted as long as 25 seconds, during which time the pilot was able to maintain adequate control. The drag decelerations during reentries, when combined with pullout normal loads, increased the blood pressure in the limbs. Petechia (small skin hemorrhages) were noted on the forearms and ankles. Tingling and subsequent numbness of the limbs were noted and in a few cases definite pain was reported.

Several arrangements of display instruments and display information were tried, in an effort to reduce the required eye motions. Under "greyout" conditions where the peripheral field of view is reduced, or where head motions might affect vision, the minimum amount of scanning required was found to be important.

The acceleration histories examined in this program, obviously, will not necessarily be similar to those expected for orbital or space vehicles. Consequently the specific control problems might be somewhat different. However, the points considered in this study such as, pilot restraint, controls, control techniques and display instrumentation, are factors that will require some consideration for any valid control evaluation for manned vehicles which will undergo accelerations during their launch and reentry. The pilot-controlled centrifuge simulator offers to the designer and engineer the means to carry out this control evaluation under the expected flight accelerations.

POTENTIAL PROBLEM AREAS FOR FUTURE CENTRIFUGE RESEARCH

Centrifuge Flight Validation Program

The purpose of this program would be to compare pilot performance in the centrifuge simulator for particular airplane tracking tasks and prescribed maneuvers, with pilot performance of the same tasks and maneuvers in an actual airplane. The aerodynamics of the airplane will be simulated on the computer and the same test pilots will fly both the airplane and the centrifuge. The purpose of this study will be not only to determine the limitations of the centrifuge simulator but also to make modifications, if possible, that will improve its use as a flight simulator. An evaluation will be made of the relative importance of angular motions and linear accelerations in flight and on the centrifuge.

It is of interest to note here, a problem encountered by the Navy during the early stages of developing the closed-loop technique and how the problem was solved. When pilots first began flying the centrifuge under closed-loop control, they were asked to make a high G pullout from a dive maneuver. During the pullout the main acceleration force was to act along the head to seat axis of the pilot. In order to accomplish this, the inner gimbal rotated, as the angular velocity of arm increased to produce the buildup of normal load. In the first attempts, as the pilot initiated the pullout by pulling back on his control stick the rotation of the inner gimbal was such to pitch him forward even though the normal load increased correctly. The pilots had strong reaction against this unusual angular motion. The problem was solved very simply, however, by running the arm of the centrifuge in the opposite direction so that now, when the pilot pulled back on the stick the gimbal rotation was such to cause the pilot to be tilted backward. The pilots liked this much better. Although all six degrees of freedom can never be completely reproduced on the centrifuge, such a validation study may indicate other changes that would improve the simulation.

Study of Reentry From Orbit

The purpose of this study would be to determine the capabilities and limitations of a human pilot to control a manned satellite vehicle during reentry under moderate to high sustained accelerations. Both winged and capsule configurations, capable of generating small amounts of aerodynamic lift, would be considered.

Calculations have shown that by properly controlling the entry angles and the angle of attack (or L/D) of a high drag-low lift vehicle, any level of deceleration between 1 and 8G can be maintained during an entry into the earth's atmosphere. The ballistic trajectory of non-lifting vehicles results in decelerations having a relatively short duration but high-peak values - about 8G minimum for shallow entry angles. For lifting trajectories, the high-peak value does not occur and a lower value of deceleration is maintained until the vehicle has dissipated most of its energy. Depending upon the lift produced, duration of the lifting trajectory is longer than the ballistic trajectory, varying from 5 to 15 minutes.

One principle difficulty in controlling an entry trajectory is that the pilot has no direct control over the deceleration. By changing the angle of attack and producing a lifting force, the pilot can reduce the rate of descent and the deceleration only after a considerable period of time has elapsed. However, this lag in time between a change in angle of attack and its effect on deceleration requires anticipation which must be supplied by pilot's experience and/or a prescribed flight program. J. M. Eggleston of the NASA has recently done some research on the lead (anticipation) afforded by controlling the angle of attack according to the local deceleration and the rate of change of deceleration. This work is reported in reference 4. A zero-reader type instrument incorporating this lead information has been used on a fixed base simulator with success. It would seem desirable to utilize this instrument in the centrifuge program.

Study of Multistaged Boost of an Orbital Vehicle

The purpose of this study would be to determine the optimum utilization of the pilot during the boost into orbit. Specific points to be considered include: definition of minimum and desirable stability and damping characteristics for the vehicle, comparison of piloting performance using both direct and command-type control systems, presentation requirements, and assessment of emergency techniques. Wind-shear and staging moments should be included in the simulation.

CENTRIFUGE MODIFICATIONS

Several modifications of the Johnsville centrifuge are being contemplated to increase the utility of this device. For detailed simulation programs, such as the closed-loop studies, cockpit installation and check-out times of two or three weeks have been required. During most of this period the centrifuge is not used. To eliminate this waste of centrifuge time, it has been proposed to alter the gimbal mountings so that the cockpit installations could be made in demountable capsules, which could be fully instrumented and checked prior to mounting on the centrifuge. This would reduce the changeover time from one experiment to the next from days or weeks to hours. Another limitation of the present centrifuge is that the outer gimbal ring has a motion limitation of 90° (fig. 1). This imposes limitations: (a) on the control of the position of the resultant acceleration with respect to the pilot, limitations which reduce the ability of the centrifuge to simulate uncoordinated and oscillatory maneuvers, and (b) on the ability to use the same cockpit installations for the simulation of two or more conditions for which the resultant acceleration may differ in position by 90°. For example, in some recent work involving standard maneuver loads and flat-spin loads, it has been necessary to remove the cockpit installation and reassemble it in the centrifuge gondola with a rotation of position of 90°. For these reasons it would be desirable to increase the outer gimbal motion to more than 90°. The advantages of a third gimbal system, powered or unpowered are also being examined.

CONCLUDING REMARKS

This paper has by means of some past and future projects indicated some of the capabilities and potentialities of the centrifuge and its use as a flight simulator. Perhaps its real value will be properly assessed only after some actual flight experience is obtained under conditions and with vehicles similar to those it has simulated. Till then, the centrifuge provides an important and logical step in the simulation of manned vehicles that will have to experience unfamiliar accelerations during certain phases of their missions.

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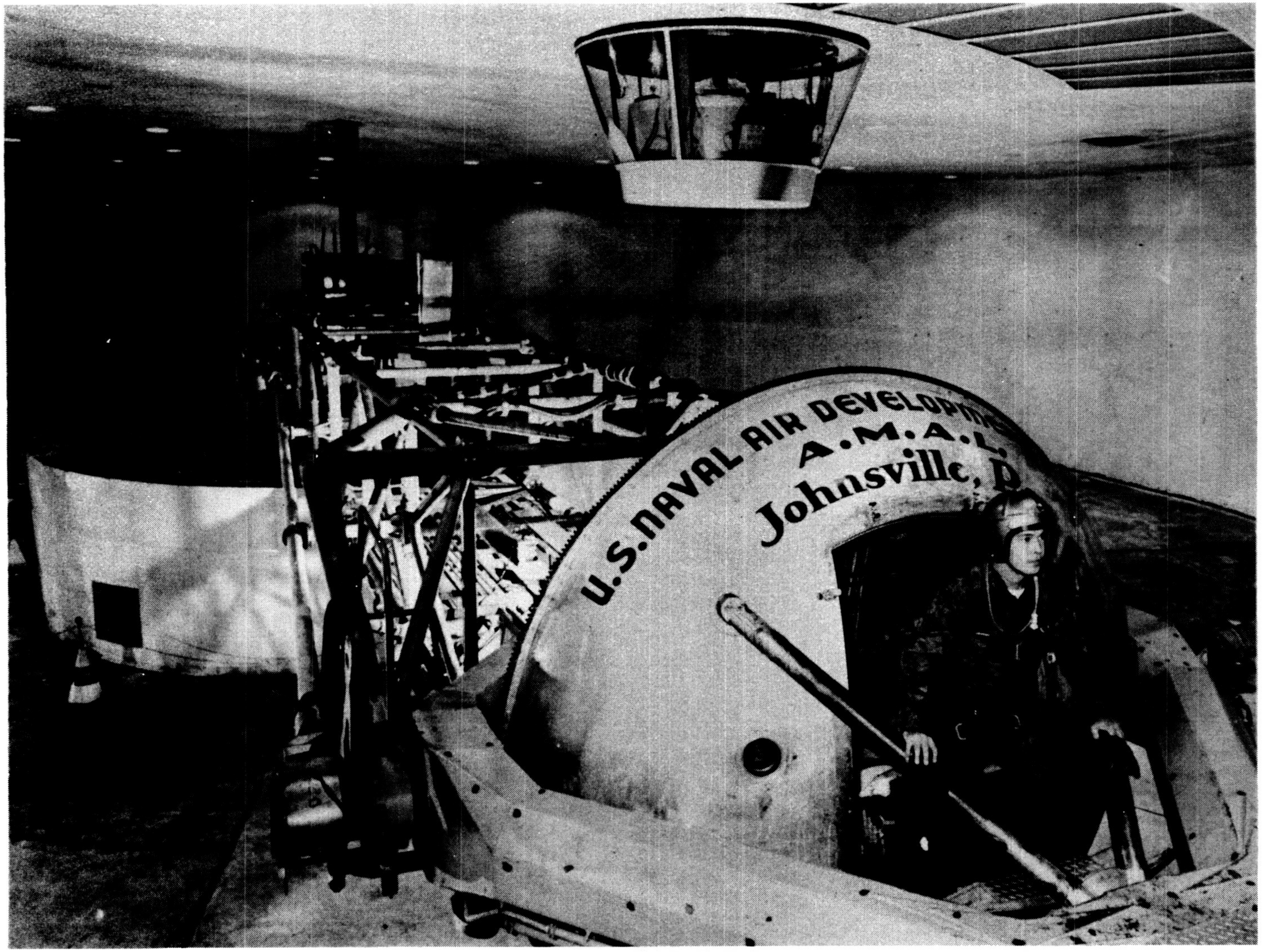


Figure 1.- The human centrifuge.

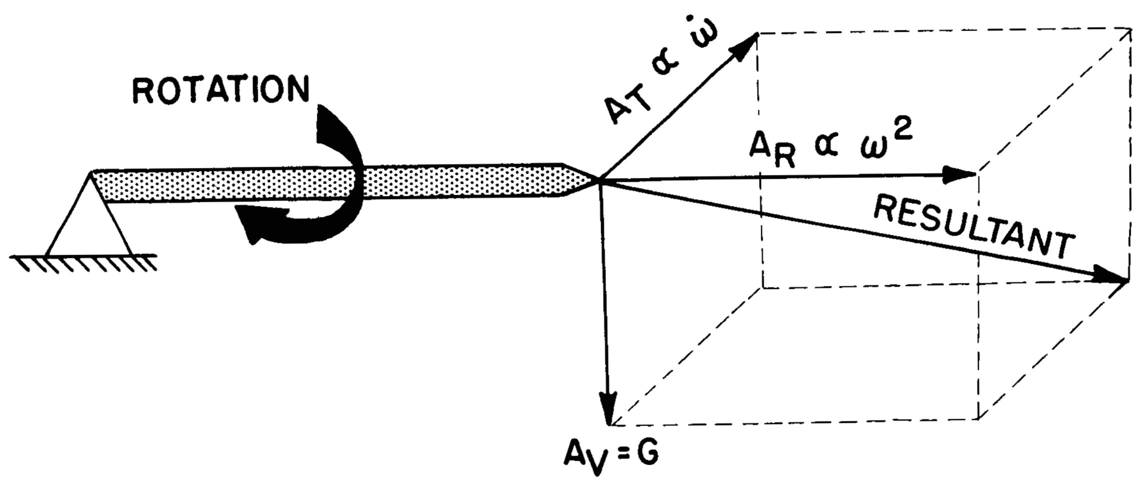


Figure 2.- Centrifuge accelerations. **NASA**

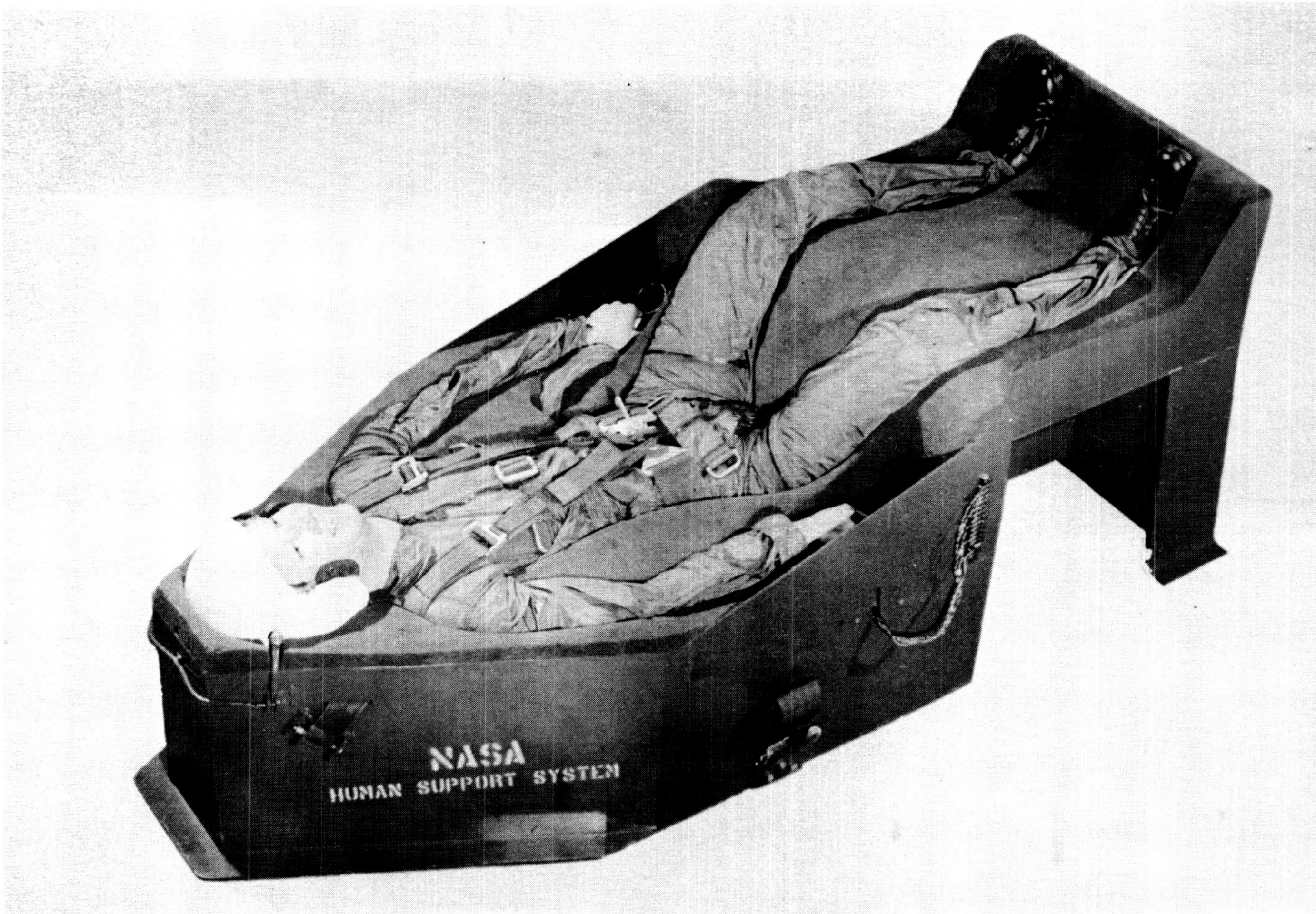


Figure 3.- NASA contour couch. NASA
L-58-827.a

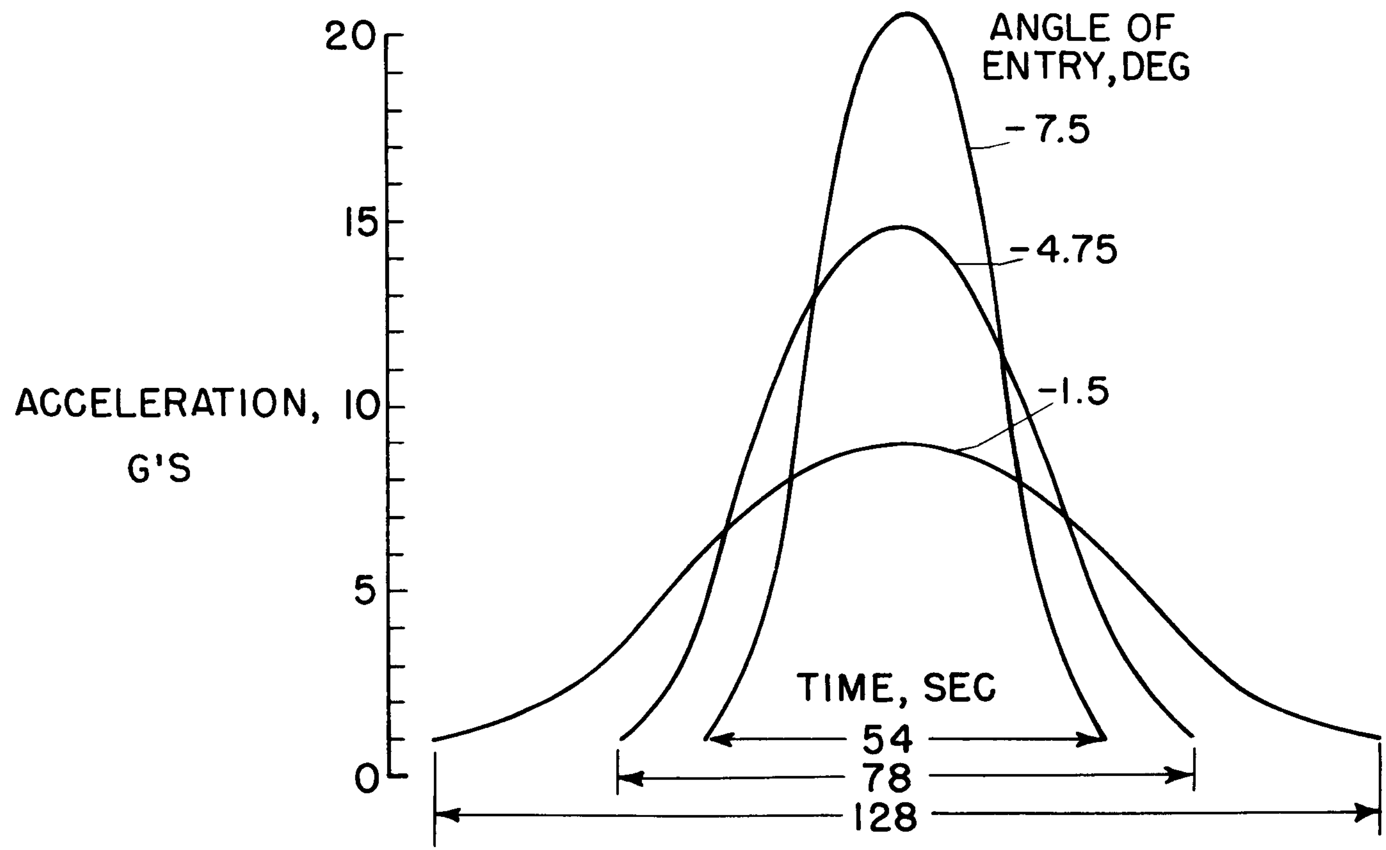


Figure 4.- Entry accelerations from orbit for high-drag vehicle. NASA

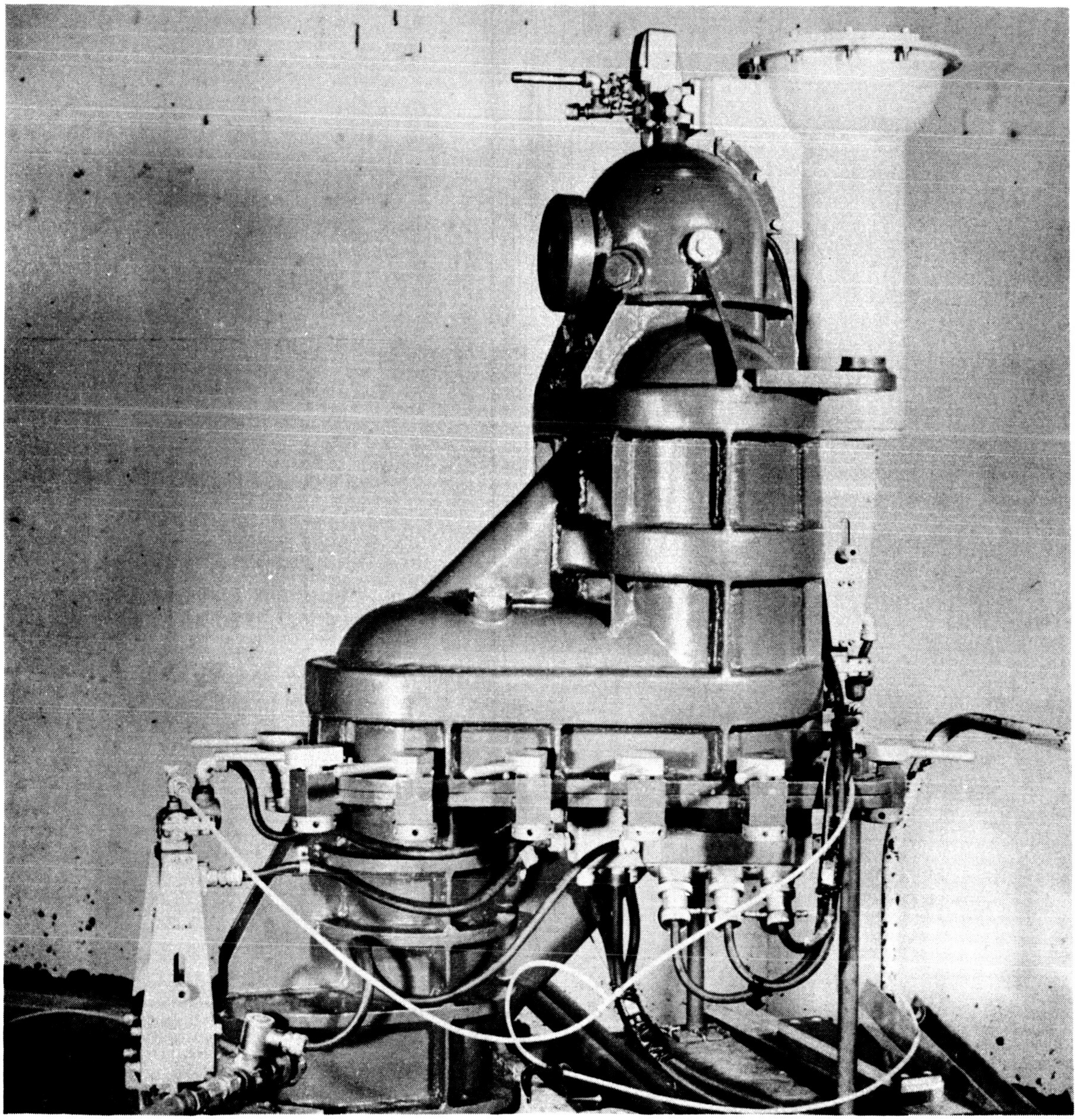


Figure 5.- Gray G-capsule.

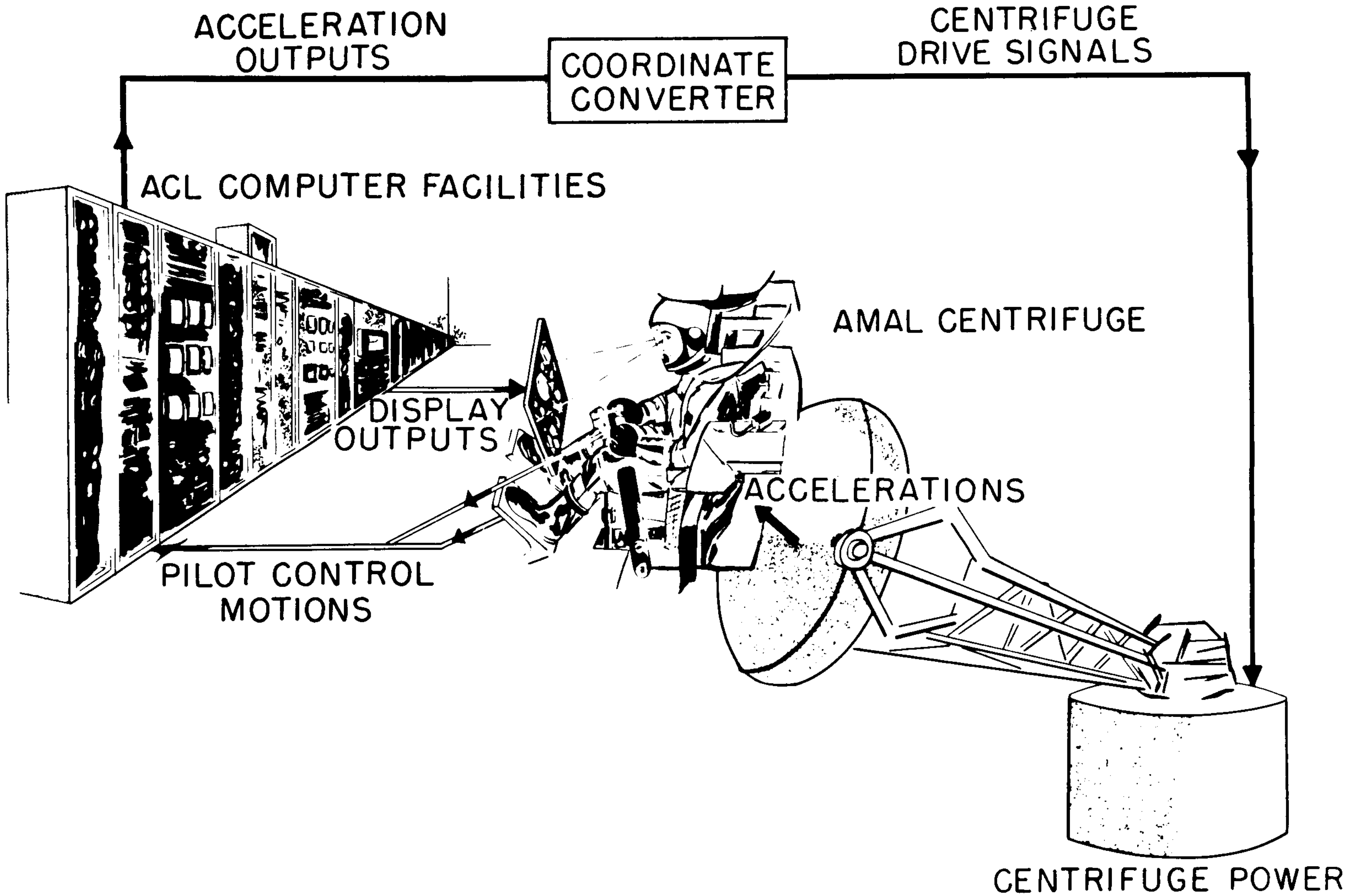
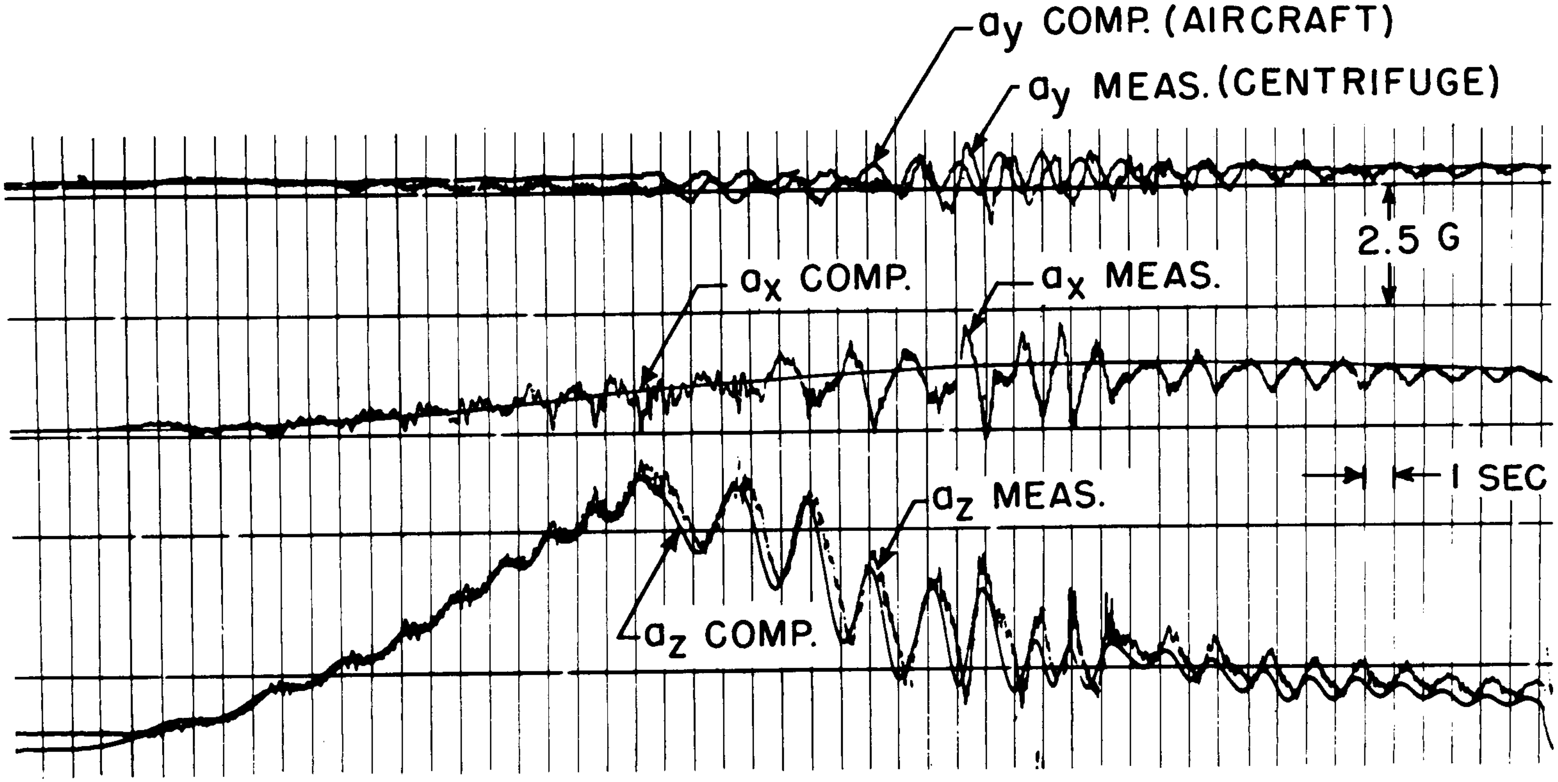


Figure 6.- Centrifuge pilot-controlled flight simulator.



NASA

Figure 7.- Comparison of accelerations obtained under centrifuge closed-loop control.