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PART D

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SIMULATION OF THE STRUCTURAL DYNAMICS OF SPACECRAFT

DURING LUNAR LANDING

by

John M. Bozajian

Hughes Aircraft Company

ABSTRACT

Current methods of simulation utilized in development of a landing system for a lunar soft-landing spacecraft are presented. The technology is based on the Surveyor, an unmanned, lunar spacecraft being developed by the Hughes Aircraft Company for NASA under contract to the Jet Propulsion Laboratory. A brief general description of Surveyor, its mission and three-legged configuration are discussed. The functional requirements of the landing system are described with respect to both lunar surface and vehicle touchdown conditions. A landing dynamics computer program has been used to determine toppling stability and results are shown for a range of lunar surface and spacecraft parameters. Scaling parameters for earth gravity testing are reviewed.

The work described herein was performed under Jet Propulsion Laboratory, California Institute of Technology contract number 950056 under contract number NAS7-100 sponsored by the National Aeronautics and Space Administration and has resulted from efforts of many persons in the Hughes Aircraft Company. The author wishes to acknowledge outstanding contributions of R. E. Dietrick and R. H. Jones for the analytical design of the landing system and the associated landing dynamics analysis and drop test program; R. J. Switz, R. J. Harter and W. S. Short for the structural static and dynamic analysis and test program; I. Baker and R. E. Harvuot for the test facility development and testing; and P. E. Rentz for instrumentation and data acquisition systems.

Methods for lunar gravity testing are discussed. A lift-force method of gravity simulation was found to be appropriate for Surveyor and the drop test facility is described in detail. Drop tests of a full-scale dynamic model have shown favorable agreement with toppling stability computations. The structural dynamic response of the spacecraft has developed from computer analysis using normal modes from modal vibration tests. Component and structural responses from drop tests of a full-scale structural dynamic model have shown good agreement with the transient modal analysis.

INTRODUCTION

The purpose of this paper is the description of the landing dynamics simulation program undertaken in the development of a lunar soft-landing spacecraft. Analytical and experimental methods employed in lunar landing system technology are discussed based on the Surveyor program.

Surveyor is an unmanned, lunar soft-landing spacecraft being developed at Hughes Aircraft Company for the NASA under contract to the Jet Propulsion Laboratory. Under the current plans, seven Surveyors will be launched by Atlas/Centaur boosters. The earliest Surveyors will emphasize lunar television and measurements pertinent to lunar spacecraft development. Later versions will add experiments sampling the lunar surface and related scientific measurements.

The Surveyor Spacecraft is shown in its landed configuration in Figure 1. The configuration is centered about the three-legged, triangular planform. The basic spaceframe is a tubular truss of 7075 aluminum. The spherical, solid propellant main retro engine (separated before landing) is mounted up inside the spaceframe providing a compact design for Centaur installation.

The main retro engine and the liquid vernier engine system comprise about two-thirds of the 2200 lbs. gross weight and together provide the propulsive impulse to reduce Surveyor's relative lunar surface velocity to the soft-landing range. Telecommunications, power control, batteries, and other electronic equipment requiring continuous thermal control are contained in the major compartments shown in two of the three sectors of the spacecraft. The third sector contains most of the Surveyor mission payload.

The landing system (Figure 1) is composed of three, foldable landing gears and a crushable aluminum honeycomb block mounted near the pivot point of each gear. Each landing gear consists of a hydraulic shock absorber, structural leg and aluminum honeycomb footpad. To establish the size and scale of Surveyor, the one foot diameter footpad centers are on a 12'8" circle. The shock absorbers provide orifice (velocity squared) damping varying with compression stroke, separately controlled extension (or rebound) damping and liquid spring action. The nominal maximum stroke of a landing gear is one foot parallel to the longitudinal (roll) axis of the Spacecraft.

The Reference contains a detailed report of the analytical design procedures for the landing system, the rigid-body touchdown dynamics computer program and the drop tests conducted prior to January 1963. This paper summarizes the earlier work and presents results of additional drop tests and some accomplishments to date in the structural dynamic phases of the program.

LANDING SYSTEM REQUIREMENTS

The vents during the lunar approach or terminal descent phase of the Surveyor mission establish the spacecraft landing or touchdown conditions.

A typical surveyor descent trajectory is shown in Figure 2. The descent begins with ignition of the main retro at 52 miles where spacecraft relative velocity is 8600 fps. The vernier engine phase ends in cutoff at 13 ft. to minimize possible lunar dust raising and contamination. The resultant vertical landing velocity is about 12 ± 3 fps accounting for various dispersions.

The spacecraft touchdown requirements and a lunar surface model (provided by JPL/NASA) together comprise the lunar landing conditions summarized in Figure 3. The presence of an effective surface slope is a harard to spacecraft landing causing high pitching accelerations due to multiple leg contact and by creating conditions conducive to overturning or "toppling" instability during landing. Surveyor has been designed to accommodate slopes of 15 degrees and protuberances of the order of 10 cm. Required surface hardness range of 50 to 25,000 psi confines all the kinetic energy absorption to the spacecraft or to sliding friction. (The unit crushing strength of the blocks and footpads is less than 50 psi.) Some penetration ($\approx$ 7-8 inches) occurs in the soft surface with an inelastic bearing strength gradient of 10 psi per foot depth.

Spacecraft conditions at touchdown lead to vertical and lateral velocities less than 15 fps (3σ) and 5 fps, respectively, with respect to expected flight control design. The structural design, however, has been that appropriate to landings up to 20 fps vertical and 7 fps, lateral velocity. For the 20 fps case, the dynamic load factors on most components are less than 25 earth g.

Two terminal lunar surface pictures from Ranger VII are shown in Figure 4. Careful analysis of these and other Ranger pictures is being performed by others and will be interpreted for Surveyor by the Jet Propulsion Laboratory. It is promising, however, that the average slope appears small, large boulders or protuberances (> 2 feet) do not appear in high density and crater depth appears to reduce with diameter.

LANDING DYNAMICS ANALYSIS

The primary tool for Surveyor landing system development has been an IBM 7094 digital computer program for the two-dimensional motions of a rigid spacecraft with forces applied by three landing gears and three crushable blocks. The model for the computer and some of the parameters are shown in Figure 5. Some typical quantities for Surveyor are Δ cg = 18 inches, ℓ_p = 38.25 inches, ℓ_ℓ = 40.5 inches, $\alpha = 18°$. The input forces include variations in shock absorber orifice damping (to alleviate loads) and liquid spring force with stroke, static and kinetic friction on blocks and footpads and variation in crushable block force with angle of block load. The extension or rebound damping coefficient is constant and is selected such that the spacecraft is critically damped (no rebound) during a 20 fps normal impact on a flat surface. Other parameters are the hydraulic preload in the shock absorber that keeps each leg fully extended and shock absorber friction force. For the hard surface computer program an iteration is performed between the shock absorber force and crushing of the footpad. For the soft-surface version, initially, no footpad crushing occurs and iteration occurs between shock absorber forces and the inelastic surface bearing strength which increases linearly with penetration depth. The soft-surface program also includes the variation in effective cross-sectional areas of the landing gear leg structure and other spacecraft components with penetration depth.

The landing dynamics computer program has been used to size and tune the shock absorber and crushable block parameters to meet the desired deceleration levels and maximize toppling stability. The legs contact first and act to stabilize the spacecraft against toppling. The crushing action of the blocks begins later in the motion and in parallel with the leg forces providing weight efficiency in the energy absorption required at the higher landing velocities. Normally, only the conical portion of the footpad (Figure 22) crushes to act as an impact limiter for the landing gear. The crushing load for the cylindrical portion is higher than the typical applied loads. Therefore, crushing of this portion occurs usually only to accommodate small protuberances.

The damped, spring-back action of the shock absorber is a vital factor in providing toppling stability without excessive leg length (or additional legs). The choice of three legs was dictated primarily by a desire for simplicity in attainment of post-landing static stability, and by structural configuration and Centaur shroud considerations. The landing system including the telescoping lock struts (to fold each landing gear) and the crushable blocks weighs about 6% of the landed weight.

The toppling stability has been examined by computation for a wide variety of spacecraft and landing conditions resulting in two-dimensional motion of the Spacecraft. Three seconds in real time is generally sufficient to establish toppling stability. The integrating time period is 0.002 seconds. For the two-dimensional motions, the critical stability cases arise when a single leg points uphill and the lateral velocity is either uphill (positive) or downhill. Note, for the uphill case, toppling still occurs in the downhill direction after the pitching impulse imparted by the uphill single leg contact. The maximum angular acceleration (and maximum leg forces) are experienced when the single leg points downhill. Toppling stability boundaries are established for critical values of combined vertical and lateral touchdown velocity as shown for parameter variation in Figures 6-9 for landings on a hard surface. For these figures the spacecraft is oreinted with the single leg uphill.

Figure 6 shows variation with lunar surface friction coefficient (μ). Since μ is not defined it has been varied over a large range. In general μ = 1 is safe for both stability and load prediction purposes. The size of the region of instability for uphill landings is fairly sensitive to friction coefficient. The straight line "approximated abutment" is a simple approximation (independent of slope) assuming no leg deflection and the landing energy converted to rigid body pitching about the two legs opposed only by the lunar gravity. The implied infinite friction is an extrapolation of the computer runs which do not apply at extreme friction levels. Another important lunar surface characteristic, site slope, is shown in Figure 7. Five degree changes in slope affect lateral velocity capability about 2 fps. Note that there is no uphill instability for the 15° slope, as in Figure 6 since Figure 7 is for zero spacecraft incidence (θ in Figure 5).

Two important spacecraft parameters, center of gravity height and leg length are varied in Figures 8 and 9. Figure 8 shows a two-inch increase in Δ cg can reduce allowable lateral velocity by 1 fps on the downhill side and about 3 fps on the uphill instability. As expected, leg length is very effective in providing stability. The coalescence of the uphill and downhill regions of instability is shown at lower leg lengths (30 inches).

Single block crushing forces are 2707 and 2070 pounds for the 772 and 643-pound vehicles, respectively.

Similar stability boundary variations have been established for variations in shock absorber parameters and other landing conditions such as pitch rate and incidence. Many crossplots may be obtained. One useful form is plotting maximum allowable lateral velocity (from each side of the stability curves) independent of vertical velocity versus spacecraft incidence (Figure 10).

Each point on these curves requires establishment of a complete stability boundary. The coordinates of Figure 10 are significant since in the flight control system the spacecraft lateral velocity and incidence are correlated as shown by the 3σ and 10σ dispersion ellipses. The parameter in this plot then allows selection of a maximum Δ cg value.

VEHICLE TESTING

The primary consideration in landing tests for a lunar vehicle is the presence of approximately 1/6 gravity field at the lunar surface compared to earth. The choice is either to scale the test vehicle to operate in earth gravity or to simulate lunar gravity.

Some significant scaling parameters for dynamic similarity of a rigid body earth gravity model of equal mass to the lunar spacecraft are shown in Figure 11. These scaling criteria were obtained by normalizing the equations from the landing dynamics computer program. In the program the dimensional equations have been divided by mass so that all parameters are per slug of spacecraft landed mass. It is seen that spring, damping and crushable block forces are higher by a factor of 6.06 (the gravity ratio) on the model, independent of geometric size ratio, n. (Note that orifice damping force is proportional to velocity squared and spring force to scaled length.)

In general, the higher forces present problems in model structural design and proper mass distribution. Landing forces would be equal only if model mass were roughly 1/6 of the spacecraft. If full-size and 1/6 mass are combined, then the possibility exists of using at least some of the lunar spacecraft hardware and achieving force simulation. For this scaling, crushable blocks and spring constants are identical and the orifice damping coefficient must be reduced by 1/6 in the model. Achieving 1/6 mass, however, in the model may result in lack of similarity in mass distribution. In the case of Surveyor, this type of scaling would result in landing gear mass of about 30% of the model mass compared to 6% for the lunar spacecraft.

The problem of model mass distribution was raised quite early in the Surveyor program when a 1/4 size, one slug mass dynamic model was constructed and drop tested in earth gravity. The model is shown during a drop in Figure 12, where a pendulum has been used to impart lateral velocity and control initial incidence. This model was stable compared to analytical predictions and much of the disagreement appears to be assignable to excessive relative leg mass in the model. Another result of this phase was early qualitative examination of 3-dimensional crosshill landings. In addition it was observed that crushable block length to diameter ratios must be kept down near unity for resistance to tensile failure from side loads.

Having illustrated some aspects of earth gravity testing, what are the prospects for lunar gravity simulation? Three methods have been considered: gravity component; lift force; and dropping platform.

The gravity component method is illustrated in Figure 13 where the test model is suspended through its c.g. on a cable parallel to a plane inclined 9.4° from the earth gravity vector. The angle is that required to provide lunar gravity normal to this plane as a component of earth gravity. Large variations in vehicle displacement normal to the surface could create gravity variations. Other problems such as construction of the steep compound slope also are apparent. This method has been explored at the Langley Research Center in some experiments involving walking and running in simulated lunar gravity.

The lift force method is shown in Figure 14. In this method a constant lifting force of about 5/6 earth gravity is applied vertically through the center of gravity of the test model. Since gravity simulation is lumped, the method applies strictly for only rigid body testing but should be adequate when landing gear mass is small compared to vehicle mass. (This is a necessary condition also for the gravity component method above.) One method for providing a nearly constant lift force is the use of a piston in an air cylinder manifolded to a tank of volume large compared to the cylinder. This method has been used in simulating wing lift in aircraft landing gear drop tests and has been further developed at Hughes for lunar gravity simulation on Surveyor. The use of a long cable to minimize gravity variations can be avoided and will be described later.

Artificial gravity can be produced by regulating the acceleration of a dropping platform with counterweights as shown in Figure 15. The required condition is achieved by making counterweight mass about one-eleventh of the platform mass. Complete simulation can be achieved (neglecting drag) by dropping the vehicle onto the falling platform provided platform/vehicle mass ratio is large. The primary disadvantage is that a 200-foot platform drop is required to achieve 3-4 seconds of test time necessary for many touchdown conditions. Aerodynamic forces may also be a problem at the longer test times. Pilot versions of this method have been investigated at the Langley Research Center.

Gravity simulation was selected as appropriate for Surveyor since it is in a size range feasible for full-scale testing and because of the desire to test actual landing system hardware. The lift-force method was considered the most practical method for examining the toppling and other gross landing characteristics. A schematic of the Hughes lunar drop test facility is shown in Figure 16. The air-lift method of supplying the "anti-gravity" force is applied through a unique rolling pulley. The pulley rolls on a horizontal track allowing vehicle lateral motion while maintaining a vertical lift force. The lifting force is provided equally by two matched air cylinders connected to a common air tank. The moving parts, pulleys, cables and pistons weigh less than 10 pounds. Friction is about 25 pounds.

A photograph of the drop test facility showing the T-1 drop test vehicle is shown in Figure 17. The T-1 vehicle is being prepared for a drop on a 15-degree simulated rough slope. The available drop area is 20 feet wide and 40 feet long. The grid spacings in the photograph are one foot. The drop platform is constructed of 12" x 12" beams laid on 6 x 12 joists supported on 6 x 6 columns and is designed to absorb less than 1/2% of the vehicle landing energy.

The T-1 vehicle is a rigid body, full-scale dynamic model using actual landing system hardware. Ballast weights are adjusted in position on three rack-type frames to vary inertial properties of the vehicle. The vehicle is shown mounted on the pendulum used to impart lateral velocity. Lateral and vertical velocity are controlled by the swing of the pendulum and the portion of vertical drop height in free fall (earth gravity) and that under the action of the lift force (lunar gravity). Instrumentation consisted of accelerometers and strain gages on legs and some frame members, shock absorber loads and deflections, vehicle pitching attitude, load cell for lift-force and high speed motion pictures.

About 80 drops have been made with the T-1 vehicle on smooth, rough, and soft slopes. The first series of drops was conducted early in 1962 (vehicle, T-1 (A-25)) followed early in 1963 with another series using a slightly lighter vehicle (T-1 (A-21)) with a higher center of gravity. Most of the drops were made with the single leg uphill or downhill to verify the most severe toppling and load conditions associated with two-dimensional motions. Some crosshill drops were performed to examine, briefly, the three-dimensional behavior. Even at lateral velocity of 12 fps, the crosshill landings were fairly uneventful and excessive roll rates were not realized.

The smooth surface was the 12-inch beams. The rough surface was created by fastening 2 and 4-inch high blocks to the wood surface on 16-inch centers. The soft surface was composed of the three-foot deep bed of hardwood shavings and sawdust. Other materials were investigated such as sand, talcum, popcorn but this mixture was found to give the closest dynamic approximation to the desired soft surface bearing strength of 10 psi per foot of penetration.

T-1 (A-25) test results on rough and smooth 15-degree slopes are shown in Figure 18. The agreement with theory is fairly good. The effect of the average higher friction on the rough slope is evident. Note that the effective friction level may vary somewhat from drop to drop on the rough slope because of random block encounters. Similar results of a 25-degree slope are shown in Figure 19. The agreement here is not as good as for the 15-degree slope. The lack of improvement of the uphill instability for a smooth slope may be that uphill friction is not significant on a steep slope.

Results for a lighter vehicle, T-1 (A-21), with higher center of gravity are shown in Figure 20. Again the agreement with theory is good. Tests on the soft slope are shown in Figure 21. The agreement is not too good due proably to some undesirable, unavoidable springiness in the wood shavings. The attempt was made to reduce the springback by addition of finer sawdust but a residual amount of springback was still in evidence.

STRUCTURAL DYNAMICS STUDIES

The structural dynamics phase of the soft-landing program has involved touchdown structural response computer analyses based on modal vibration tests and experimental confirmation in drop testing a full-scale structural dynamic model (S-2).

The structural dynamic analysis of the spacecraft is a modal analysis in which responses of various spacecraft components are obtained by addition of the rigid body and elastic modes. These responses result from the application of forces on the footpad of each landing gear and on each crushable block obtained from the rigid body landing dynamics program. The elastic model lumps the spacecraft into 25 mass elements with a total of 97 degrees of freedom. The larger masses (e.g., a major equipment compartment) are assigned six degrees of freedom. Three translational degrees suffice for many of the smaller masses.

The normal modes of the spacecraft were determined from a modal vibration test using a number of small shakers. A full-scale structural dynamic model (S-2) of Surveyor was used for this purpose. S-2 is similar to a flight spacecraft in its structural elements using dummy ballast of proper inertial properties to replace spacecraft components. For testing in the landed configuration, S-2 was supported on very soft compression springs at each footpad. The modes were excited by 25-pound electrodynamic shakers placed where large responses were expected. A mode was tuned in by adding shakers in proper phase and magnitude. For most modes this was accomplished with two or three shakers with a maximum of eight used in some cases. A roving accelerometer was used to survey and establish the response in each mode. The modal survey yielded ten elastic normal modes in the frequency range from 12 to 60 cps.

The sixteen modal equations corresponding to the six rigid body and ten elastic modes have been solved in an IBM 7090 computer program to yield the dynamic response of the spacecraft for various touchdown conditions.

A consideration is the validity of using landing forces (on footpads and crushables) from the rigid body analysis directly in the elastic analysis. This question was examined in an early direct analog study of spacecraft structural response performed for Hughes by Computer Engineering Associates (CEA).

Computer runs were made for an elastic model at touchdown and for the same conditions with elastic members rigidized. Comparison has shown only small differences in the applied loads for the elastic and rigid body cases.

The S-2 structural dynanic model has been drop tested to prove the design and to compare test responses with those predicted by the transient modal analysis. Figure 22 shows the S-2 vehicle prior to a vertical drop on a flat, smooth surface. The design of this vehicle precluded access to its center of gravity and use of the lift-force technique for lunar gravity simulation. Earth gravity drops were used since the significant structural response is in the initial phase of touchdown when decelerations are large compared to either earth or lunar gravity. The drop test conditions are shown in Figure 23. The equivalent touchdown velocity shown is the lunar value required to provide the same energy dissipation as in the earth drop tests. The difference results from the added potential energy acquired by the vehicle in earth gravity after first contact with the surface.

S-2 was instrumented with strain gages on landing gear and key structural members and accelerometers on significant mass components. High speed motion pictures were taken on each drop.

Earth gravity was used in the rigid-body landing analysis to correlate the magnitude and phasing of the various footpad and crushable block forces in the drop tests. These forces were used in the transient modal analysis to evaluate elastic response for test comparison. The agreement was quite good as shown by examples in Figures 24 and 25. Figure 24 shows the correlation of dynamic bending moments in the vertical mast supporting the high-gain antenna and solar panel during drop No. 3. Figure 25 shows that touchdown accelerations during drop No. 1 agree well with analysis and are below the maximum design levels in a major equipment compartment.

CONCLUSIONS

Landing dynamics computer analysis has been a valuable tool in establishing lunar soft-landing system design and in describing spacecraft stability and loads for various touchdown and lunar surface conditions. Lunar gravity simulation was found to be preferable to scaling for earth gravity testing. A lift-force technique has proven to be a simple, effective method of lunar gravity simulation for application to rigid-body model testing. Drop of tests of a full-scale dynamic model under simulated lunar gravity have verified the landing system hardware and the test method and have provided confidence in analytical predictions. Similar confidence exists in predicting structural loads and component accelerations under various touchdown conditions based on correlations between modal analysis based on modal vibration data and drop tests of a full-scale structural dynamic model.

REFERENCE

Deitrick, R. E. and Jones, R. H., "Touchdown Dynamics Study (Preliminary Report)", Hughes Aircraft Company Report SSD 3030R, January 1963.

SURVEYOR SPACECRAFT (A-21)

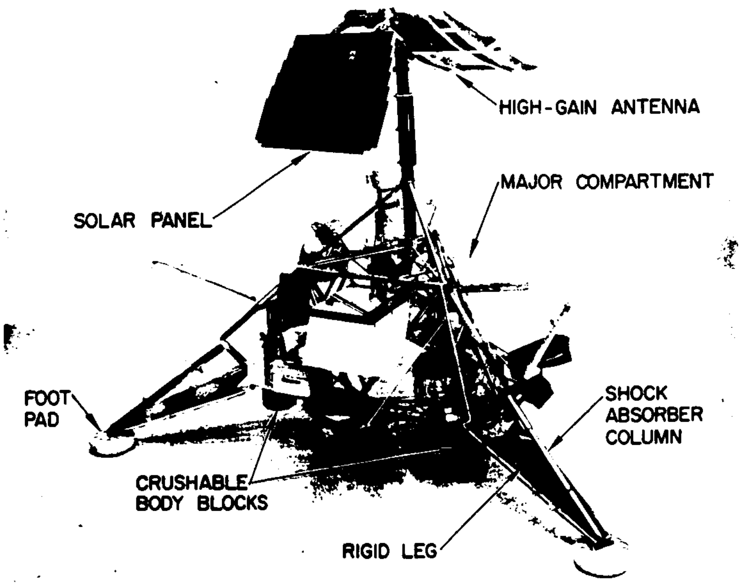

Figure 1

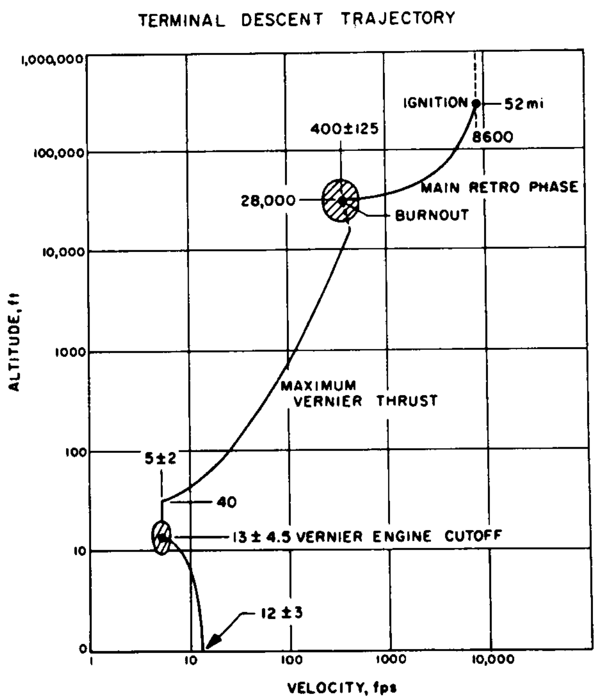

Figure 2

LUNAR LANDING CONDITIONS

LUNAR SURFACE

- SLOPES UP TO 15 deg
- PROTUBERANCES UP TO 10 cm
- SURFACE HARDNESS: 25,000 psi (HARD) TO 50 psi (SOFT), REQUIRED

  SURVIVAL ON SURFACE WITH HARDNESS GRADIENT 10 psi PER FOOT DEPTH, DESIRED
- SURFACE FRICTION NOT DEFINED BUT VARIABLE

SPACECRAFT TOUCHDOWN REQUIREMENTS

- VERTICAL VELOCITY < 15 fps, LATERAL VELOCITY < 5 fps WITH RESPECT TO FLIGHT CONTROL DESIGN
- STRUCTURAL MECHANIZATION TO 20 fps, VERTICAL AND 7 fps LATERAL VELOCITY
- LANDING SHOCKS ON COMPONENTS AND PAYLOAD, < 40 EARTH g REQUIRED, < 25 EARTH g DESIRED

Figure 3

TERMINAL LUNAR SURFACE PICTURES FROM RANGER VII
6:25 A.M. PDT JULY 31, 1964

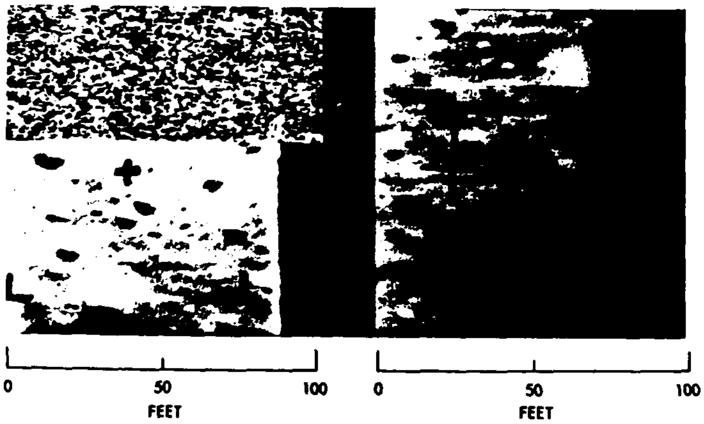

Figure 4

TOUCHDOWN DYNAMICS COMPUTER PROGRAM MODEL

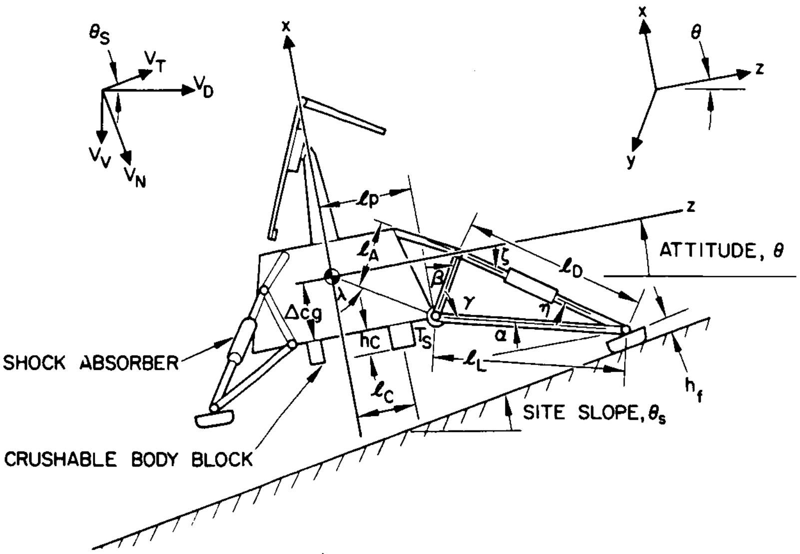

Figure 5

STABILITY BOUNDARY VARIATION WITH FRICTION COEFFICIENT

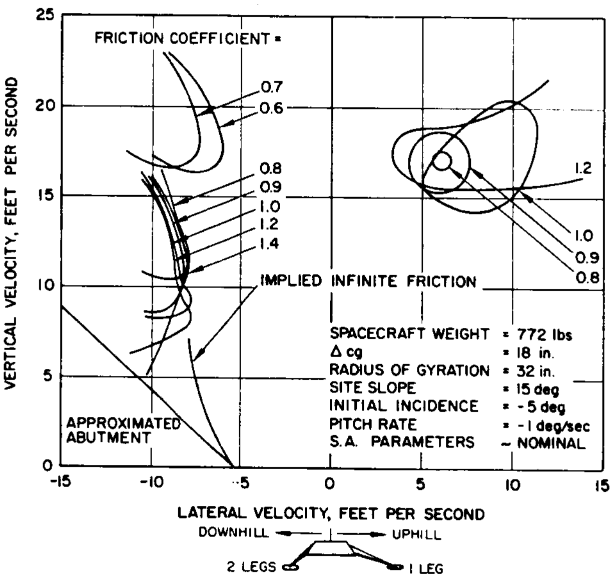

Figure 6

STABILITY BOUNDARY VARIATION WITH SITE SLOPE (INITIAL INCIDENCE = 0 DEGREES)

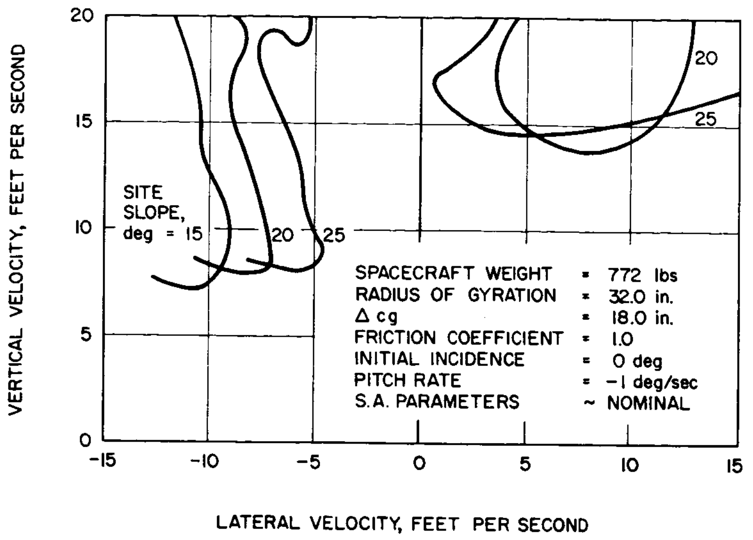

Figure 7

STABILITY BOUNDARY VARIATION WITH CENTER OF GRAVITY HEIGHT

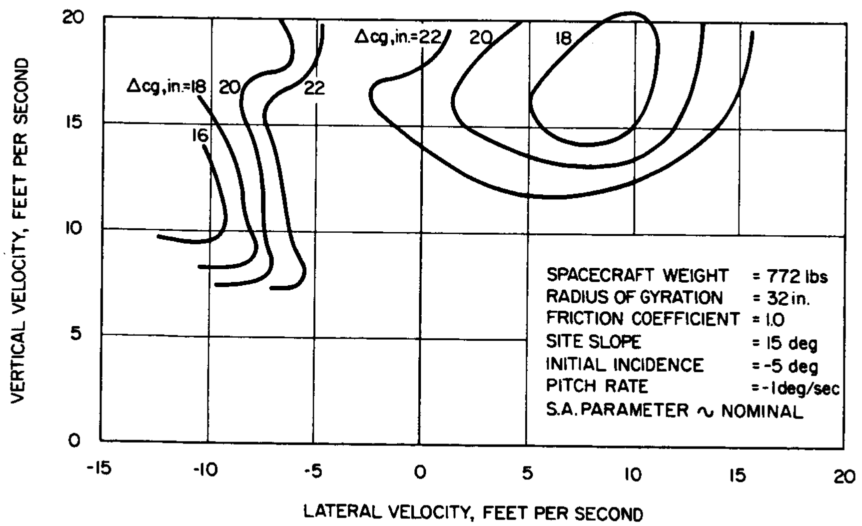

Figure 8

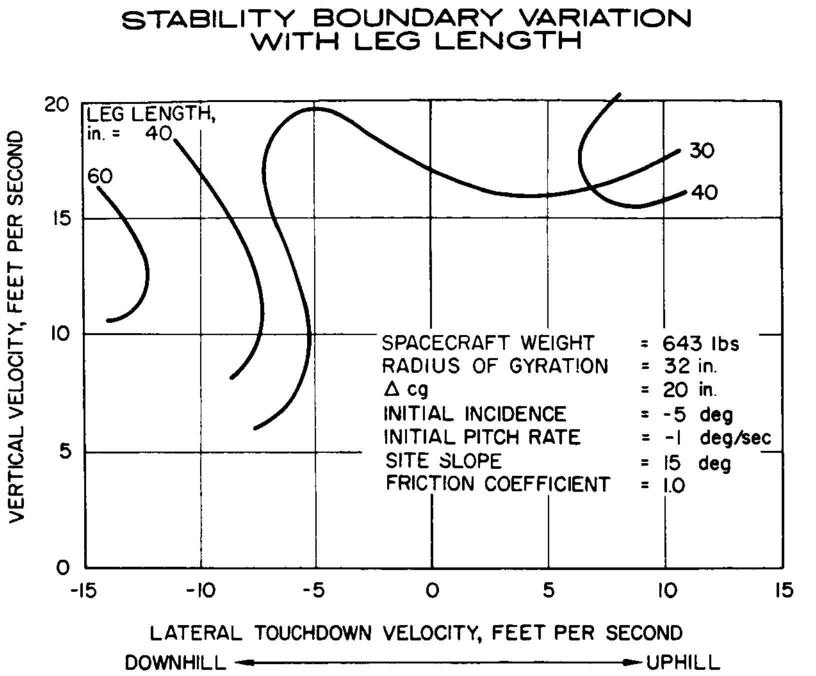

Figure 9

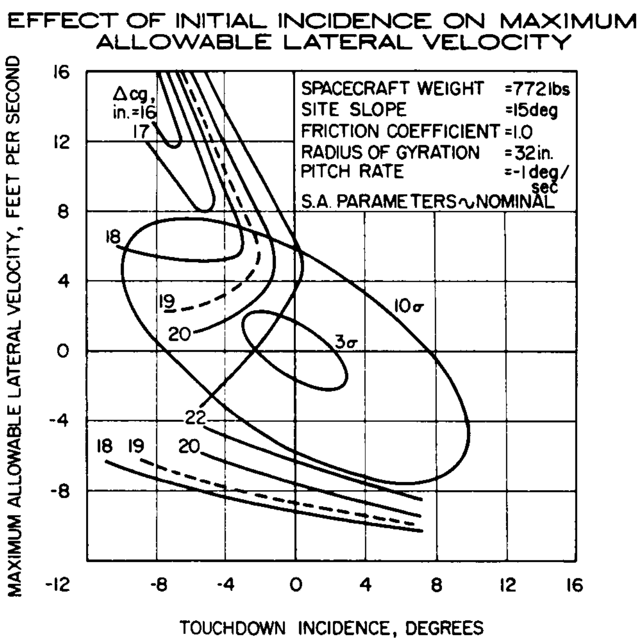

Figure 10

PARAMETER RATIOS FOR SCALED TEST MODEL

PARAMETER	RATIO OF MODEL TO SPACECRAFT PARAMETERS (FOR EQUAL TOTAL MASSES)
LENGTH	n
TIME	$\sqrt{\frac{n}{6.06}}$
DAMPING CONSTANT	
VISCOUS DAMPER	$\sqrt{\frac{6.06}{n}}$
ORIFICE DAMPER	1/n
SPRING CONSTANT	$\frac{6.06}{n}$
CRUSHABLE BLOCK FORCE	6.06
ACCELERATION OF GRAVITY*	6.06*
ANGLES	1
VELOCITIES	$\sqrt{6.06n}$
ACCELERATIONS	6.06

*ACCELERATION OF GRAVITY USED IS 32.17 ft/sec^2 ON THE EARTH AND 5.31 ft/sec^2 ON THE MOON

Figure 11

DROP TESTING OF 1/4 SCALE SPACECRAFT MODEL

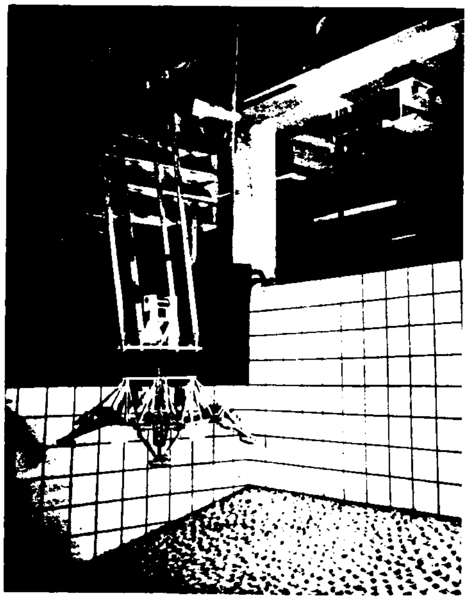

Figure 12

GRAVITY COMPONENT METHOD OF LUNAR GRAVITY SIMULATION

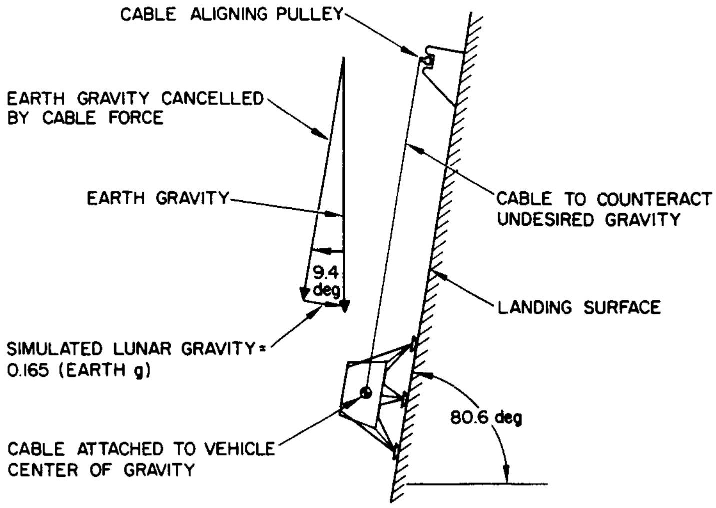

Figure 13

LIFT FORCE METHOD OF LUNAR GRAVITY SIMULATION

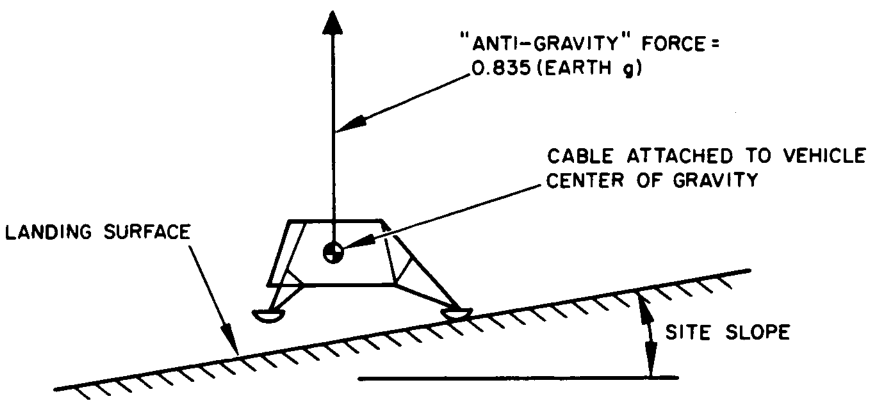

Figure 14

DROPPING PLATFORM METHOD OF LUNAR GRAVITY SIMULATION

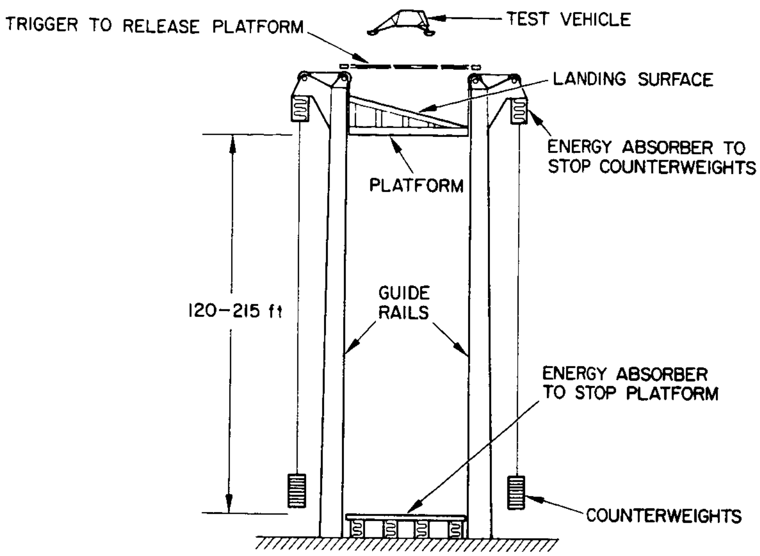

Figure 15

SCHEMATIC OF LUNAR DROP TEST FACILITY

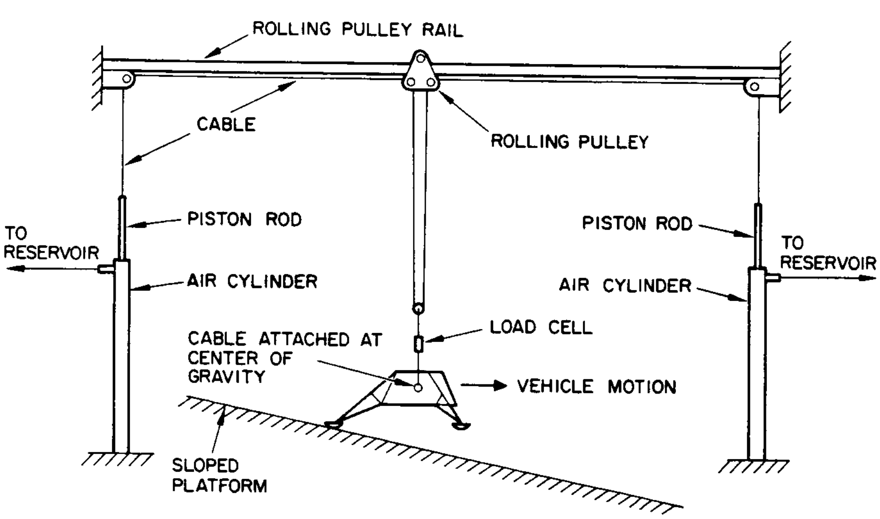

Figure 16

T-1 DROP TEST FACILITY AND VEHICLE

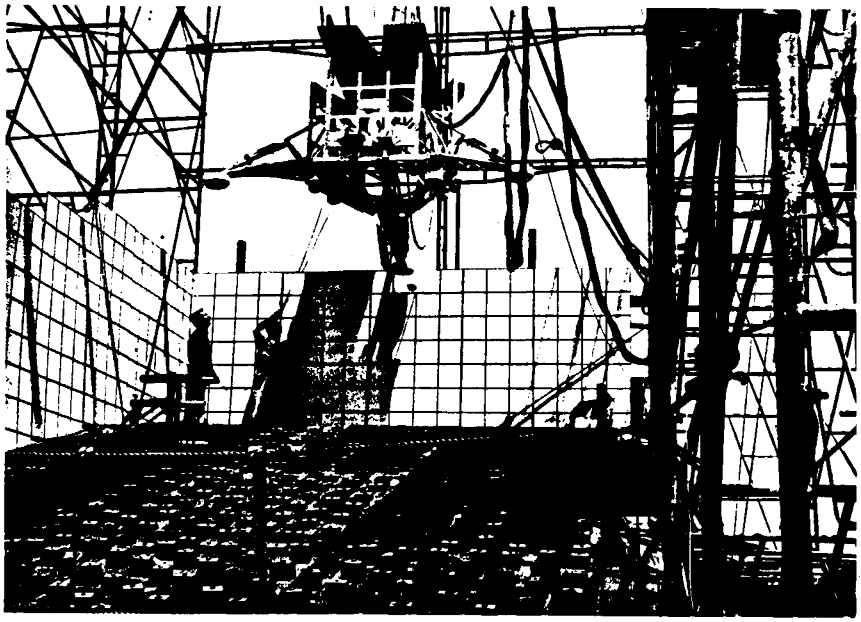

Figure 17

T-1 (A-25) TEST RESULTS ON ROUGH AND SMOOTH 15 DEG SLOPES

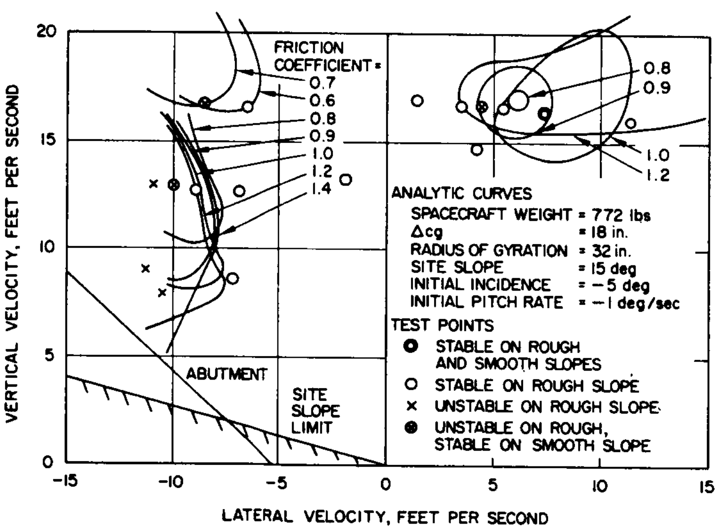

Figure 18

XX-27

T-1 (A-25) TEST RESULTS ON ROUGH AND SMOOTH 25 DEG SLOPES

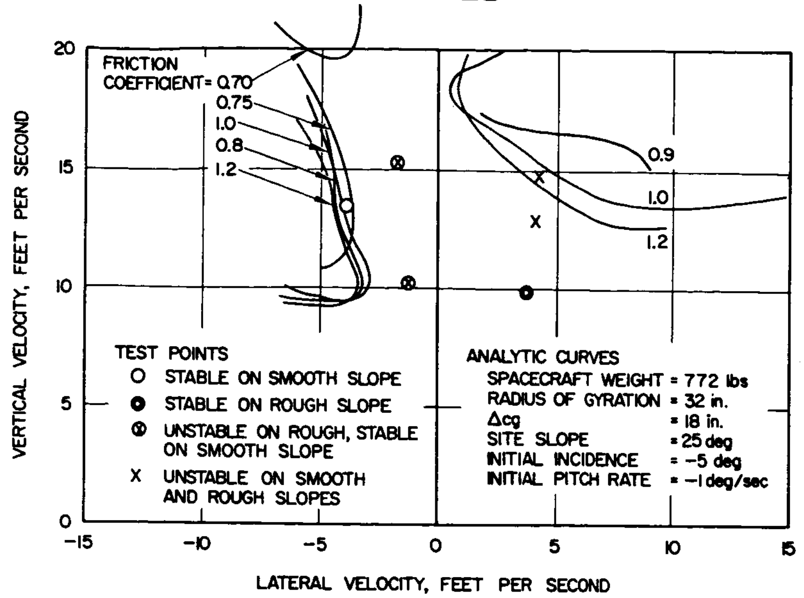

Figure 19

T-1 (A-21) TEST RESULTS ON ROUGH 15 DEG SLOPE

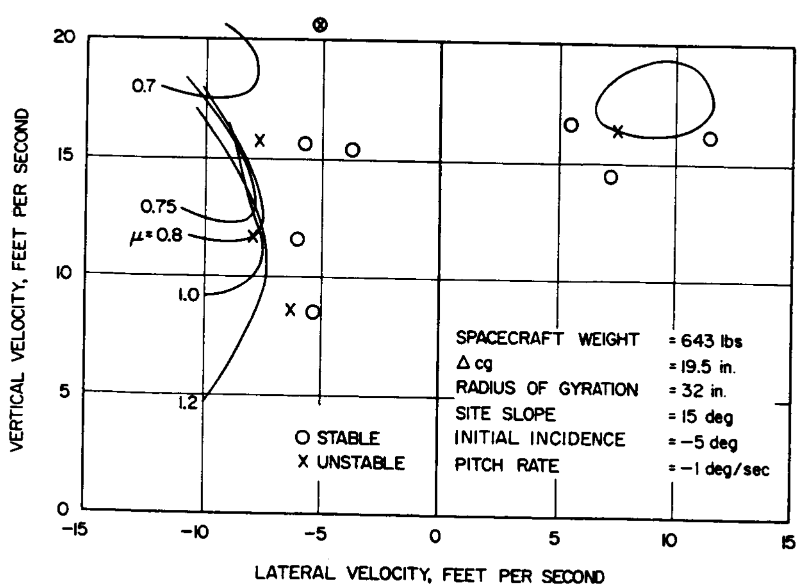

Figure 20

XX-25

T-I (A-21) TEST RESULTS ON SOFT 15 DEG SLOPE

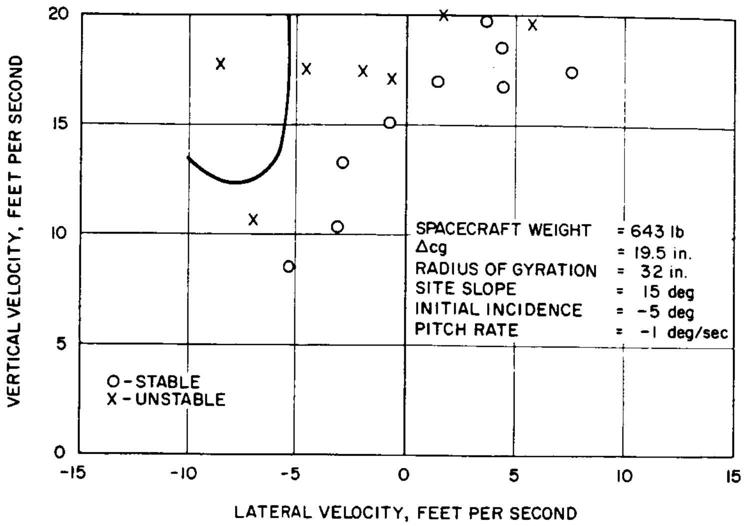

Figure 21

S-2 VEHICLE PRIOR TO VERTICAL DROP TEST

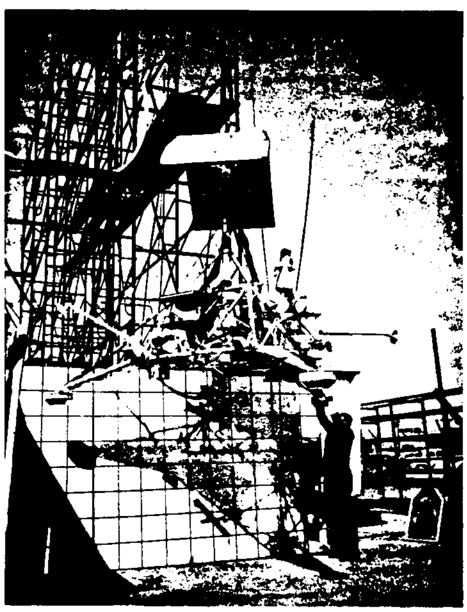

Figure 22

IX-24

S—2 DROP TEST CONDITIONS

CONDITION	DROPS		
	1	2	3
VERTICAL VELOCITY AT TOUCHDOWN, fps	20	20	20
VEHICLE INCIDENCE, deg	0	0	5
SITE SLOPE, deg	0	15	15
SINGLE LEG DIRECTION	NOT APPLICABLE	UPHILL	DOWNHILL
SURFACE	SMOOTH	ROUGH	ROUGH
TOUCHDOWN VELOCITY FOR EQUIVALENT LUNAR LANDING, fps	21.3	23.2	22.7

Figure 23

S—2 LOWER MAST BENDING MOMENT (X—COORDINATES)

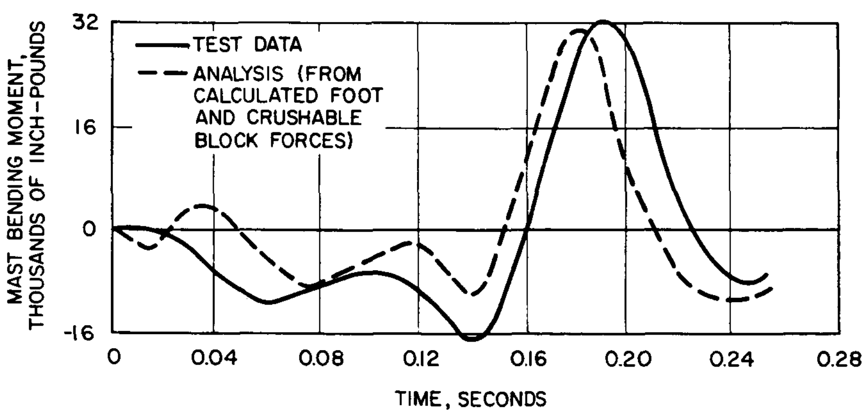

Figure 24

IX-27

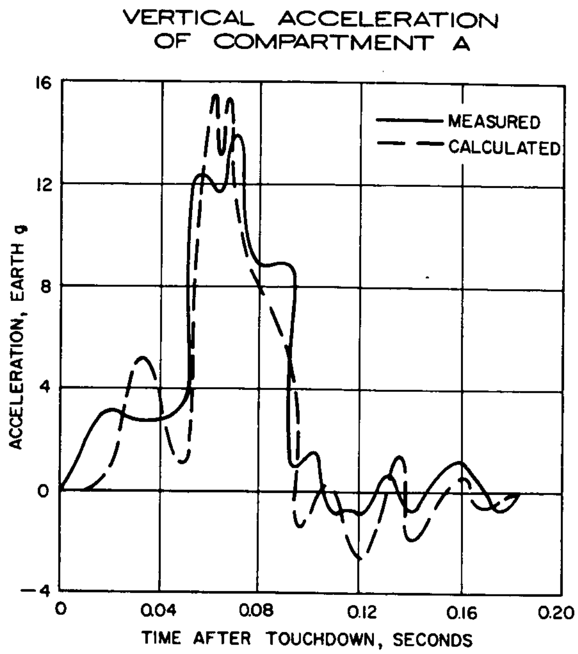
VERTICAL ACCELERATION
OF COMPARTMENT A
MEASURED
CALCULATED
ACCELERATION, EARTH g
16
12
8
4
0
−4
0
0.04
0.08
0.12
0.16
0.20
TIME AFTER TOUCHDOWN, SECONDS

Figure 25

ADDRESS BY

DR. RAYMOND L. BISPLINGHOFF

ASSOCIATE ADMINISTRATOR FOR ADVANCED RESEARCH AND TECHNOLOGY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SUMMARY OF REMARKS ON

SIMULATION IN AERONAUTICAL AND SPACE TECHNOLOGY

In order to prepare to address the members of this conference tonight, it seemed like a good idea to consult Webster's dictionary to find out the definition of the word "simulation". For those of you who were unable to prepare yourself for this meeting, I can report that Webster describes simulation as "the act of simulating or assuming an appearance which is feigned, or not true; pretense or profession meant to deceive." He describes furthermore, by example, certain practitioners of simulation as "men attired in greasy black suits with dingy black neckties - all gifted with a sanctimonious snuffle, all avid for buttered toast and muffins". Since I have been unable to relate Webster to what I have observed here, or even to the fare which we have received for dinner, I have concluded that we have simply found another case where science has outrun Webster's dictionary.

This brings to mind a request received some time ago by the NASA for a statement on the number and location of all simulators possessed by the agency. It turned out in this case that the requester desired to know simply how many flight simulators existed in which the human being played his appropriate role as a subsystem in the control apparatus. As you know better than anyone, such simulators are really only one class of a large number of classes of simulators and simulation devices in the nation's aeronautical and space program. Simulation is, in fact, at the heart of virtually everything we do in the laboratory and even in many flight experiments. The more I think about it the more I am convinced that you could not have chosen a topic which covers more ground in our nation's aeronautical and space program. The classical simulator of atmospheric flight, the wind tunnel in all of its various forms, is replaced as we move beyond the atmosphere, by the vacuum chamber. An aerial view of a NASA Center a decade ago was dominated by the worm-like appearance of return flow wind tunnels. Now the distinguishing features are spheres which appear from the air to range in size from marbles to basketballs. Most of these are for the purpose of simulation and hence are simulators -- and although they are not necessarily staffed by "men in greasy black suits with dingy black neckties" a good part of their professional operators are engaged in the arts and sciences which are the subject of this conference.

This history of applied science and engineering is really a history of simulation -- a history of searching for methods of observing apriori the behavior of engineering systems and of varying the parameters of such systems in order to seek optimum results. The approach of the pure scientist seeking to explain observable phenomena likewise leans heavily on simulation and analogs. The human mind being what it is, it is natural that hypotheses should be constructed employing analogies with known and familiar phenomena. An amusing instance of this approach was the "law of octaves" proposed by Newland. Here the resemblances among the different chemical elements were formulated on the basis of an analogy with musical notation. Although Newland's law was rejected and laughed at by his contemporaries, the proposal was, in fact, the forerunner of the periodic table of the elements.

Mechanical models have long been employed in physics even as a means of describing and studying the behavior of electrons and protons as in the case of Bohr's classical model of the hydrogen atom. In recent years there has been a tendency to discard the use of such models and they are replaced by abstract mathematical relationships. Mathematical tools themselves serve as simulators in the physical sciences just as an airplane model in a wind tunnel or a spacecraft model in a vacuum tank. Mathematics differs from the natural sciences in that it is based on axioms which do not necessarily rest on observed phenomena in nature. For example, plane Euclidean geometry is a legitimate branch of mathematics whether or not there exists in the real universe entities with the properties of Euclidean lines and planes. However, when a portion of science has principles which coincide with the axioms of some branch of mathematics, then all the theorems based on these axioms can be interpreted in terms of the physical principles. Thus applied mathematics, coupled with the modern computer, provides us with universal and relatively inexpensive simulation. In spite of the strides which have been made in the development of computing machinery, the field of applied mathematics should be encouraged and brought to bear much more vigorously in this country than is now the case.

As every applied scientist knows, practically all simulators provide something less than complete simulation and sometimes introduce spurious effects. A chemist who displays a wooden model of an organic compound does not expect his audience to believe that carbon atoms are black and oxygen atoms blue. The successful engineer or scientist is one who can strip away in the process of simulation all of the extraneous unessential parameters and who knows which of the features of his model are appropriate and which are irrelevent. A metal beam to an engineer is a mass of homogeneous elastic isotropic material subjected to boundary conditions; to the chemist a collection of molecules; the metallurgist an assemblage of grains and crystals; to the solid state physicist a swarm of nuclei and electrons. Each constructs a model at his own level of abstraction and understanding and by applying reasoning he infers new information. Unfortunately each model provides partial simulation and none represents the total intrinsic realities of nature.

We are often confronted with the intellectual exercise of interpreting simulation results in the light of actual experience. The "method of agreement" is an example of a rule of science, or perhaps I should say of common sense, which we all employ daily. It states that if the circumstances leading up to a given event have one factor in common, that factor may be the cause sought. Even such an obvious rule has its pitfalls as witnessed by the scientist who enjoyed scotch and soda at a party. The next morning he felt badly, so that night he tried rye and soda which resulted in the same distressing symptoms. The third night he switched to bourbon and soda with similar results. Acting like a true scientist and analyzing the evidence by employing the "method of agreement" he concluded that thereafter he would omit soda for his drinks.

Our ability to develop the engineering systems of atmospheric and space flight depends in turn upon our ability to simulate in the laboratory and thereby study new concepts as well as systems and their components prior to flight.

In general, two kinds of simulation facilities are required. Those which are used to develop new concepts and physical understanding may often be relatively small and inexpensive. In addition there are required the larger simulation facilities needed for the ad-hoc testing and development of subsystems and systems in preparation for flight. In addition to facilities, however, there is needed a certain level of knowledge of the arts and sciences of simulation. Certain similarity laws for elastic structures were formulated as early as the seventeenth century by Galileo. Since that time many useful tools have been added so that modern engineers are familiar with the dimensionless variables required to model airplanes, surface vessels, structures, heat transfer systems, re-entry devices and many other engineering systems. Accurate simulation, however, requires physical understanding of the dimensionless variables required for similitude and the development of this understanding is just as important as the development of facilities. There is no shortcut to physical understanding. Dimensional analyses is, for example, often ascribed mystical power which it does not possess. I wonder if the Pi theorem is still being taught in the same way that it was taught to me by carefully choosing illustrations where the answers were already known, and benefiting from these answers in the construction of a solution.

The nation's plans for increasing its mastery of aeronautical and space flight are familiar to most of us. A supersonic transport is desired early in the 1970's and hypersonic commerical air transportation is a dream which many expect to be realized before the turn of the century. We talk of exploration of the surface of the moon, orbiting manned space stations and of manned expedition to the planets and beyond. Have you stopped to consider the importance anddifficulty of ground simulation of these activities? Unless adequate means for ground simulation can be employed, these ambitions will never get beyond the planning stage because of the high expense of developing and testing in flight. How can the structure of a supersonic transport with a 50,000 hour lifetime of cyclic cooling, heating and loading be developed at minimum weight and with maximum reliability? Even if a facility were available, nearly six years of real-time testing would be required. Already ground simulators are being used to great advantage at the NASA's Langley and Ames Research Centers in evaluating the piloting and handling qualities of supersonic transport aircraft and in assessing the compatibility of such aircraft with the airway traffic control system. A subsonic jet aircraft at the Flight Research Center is being fitted with computers which will permit it to simulate a wide range of stability and control characteristics in flight including those of the supersonic transport. Simulator studies such as these will provide information in time to influence the design of the supersonic transport.

How shall we develop the lightweight nuclear-electric power systems with 10,000 hour maintenance free lifetime required for spacecraft on-board power and electric propulsion? Not only elaborate facilities are required but similarity laws are needed which will allow us to extract meaningful results from tests conducted in less than real time. By what means can we simulate the environment of an air breathing propulsion system for Mach 6 flight or beyond? How can we achieve on the ground a full or partial simulation of the space environment including the vacuum, the full energy levels of elementary and finite particles and the electromagnetic radiation? There is much speculation concerning life behavior under zero g conditions, and we generally conclude that it is impossible to obtain long time simulation of zero g conditions for such studies. The zero g environment also produces difficult problems for the engineer especially in establishing the behavior of liquid and vapor systems.

These include positioning of fluids in propellant tanks and liquid-vapor equilibrium configurations in condensers and radiators.

Liquid in a tank under normal one-g conditions rests on the bottom in the manner familiar to all of us in everday life. This is due to the overwhelming predominance of gravity over surface tension forces. However, under zero g conditions, the liquid mass may assume an odd equilibrium configuration, due now to the predominance of surface tension forces quite unlike that under normal conditions. We have found it possible to study these phenomena in aircraft flying zero g flight paths and by freely falling bodies in a drop tower. A basic understanding of this behavior has already been achieved in a 100 ft drop tower at the Lewis Research Center and a 500 ft tower is being constructed at Lewis which will give us over ten seconds of zero g test time in an up and down test.

These are but a few examples of progress in simulation that will be required in order to sustain national aeronautical and space goals. It is quite clear that simulation technology must make great strides over the next decade in order to accomplish these ends.

The fabric of our country's technological society is woven from three principal threads; government agencies such as the NASA, industry; and the university. Each of these entities must play a role in achieving a higher level of simulation technology. The federal government has been involved and it will continue to be involved. This is required since these matters affect national security and our nation's image in the world. Many of the facilities required are clearly beyond the means of private enterprise. This has been the business of NACA since its founding in 1915 and later became the business of the NASA when the responsibilities for space flight were added by the Space Act of 1958. The continued development of simulation technology and of proper facilities for this purpose is one of the primary responsibilities of the NASA. Because of the expense and the long development and construction time of new facilities, exceptional foresight is required on the part of the managers of the NASA Centers. In retrospect, it is clear that our country's preeminence in atmospheric flight has been based very largely on the existence of NACA wind tunnels.

If industry is to play its traditional role of creating hardware, it must possess or have access to the tools for ground simulation and development. Possession of these tools will be clearly impractical for many of our contractors and they must therefore be provided them through government or other private facilities.

The university will play a part through its classical role of gaining and distributing knowledge. The mutually supporting functions of research and teaching give the university enormous leverage. In our increasing complex socity, technical schools such as the Virginia Polytechnic Institute must assume more leadership than ever before. The need here is for quality and not quantity. There is no shortage of scientists and engineers, nor is there a shortage of unimaginative projects. There is only a shortage of qualified scientists and engineers and new ideas. The university, acting as a closely coordinated entity, as well as its individual scholar, will be called upon increasingly to aid the government at all levels in its decision making. An even greater role must be assumed in continuing education. As the faculty of VPI well knows, the engineer is in the most difficult position. The practicing scientist or engineer may soon need to spend one year our of every ten in refurbishment of his technical knowledge. A. C. Montieth, former president of the A. I. E. E., has said that "today's graduate engineer has a half life of about ten years", in other words half of what he knows will be obsolete in a decade. Montieth adds that "half of what he will need to know ten years from now is not available to him today." This brings to mind the classical story of the medical school dean who confessed to his graduating class that half of what they have been taught was incorrect. What is worse, said the dean, we are not sure which half.

The City of Washington is strewn with relics of the past, not the least of which are monuments. Most of these commemorate military officers or politicians, but the other day I ran across one within a block of NASA headquarters in memory of the French inventor, Daguerre', who developed the daguerreotype photographic process. This monument, which was erected in 1890, bears the inscription "Photography, the electric telegraph and the steam engine are the three great discoveries of the age. Not in five centuries of human progress have we seen such strides as these." Such a reminder brings home sharply a realization of the enormous growth in science and technology since the erection of that monument. This growth seems to follow the law of geometric progression. In other words, the growth is proportional to the amount of science and technology that already exists.

Space technology is, comparatively speaking, in the stage of the daguerreotype photograph. Its continued growth is certain but it will depend very much on improved understanding of the subject matter of this conference.

Thank you and good evening.

SENSORY, PERCEPTUAL, AND PHYSIOLOGICAL ASPECTS OF SENSORY DEPRIVATION[1]

by

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Sensory deprivation, the topic which I am going to speak about today, is unusual from several points of view. In sensory psychology and physiology we are usually concerned with the effect of a stimulus upon the organism or upon a given system of the organism. Sensory deprivation, in general, is concerned with the exact opposite: the effect of total or partial deprivation of stimulation upon the organism.

Although the field of sensory deprivation is comparatively new from the viewpoint of scientific psychology, we have been continually made aware by laymen of the effects of depriving an individual of stimulation. Even fictional accounts of the last century have included references to the effects of various forms of isolation upon the individual. We all recall Ben Gunn of "Treasure Island," a victim of social isolation, and Dr. Manet of "A Tale of Two Cities." Descriptions of the effects on men placed in isolation in prison are fairly common. Reports of shipwrecked sailors, lost explorers, and prisoners of war have also given evidence of the bizarre reactions of

[1]The preparation of this report and the author's program of research described as supported through Grant NsG 489 from NASA.

individuals who were in isolation. Admiral Byrd wrote of the severe depression and of the disturbing thoughts that plagued him after being alone for three months in the Antarctic.(9) [2] Dr. Alain Bombard also described depression and inability to discern truth from falsity in his description of his experiences alone on a life raft in the Atlantic for two months.(7) Christine Ritter also reported uncontrollable hallucinations and delusions in discussing the effect of her solitary life in the Arctic.(40)

Similar mental and perceptual abnormalities have been frequently reported by individuals who have experienced periods of isolation, including prisoners of war who were "brainwashed" (a procedure based mainly on isolation) in prisons of the Russian and Chinese Communists.(28) The effects of unchanging stimulation are also well known to road engineers who use the term "road hypnosis" to describe such effects of unchanging visual stimulation and relative motionlessness. Graybiel also has described the effects of such unchanging vistas in pilots flying at altitudes over 40,000 feet. He spoke of sudden banking of the aircraft for no reason that the pilot could explain, and other unusual behavior.(10)

Despite these various accounts of the effects of lowering the absolute level of stimulation on the individual, no serious attempts were made to study the phenomenon until the work of Bexton, Heron, Scott, and Doane working with Hebb at McGill University.(6, 26) These investigators were interested in the effects of decreased variation in the sensory environment on suggestibility, or as it has popularly been called, "brainwashing" a procedure initiated by the Communists. These investigators reduced the

[2] Parenthetic numbers refer to studies listed in reference section. These references are representative rather than exhaustive.

pattering of stimulation rather than its absolute intensity, and determined the effectiveness of such a procedure on increasing the susceptibility of graduate students to Communist propaganda. They found not only an increase in suggestibility to propaganda, but also that many of the subjects refused to remain in isolation, in spite of the fact that they were kept relatively comfortable, were fed, and were well paid. The experimenters were surprised to find that 25 of 29 subjects reported hallucinatory experiences, which progressed usually from simple sensations to more highly organized hallucinations and which occurred anywhere from 20 minutes after the start of isolation to 70 hours later.

Let us now consider some of the effects of sensory deprivation and their implications for space travel. One of the common effects reported after sensory deprivation is that of spatial disorientation. In the McGill studies, when the subjects were permitted to leave the cubicles to go to the bathroom, in spite of the fact that they had been there several times previously, many of them were unable to find their way. The implications are clear for a capsule under the guidance of an individual astronaut. Another effect frequently mentioned is change in the "autokinetic effect." The autokinetic effect is a subjective impression of movement of a small light in an otherwise dark room. Usually such a light is reported to be in motion in spite of the fact that it is actually stationary. After deprivation, enhancement of the rate of movement of stationary points of light, has been reported.[15, 26] A traveller in space who guided himself by the constellations, might tend to believe his course was changing if such points of light, that is, the stars, appeared to change their positions. Other changes commonly noted are those of size constancy.[11, 15, 17, 38, 57] Size constancy is the term given to the fact that we tend to perceive objects of known size as constant, despite the fact that our distance from them, and hence their retinal angle, changes, etc. Landing or docking activities would be severely handicapped if size constancy were impaired in an astronaut maneuvering his capsule. Without laboring the point, it is apparent that such effects as we have noted, as well as hallucinations, motion after-effects, increased susceptibility to illusions, distorted time estimations, impaired judgment of three-dimensional forms, etc. may have extremely dangerous consequences for an astronaut whose judgment and reaction time must remain at the highest levels.

Research in sensory deprivation has increased rapidly in the past years and with such increase in the number of studies has come a great deal of confusion of terms because of divergent usage. I will therefore define some of the more frequently used terms and describe some of the usual techniques employed. Deprivation is a very general term and has been used to refer to a reduction of the sensory stimulation impinging upon an individual. Thus, "sensory deprivation" is the term generally employed in this area.[30] The deprivation may be total or partial. That is, there may be some lowering, or a total elimination of the level for example, of illumination. "Perceptual deprivation" has been employed to refer to the elimination of the subject's ability to perceive objects.[30] Thus, to have a subject visually-perceptually deprived, he usually wears frosted goggles which permit diffuse illumination to stimulate him, but which eliminate his ability to perceive shapes. The term "isolation" has usually been employed in dealing with a social situation, that is, relations with other individuals, and is often referred to as "social isolation." In such a situation it is the social nature of the deprivation which is stressed, although here too, it may be combined with sensory deprivation. Finally, the sensory deprivation may be restricted to one or two modalities, or be complete. Thus, in some studies the deprivation was restricted only to vision, or only to kinesthesis, that is, depriving the individual of feedback concerning his own bodily movements.

With regard to the many techniques employed in deprivation studies, these have varied as often as new investigators have entered the field. Among the procedures employed are the use of small soundproof cubicles, or small rooms containing a cot or mattress.[6, 17, 37, 42, 44, 55] Some researchers have employed coffin-like devices to hold the subject,[56, 60] while others have employed respirators such as those used in treating patients with poliomyelitis.[14, 32, 36, 62] The most ingenious departure is a technique which submerges the subject under water, permitting him to breathe through a tube.[31, 41] Such a procedure also provides a degree of weightlessness for the subject. In providing visual deprivation, the techniques have ranged from darkening the room to having the subject wear opaque goggles,[4] or frosted goggles[54] in the case of perceptual deprivation. For auditory deprivation, relatively soundproof cubicles, with sound attenuation to 70 or 100 db,[43] have been employed. In some experiments, air conditioners which produced a source of white noise which masks any unwanted sounds were used.[26] Occasionally, earphones have been worn by subjects both to eliminate sound and to provide means by which the experimeter could communicate with the subject or to transmit white noise.[46] Tactual isolation of the body surface has proved to be more difficult, since the subject must lie upon some portion of his anatomy. However, some researchers have employed large cardboard tubes over the hands,[14] or large mittens padded with fur.[43] In some of the partial deprivation studies, the hands have been placed in containers resembling cigar boxes which keep the fingers relatively isolated from objects and from one another.[48] In other studies rods[27] or cups[1, 2, 3] have been attached to the surface of the arms and covered over by adhesive tape, which keeps the forearm relatively isolated from stimulation.

The times of stimulation also have been quite varied. In some studies isolation occurred for only 30 minutes[36] in others for a few hours,[42] in the usual ones for one or two[4] days and for the highly ambitious ones seven to fourteen days.[59] During these periods of deprivation some experimenters permitted the subject to take food or toilet breaks, whereas others permitted ad libitum feeding and accessibility to toilets. The types of subjects employed were also varied. Although most studies employed college or graduate students,[58] others utilized unemployed actors,[20] and some even tested psychotic patients.[38]

Among the more critical variables employed, was that of varying the form of instructions or suggestions to the subject. In some experiments no instructions of any kind were given to the subject; in others the serious nature of the experiment and its importance were emphasized.

One other independent variable worthy of note employed was species differences. Although most of the studies have been done on man, other studies have employed ducks, rats, cats, monkeys, or chimpanzees.[16,29,34,39]

In the approximately 100 studies which have been surveyed to date, there have been some 35 to 40 dependent variables studied. These have consisted of various measures of the sensory changes within vision, audition, and somesthesis. Other variables have been concerned with physiological measures such as heart rate, body temperature, phospholipid metabolism, catechol amine excretion, electroencephalography, galvanic skin reflex, measures of bodily activity, motor performance, cognitive functioning, and learning ability. Some studies have been concerned with such extremely abnormal behavior as hallucinations, or delusions, confused thought, etc.; however, we will not concern ourselves with these phenomena today.

Let us now consider some of the effects produced by sensory deprivation, restricting our observations to only a few of the variables measured. Let us first consider the visual constancies. Visual constancy has been defined as the ability of an individual to continue to identify a known object e.g., according to its size, its shape, its color, or its brightness, in spite of the fact that there are variations in the distance, the visual angle, and the illumination under which the object is perceived. Thus, with regard to size constancy, even though an automobile and a lump of sugar may occury the same area on the retina, that is the same visual angle, the automobile is seen as much larger than the lump of sugar. The tendency to judge an object according to its retinal angle or its true size can be measured rather accurately. In 10 studies which have considered size constancy, 5 were able to demonstrate an impairment after a deprivation period which lasted from only 4 hours to as much as 14 days.[11, 15, 17, 38, 57] In two studies performed by the group at McGill University, deprivation lasting from 24 to 96 hours was sufficient to produce an impairment of shape constancy.[15, 26] Interestingly enough, in one of these studies visual acuity was found to increase significantly.[15] In two other studies color discrimination was studied, that is, the subject's ability to differentiate hues.[56, 60] In both studies this ability was impaired after deprivation of movement lasting from 3 hours to 7 days. Several studies have also dealt with the effects of deprivation upon form perception. With little exception, the subjects, who were deprived from as little as 3 hours up to 14 days, misperceived visual forms presented. They perceived the shapes of objects as distorted, straight edges tended to appear curved, at the region of fixation flat surfaces appeared to bulge toward the subject, and even simple geometric patterns were misperceived.[17, 26, 56] Studies of the autokinetic effect revealed somewhat more ambiguous results. In three studies,[37, 46, 53] the degree of perceived movement diminished, and in two other studies the degree of subjectively perceived movement increased.[15, 26] It is unclear what factors contributed to the increase or decrease of the subjective movement of the point of light presented. In two studies concerned with estimation of the speed of motion, subjects tended to underestimate the rate of motion of moving objects.[18, 37]

Interestingly enough, the modality tested also seems to be important with regard to whether there was improvement or impairment. Thus, whereas most of the studies of vision showed an impairment, most of the studies of tactual sensitivity show the opposite. In measuring two-point discrimination thresholds, that is, the ability of subjects to differentiate two points simultaneously applied to the skin from a single point, with varying distances between the points, five studies showed that deprivation produced an enhancement of this ability.[3, 15, 27, 37, 42] That is, the subjects were able to discriminate two points from one when the two points were applied at much smaller distances between them than they could before deprivation. The same effects were obtained in tests of tactual fusion.[1, 2, 3, 53] In these measures the subject's ability to resolve the individual stimuli of an interrupted jetstream of air applied to the skin improved after deprivation lasting up to seven days.

Varying results have been reported for example, in the auditory modality, the data bearing no apparent relationship to differences in the independent variables employed.[19, 35, 57] Similar statements could be made for studies of the heart rate.[5, 13, 14, 33, 41]

With regard to chemical studies of the effects of deprivation, phospholipid turnover was found to decrease in mice after 14 to 31 days of isolation.[47] Catechol amine excretion was increased after 36 hours of deprivation in a tank type respirator.[32] Among the more consistent of the physiological changes is that of the electroencephalogram. In nine studies which measured the spontaneous electrical activity of the brain, all showed changes as a function of sensory deprivation.[5, 12, 26, 42, 52, 54,58, 59] In general, the frequencies in the alpha band, that is in the 8 to 12 cycles per second range, tended to be slower after deprivation than before it. In studies dealing with the galvanic skin reflex, a measure of skin conductivity, all showed changes to stimulation after periods of deprivation lasting from 2 to 3 hours.[12, 42, 61, 63]

Other studies have been concerned with the effects of various drugs during the deprivational state and have measured cognitive or motor performance as well as learning ability.

How can these data all be summarized simply. The answer is, unfortunately, that they cannot. However, it is safe to say that the effects of deprivation are rather pervasive and quite apparent. Regardless of the type of study, there is no question that an individual who has been deprived of sensation is a changed individual. His judgment suffers, he is spatially and temporally disoriented, his ability to perceive things visually, auditorily, and tactually, is changed. In general, he is sufficiently altered so that he would become a danger to himself and to others dependent upon him if any responsibility such as that of guiding a space craft, were placed in his hands.

Research in this area, if it is to have any practical significance for space travel, must therefore answer three rather broad questions: 1. What are the abilities relevant to space flight which are impaired after restriction of motion and relatively unchanging stimulation such as would occur in long flights in a capsule? 2. What are the characteristics of individuals which makes them relatively less susceptible to the effects of such restrictions of motor activity and sensory stimulation, and 3. What manner and intensity of stimulation is required to offset the effects of such motor and sensory deprivation? Such research must first start to clarify some of the unanswered problems posed by the ambiguous results of previous research. Having ascertained the primary effects resulting from sensory deprivation, we must select those individuals who are minimally impaired by deprivation, and compare their characteristics with those of individuals who show maximal impairment. Finally, we must titrate the stimulation which is necessary to inhibit the deleterious effects of deprivation. This program, as outlined, is an ambitious one. In my laboratory at the Albert Einstein College of Medicine, we have initiated such a program of research with the support of NASA.

Before outlining the program of research which we have initiated, it might be well to consider the categories of sensory change which an astronaut might undergo in his capsule, or an experimental subject in his cubicle. The first deals with the energy level of the stimulus delivered to the receptor system. Too much or too little energy would result in a complete loss of information to the subject. For example, if the energy of a light source is below the subject's threshold he would not see it. If the energy level, conversely, were too high, the glare would "wash out" the perceptual qualities of the stimulus, and although the subject would be aware of the existence of the stimulus, he could not identify it. Thus, the relationship between the energy level and the subject's performance is a curvilinear rather than a monotonic function. The second aspect worthy of consideration is that of the patterned or unpatterned nature of the stimulus. Here, examples are white noise versus patterned sounds, "snow" such as appears on a T.V. screen, versus some discrete visual stimuli, or wind blowing against the skin, in contrast to a specific touch. This variable is independent of the energy level mentioned above. It is concerned only with the degree of information transmitted. A third category which is relevant here, is that of the frequency of change. Here we are concerned, not with energy, or meaningfulness, but rather with the frequency with which one stimulus is changed from another. Thus, one might have a stimulus of medium energy, and moderate patterning, which is changed for a different stimulus of similar or dissimilar characteristics and which is changed relatively infrequently, or not changed. We are now aware that some higher centers of the brain may block such unchanging stimuli from reception by the organism. Such habituation has been frequently found even in lower organisms in which a tone of a given frequency fails to evoke a cortical response after much repetition; however, a tone of a different frequency at this time will cause the cortical response to return. Thus, the aspect of change of the stimulus is a critical one if one is concerned with maintaining the vigilance of the subject. A final aspect worthy of consideration is that of the "rearrangement" of stimuli. That is, stimuli within any of the above categories may be delivered to the organism in such a manner as to change their intrinsic meaning. For example, a receptor system may be so altered by circumstances that it misperceives stimuli; or the transmitter which delivers the stimuli may distort it before it arrives at the receptor. We have engaged in studies demonstrating the subsequent maladaptive nature of responses of an individual who has been subjected to distortion of his perceptual surroundings, by means of laterally-displacing optical prisms. I shall return to these studies and some of the results we have obtained, in a moment.

Before we can understand adequately the effects of various forms of sensory deprivation upon the individual, it is clear that we must first understand whether the energy level has been effected, what the level of patterning is, the frequency of change of the stimuli, and whether or not the environment has been "rearranged."

In addition to interpreting the stimulus situation impinging on the subject, we must also interpret at what level the effect is acting upon the subject. Let me give some reasons that a visual stimulus may not produce a response in a subject, as an example of the level of effect.

If we were faced with interpreting the cause of an individual's inability to report the presence of a complex visual stimulus, a number of hypotheses would suggest themselves. Thus, one might infer that there was a loss of the stimulus within the individual's short-term memory storage, such that he no longer had a memory sufficiently intact to permit him to respond. However, this interpretation would be at the level of inferring a highly complex neural disorder. Another alternative, also at a "higher level" of difficulty would be that his effector mechanism, that is, his ability to respond, may be impaired. Although these two "complex" alternatives are within the realm of possibility, one should always seek a lower level alternative. The following simpler possibilities may also account for the inability of an nndividual to respond to a visual stimulus. The first, and simplest, possibility is that of a clouding of the lens or cornea. The second possibility, involving a more complex mecahanicm, concerns the inability of the individual to focus upon the stimulus. A third, increasingly complex possiblity, is that the retina, a bit of nervous tissue, has become refractory because of too intense, or too prolonged a period of prior stimulation. Fourthly. one might speculate that the optic nerve, a structure concerned with the transmission of the information from the receptor mechanism to more central mechanisms, is malfunctioning. A fifth alternative worthy of consideration is that all preceding mechanisms are adequately functioning, but that the initial cerebral relay center, the lateral geniculate body of the thalamus, is malfunctioning.

adequately functioning, but that the initial cerebral relay center, the lateral geniculate body of the thalamus, is malfunctioning. A sixth alternative is that the optic radiations to the occipital cortex, are impaired; a seventh, that the projection cortex of the brain itself is involved; an eighth that the interaction with modalities and effector mechanisms is inoperative; and finally, the alternatives originally given, namely that the short-term memory of effector mechanisms themselves were not operating.

It is our intention to determine the lowest levels of impairment which may be responsible for the deficits obtained in sensory deprivation. We believe that it is inappropriate to ascribe impairment to higher order levels of malfunctioning. One simple analogy may make much of the foregoing clear. We believe it is more appropriate from the point of view of imparting information, to state that a man's occipital cortex does not respond to light flashes, than to say he is incapable of celestial navigation from astral charts. Although the latter statement is also true, it may imply the existence of other abilities and could not enable us to predict his failings by its lack of exclusivity. It is for such reasons that we seek what might be called the lowest common denominator of human functioning when we seek the effects of sensory deprivation upon loss of abilities.

I shall now outline to you very briefly our program of research. Firstly, we plan to place individuals under conditions which would provide deprivation in any one or all three of the major modalities, or under any combination of two of them. We plan to isolate them for from one to three days. As one control group, we will test individuals before and after one, two, or three days, who will spend the interim period engaged in their normal activities. Another control group will comprise individuals who will have no sensory deprivation, but will have restriction of motor activity. Similar groups of subjects will have only a loss of patterned stimulation. That is, instead of being placed entirely in the dark, they will wear frosted goggles which will provide continuous, diffuse stimulation, and earphones which will provide continuous white noise. The dependent variables studied will provide measures of absolute sensitivity for vision, audition, and somesthesis. That is, we will measure brightness thresholds, loudness thresholds, and touch sensitivity thresholds. We will also determine discrimination threshold in each of the modalities: for example, tone, color, and two-point discriminations. Various other more complex abilities will be studied. We also plan to measure three-dimensional spatial orientation by having the individual navigate in three-dimensional space, utilizing visual, auditory, tactual, or combinations of these cues to guide him. We have already begun to measure the effects of intrinsic and extrinsic guidance upon the individual's ability to learn to respond to a "rearranged" environment, that is, an environment whose spatial coordinates are distorted by laterally-displacing prisms.

Emotional responses will also be measured by means of the galvanic skin reflex, and by means of pupillography. Recent reports have demonstrated that the pupil dilates rapidly and consistently to emotion-provoking stimuli. By monitoring the changes in pupillary diameter, by means of ambient infrared, to visual stimulation of an emotional nature, we plan to determine what effects deprivation has upon the emotional responses of individuals after deprivation. Finally, we are planning to study various physiological and neurophysiological effects of deprivation. Thus, we plan to determine the spectral changes in frequency of the EEG. Perhaps of even greater value is the study of the cortical evoked potential. This electrical response of the brain is time-locked to various stimuli which are presented to the sensory receptors. By using a special computer, the Computer of Average Transients, it is possible to integrate the electrical activity of the brain so as to increase the signal-to-noise of a specific time-locked response to a stimulus, over that of the spontaneous electrical activity of the brain. The importance of such measures is apparent when one considers that the ascending reticular activating system of the brain has been implicated by many authors as playing an important role in producing the effects of sensory deprivation. The diffuse nature of this system, with its role in attention, alerting, and the control over sleep-wakefulness, makes such a mechanism a very likely one to be implicated in the effects of deprivation. In addition to the neurophysiological mechanisms studied, heart rate, general bodily movement, and breathing rates will be determined after varying periods of deprivation.

I have referred to rearrangement several times. Although it it not among the techniques usually considered when one deals with sensory deprivation, I believe the central mechanisms involved may be the same, and that it is merely another method to consider which produces a modification of the usual sensory environment of the individual. Among the techniques commonly employed to rearrange the environment are the use of microphones, each leading to one ear, with positions variable such that the axis connecting them may be 0°, 90°, or at 180° with regard to the axis of the ears. Another technique employs laterally-displacing, or inverting, prisms, or lenses of various hues.

It is probable that the central mechanisms concerned with an individual's adaptation to diminished or excessive stimulation are the same as those involved in dealing with an environment which has been so modified, or rearranged.

The reticular activating system of the brain has been implicated in reducing our vigilance to stimuli, which have been shown to be without significance to us. It might similarly serve in the reorganization of our responses to stimuli which similarly have been found, through experience, not to conform with previous experience or not to bear the same relationship to our responses that previous stimuli did.

As part of our program of research concerned with factors which modify the individual's capacities and responses to an altered environment, we have also embarked on a series of experiments concerned with the rearrangement of the individual's sensory environment.

Some data have already been derived from several preliminary studies of the effects of rearrangement of the visual environment on the subject's adaptation to stimulation (49, 50, 51). The major theory which is concerned with the effects of rearrangement; the theory of reafference, originally proposed by von Holst, (45), contends that one learns to respond to visual stimuli through reafference rather than exafference.

These terms may be distinguished as follows: Exafference refers to stimulation of the individual by sources which are independent of his own actions. That is, a butterfly moving past one's eyes is a source of exafference. By contrast, reafference results when one is the source of his <u>own</u> stimulation. For example, moving about actively, or waving a hand before one's eyes are sources of reafference.

According to Held, (22), one of the major proponents of reafference theory, one cannot adapt to a visual environment which has been rearranged, unless he has been subjected to reafference, that is, unless he has had active commerce with the environment. In support of this statement, Held and his collaborators have completed a series of experiments which have demonstrated the necessity for reafference in visual adaptation, (8, 21, 22, 24, 25).

A paradigm of this research is a study employing 20 diopter prisms which displace the visual field laterally (23). The experimental group, wearing the prisms, walked about a campus for an hour, having first been tested for egocentric localization. That is, after locating the angle at which they had to rotate themselves in a revolving chair so that they faced exactly a given point, they had a full hour of reafferent experience with the prisms. Upon retesting in the egocentric localization equipment, it was found that the group had a significant positive after-effect. That is, they tended to position their body in the direction opposite to the original displacement of the prisms. This opposite rotation, or after-effect, is considered evidence for adaptation to the prisms. In other words, the subject adapted to the prisms, and when they were removed, he then responded to the localization task as though his normal state of perception involved the wearing of prisms.

The control group of subjects also wore prisms. However, to avoid reafference, they sat passively in wheel chairs, and were transported by another person. The results demonstrated that these subjects did not adapt. The conclusion was that exafference is insufficient to yield adaptation.

There are several criticisms one can make of this experiment. For one, the visual experience of a person walking with concomitant head bobblings, etc., is not equivalent to that of a seated person who is being wheeled. The other problem which disturbed us was the equivalence of vigilance or motivation of a passively-transported subject with one who must actively avoid obstacles, steps, etc. in walking about.

We decided to repeat the experiment, correcting the flaws we mentioned. For one, in our experiment, (49), all subjects, active and passive, were in wheel chairs to eliminate differences in visual stimulation. And, in order to study the relative roles of self-induced movement and informational-feedback, we separated two variables: self-induced movement, and self-guidance.

A subject could have either, neither, or both of these variables operating.

Thus, the ones who had neither self-produced movement nor self-guidance were passively pushed in a wheel chair, while wearing prisms.

Those who had both self-induced movement and self-guidance pushed, and, of course, guided themselves through the prescribed course.

The other groups had one or the other condition. The self-induced movement group without self-guidance merely pushed the chair forward at all times without steering it. The assistant who accompanied the chair steered it, and took all responsibility for its guidance.

The final group, the self-guidance group, guided the chair, but did not propel it. To insure that he alone would guide it, the one who pushed it was blindfolded and took all instructions from the subject seated in the chair.

According to reafference theorists, only those who actively propelled the chairs should adapt to the prisms. The results showed that the groups did not differ in the degree of positive adaptation. Furthermore all adapted significantly and positively.

We believe we have demonstrated in this experiment, and in several subsequent ones, that reafference is not necessary to achieve visual adaptation, but that informational feedback is. To the extent that reafference has been shown to produce visual after-effects to rearrangement, we believe that the effect may be attributable to the concomitant informational feedback which the reafference involved.

We have continued work in this area, determining the visual and extra-visual effects which may cause reactions to visual stimuli. We believe that many situations may affect an individual's adaptational responses. There is some evidence to suggest that asymmetrical visual stimulation, that is light stimulation from one side, may affect the individual's judgment of his own body midline.

The implications of these data for an astronaut being asymmetrically stimulated, for example, by sunlight coming from the right part hole of his capsule are apparent. We also have some data which show that body positions which involve slight body torsion over a small period of time to one side may also effect the individual's judgment of direction.

Studies of head and eye positions, with compensation for direction of gaze by means of prisms and mirrors are also presently being conducted in order to determine the effects of such positional variations on visual direction finding.

In summary, much attention is being paid to the hardware necessary to get a man to the moon and to the planets. There is no question that without the hardware we could not begin to get man off the earth. However, it is becoming increasingly apparent that unless we know what is happening to the man in space, we may be transporting unresponsive cargo to the moon and planets. We must therefore determine how man is likely to be affected by the conditions of space travel, how to select those men who would be least impaired by such conditions, and how to offset even the minimal effects of such impairment. One important consideration is the determination of how much of the guidance systems should be left in the hands of the astronauts and how much should be automated. Solution of the problems imposed by sensory deprivation will bring us a long way toward safeguarding man's journey into space.

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EFFECT OF LOW-GRAVITY ON PHYSIOLOGICAL PROCESSES

by

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For more than one decade, the effects of decreased acceleration on the living organism have been studied in this country and abroad.[3, 21-24, 34, 39] Actual experimental data on animal and human physiology were obtained during Keplerian and ballistic flights of relatively short durations and from orbital exposures lasting up to five days.[6-12, 18-20a, 40] Moreover, weightlessness was simulated by water immersion, bed rest, and immobilization; and the effects of these conditions on physiological, neurological and psychological functions were compared with those observed under zero-G.[2, 14-17, 20] In this paper, an attempt will be made to discuss the major problems involved in low-gravity experimentation and to summarize the data available on the effects of prolonged weightlessness.

In this context, the question must be answered about the possibility of producting low-gravity states on Earth, and about the validity of the pathophysiological symptoms obtained by simulation. First of all, let me point out that of the three conditions mentioned before - water immersion, bed rest, and immobilization - none produces the low-gravity state, and only submersion can claim to simulate weightlessness to a certain degree. This also applies to the clinostatic principle or suspension on cables. In the submersed case, terrestrial physiologic relationships continue to exist between various body tissues, organs and bones because of their differences in density. Interestingly enough, it was stated by human test subjects who were exposed to immersion and zero-G flights that the experience of both conditions was essentially the same, namely of not being heavy. Hence we have accepted the term "weightlessness" to describe the subjective ex- pereience of the individual, whereas zero-G* describes the physiological conditions involved. Since gravity as a physical force acts as a "volume force", zero-G can be obtained either in case of lack of both gravity and inertia (for example, in field-free space and during drive-off), or through the mutual cancellation of gravity and inertia (as in free-fall and orbiting), or as the compensation of gravity by another volume force.[13] This, definition, excludes the presence of any contact force, regardless of the kind or density of the supporting medium. This reveals the fallacy of using the Archimedian principle

$$W = V(d-d')g$$

to produce the gravity-free condition. At best, it can be used to simulate a certain state of weightlessness. It must be emphasized that the true zero-G condition and the concomitant state of weightlessness are physical parameters or space environmental factors which cannot be duplicated on the ground. Hence, experiments with water immersion and hypodynamics provide only limited information about the effects of low gravity on the human organism. In prolonged bed rest or submersion, gravity dependent effects are always intimately mixed with those of inactivity, and they may relate to our problem only so long as spaceflight involves a mixture of stresses produced by the

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* The capital G indicates the balance of forces, not lack of acceleration

life in a small, cramped and uncomfortable space capsule.

It must also be pointed out in this connection that gravity-dependence of biological functions is not very pronounced; at least not in the human body where stress and mass distributions are entirely different not only for the standing, sitting and lying position but also for lying on the back, on the side, or face down, and standing upright or on the head. The corresponding physiological tolerance limits differ by several hundred per cent. Thus, the change from the erect to the recumbant posture is not associated with an immediate or marked effect on the physiological functions, but a rather subtle chain of biological events is set in action for the purpose of adjusting the organism to the new condition. In general, the changes brought forth or associated with changes of gravitational vectors depend upon the alternations in the mass-weight ratio of the body and the various parts involved and also upon the functional characteristics of the various organ systems concerned. The effects of low-gravity states on physiological functions as observed during or after orbital flights will now be discussed in some detail.

Results from Manned Space Flights Conducted in the United States and in the USSR

The acceleration profile of the manned space flights conducted so far is schematically represented in Fig. 1. After a relative high acceleration during launch, which may reach a maximum of 12 or more g, a period of weightlessness prevails during unaccelerated flight. Reentry into the atmosphere generally produces a deceleration of the spacecraft and its occupants of about the same magnitude. If the pilot stays in the capsule, a short but high impact acceleration may have to be tolerated. Some of the Russian astronauts left the capsule after reentry and parachuted to the ground.

The techniques used for the recording of the main physiological parameters during flights of Soviet and American spacecraft are shown in Table 1. Additional information on weightlessness effects were obtained from the analysis of personal experiences, operational performance, verbal communications, TV, entries in log books, handwriting, vestibular tests and sensory functions, and by preflight and postflight biochemistry.[4] To date, not all of the data have been analyzed or are available for this discussion. Moreover, the identification of weightlessness effects presents serious difficulties because of the great differences in the duration of the zero-G periods, the relative small number of persons exposed to these conditions, the variety and inconsistency of the indexes used, and the multitude of factors involved which do not warrant a statistical evaluation. For example, the personal experiences of the astronauts, information on sensory functions and performance criteria were not tabulated since the numerical data were scarce. Nevertheless, a first approximation of the effects of low-gravity on human physiology can be furnished by a systematic scrutiny of the bits and pieces of information obtained from manned orbital flights.

Personal Experiences and Operational Performance

The Mercury astronauts experienced the weightless state generally as pleasant and relaxing.[27, 28] Scott Carpenter called it "a blessing--nothing more, nothing less" after sitting in his pressure suit under 1 G and the launch accelerations.[30] The men adapted very quickly to weightlessness and soon took advantage of the situation: they left their feeding tubes and the camera handing in the air when not needed. There was no overreaching or lack of coordination. After the proper visual perspective had been established, the changing views from the capsule were not disturbing, and the random orientation by means of ground, sky or horizon was of no concern. The somatic sensations during weightlessness were normal, eating and drinking were accomplished without difficulties, and taste and smell were undisturbed. No nausea or vomiting occurred in any of these flights.

During the Mercury missions, the astronauts monitored the spacecraft systems, performed the assigned inflight tasks properly and were hampered only by engineering flaws. They reported accuracely and clearly on the status of their systems and took over the control of the craft when this was required. Subjectively, the men could tell little difference between the work performed under 1 G and under zero-G; the effort of zero-G being, if anything, slightly easier. This included the calibrated physical exercise. Deceleration at retrofire was experienced by Glenn as "moving back to Hawaii", by Carpenter as a stop. As to reentry, Gordon Cooper said: "I don't feel that it is any different from what we have done on the centrifuge". The impact accelerations were less severe than expected and very well tolerated by the American astronauts.[31]

A lot of interesting impressions and observations was reported by the cosmonauts and analyzed by Russian scientists.[35] Picture drawing and writing tests were used in conjunction with the assessment of operational performance. While it was concluded that the pilots' movements were coordinated and smooth during and after transition to zero-G, their drawings of pictures and handwriting were slightly changed, however. It is known that movements in handwriting require the finest coordination. The study of handwritings of Titov, Nikolayev, Popovich, Bykovsky and Tereshkova showed that the greatest changes occurred during the first hours of weightlessness. Thereafter, the motor coordination improved at a different time for each pilot, and a gradual adaptation to the new writing condition took place. From the samples analyzed it was concluded that central nervous system functions were not disturbed by the weightless state.

During this flight period, the performance capability of the cosmonauts was sufficiently high. They performed manual control tasks, maintained orientation and radio communication, and navigated by means of celestial and terrestrial guides. They ate and drank normally and experienced no difficulties in urination and defecation. They fell asleep fast and slept soundly and quietly. After awakening, the cosmonauts immediately set to work. However, there were some difficulties and peculiarities in the individual's behavior and performance. For instance, Bykovsky was very active, moved readily and frequently, made many entries in the log book, recorder on tape, and kept up communication. In contrast, Tereshkova moved very little, her movements being slow and restricted in size, and was rather passive. These individuals differences are probably due to the different adaptability of the mechanism regulating physiological functions to the new environmental condition An analysis of the telemetry data showed no pathological disorders of the vegetative system.

The transition from the accelerated state into weightlessness was experienced as light and smooth by all the astronauts. The unusual state and the relieved nervous and physical strain after the successful launch into orbit was associated with a feeling of well-being, increased speaking, and even a kind of euphoria. This state of increased activity and excitement generally disappeared by the end of the second or the beginning of the third orbit.

Sensory and Neurophysiological Functions.

Since orientation in space depends primarily on visual and vestibular functions, tests in both areas were made on the American and Russian astronauts. Two small eye charts were attached to the instrument panel within the Mercury capsule with letters of decreasing size and with a "spoked wheel" pattern to check visual acuity and astigmatism. No change from normal was apparent. The astronauts were able to track the sustainer engine visually without difficulty. In a special experiment on depth and color vision, Carpenter described correctly the distance, color, and brightness of the objects.[30] Using only eye movements, Glenn tracked a rapidly moving light spot generated by his finger-tip lights. He had no difficulties during this task and no sensation of dizziness or nausea.[29] There were no mental aberrations or hallucinations. Details of ground features, such as villages, fields, roads, houses, a wake on the ocean, and smoke from chimneys, were reported which were thought to be far beyond the resolution of the human eye.[32] However, calculations by Duntley show that such sightings are not impossible by an observer at orbital altitudes, if his visual capabilities are like those of the astronauts, and if the atmospheric conditions and target properties are like those assumed for the calculations. As to the vestibular functions, head movements during zero-G had no effect on well-being or orientation ability. A pointing test during flight as well as caloric tests and retinal photography after flight revealed no significant changes from preflight results.

Several interesting observations were made by the Russian cosmonauts. Titov, who reportedly showed a high degree of vestibular stability in pre- and post-flight examinations, experienced short periods of vertigo upon entering weightlessness and periodic attacks of nausea after the fourth orbit. They were aggravated by head movements and the associated visual input. This type of "space sickness" which is thought by Russian scientists to be produced by a "deafferentation" of neural functions, have been described by a number of our test subjects during Keplerian trajectories. The disturbances disappeared upon restoration of accelerative forces.[35] None of these symptoms was reported, however, by any of the other American or Russian space pilots.

Titov's experience, which certainly was of vestibular origin, has led to some speculations about man's tolerance to weightlessness under unrestraint conditions. When released from his restraining devices, Bykovsky made fast movements and floated about the cabin rolling and shaking his head. No unpleasant feelings were noted during this exercise. He reported that orientation in the dark or with eyes closed was rather difficult. Popovich oriented himself in a similar situation by the sound of a fan. It is now concluded that Titov's experience demonstrates the individual differences in vestibular tolerance and that he was a poor choice as a space pilot.[26]

Electroencephalograms were recorded from the last four cosmonauts. Changes in Bykovsky's EEG were rather ambiguous. Alpha and beta rhythms varied substantially; for example, the alpha rhythm index ranged from 35 to 57 per cent during the first to fourth orbit and reached 85 per cent at the 51st orbit. Tereshkova's beta rhythm index decreased while her theta rhythm increased during the weightless state. However, both indexes varied considerably. The alpha index ranged from 25 to 40 per cent during the first two days, then increased up to 70 per cent, and later fell to 38 per cent by the end of the flight. During the first few days after the flight, Tereshkova showed a certain change in the cortical activity expressed in a decrease of the alpha rhythm. In contrast, Bykovsky showed a marked excitation of the alpha rhythm on the first and second day after his return to Earth, but his cortical reactivity determined by the bioelectrical reaction to light stimuli was lowered. The results of examinations 15 days after the flight showed no changes from the pre-flight values.

The analysis of the tracings of Tereshkova's electro-oculograms revealed short-term nystagmoid reactions which occurred at the 38th and 45th orbit. However, there were no concomitant subjective experiences or evidence of vestibular disturbances. By the end of the flight, both astronauts showed a decrease in oculomotor activity. Basic vestibular test results before and after the flight did not differ significantly and indicated a normal tolerance to complex visual and mechanical stimuli.

Respiratory Functions

Respiration rates of the Mercury astronauts have ranged from 20 to 40 breaths per minute at sustainer engine cut-off, from 8 to 20 breaths per minute during weightlessness, and from 20 to 32 breaths at reentry (Fig. 2). There was an inversion of the respiratory rates from the short to the longer flights. Astronaut Shepard maintained a breathing rate at a range from 15 to 20 breaths per minute during count-down. A peak of 40 occurred during launch, and it was 20 near the end of the short weightless period. The average respiration rate of the orbiting astronauts during weightlessness was about 15 breath per minute. Compared to the preflight values, this is a slight decrement, which is in accordance with the measured oxygen consumption of 18 liters per hour and a respiratory quotient of 0.83 for the longest coasting periods. Hence, the mean metabolic rate during the periods of weightlessness equaled that of a non-fasting man under conditions of rest and terrestrial gravity.

The recording technique used by the Russians consisted of two pick-ups which measured (a) the changes of the perimeter of the thorax, and (b) respitation rate. During Gagarin's short orbital flight, his rate of breathing increased from about 24 to 37, then decreased and later fluctuated within this range. In spite of Titov's discomfort at various portions of the flight, his respiration rate was generally lower than Gagarin's. The mean value for the first orbit was about 23, decreasing to about 15 during the 14th orbit, and slowly increasing to about 20 at the end of his flight (Fig. 3). During the first day of the Russian twin flight, a decrement in the number of breaths was observed in both astronauts.[33] Then Nikolayev's values increased somewhat and reached a maximum by the end of the third day, which was followed by a decrease. Popovich's figures showed a different trend: it decreased almost continually during the entire flight. In the second twin flight, the respiration rate was within 12 to 25 breaths per minute for the two astronauts, but no figures on respiratory volume and RQ were available for this review. Studies on breathing and gas exchange in the postflight period revealed a slight increase in minute volume: Bykovsky's rose from 211 to 284 cm^3 and Tereshkova's from 172 to 230 cm^3 per minute. All values were normal two days after the flight.

Cardiovascular Functions

Cardiac activity has been recorded during orbital flights by means of electro-, phono- and kinetocardiography.[1] Electro-cardiograms and blood pressure readings were obtained in Project Mercury.[32] Pulse rates measured during Mercury flights varied from 80 to 100 beats per minute during wakeful periods and from 50 to 60 beats per minute during sleep (Fig. 4). Elevated rates recorded during weightlessness were usually attributed to special inflight activities. The changes noted in the electrocardiogram (ECG) included alterations in the pacemaker activity with wandering pacemakers and aberrant rhythm, such as atrioventricular nodal beats and rhythm, premature atrial and ventricular contractions, sinus bradycardia, atrial rhythm, and variations of R-wave to R-wave intervals, which were unrelated to physical activity and greater than those caused by sinus arrhythmia. Systolic blood pressure increased during weightlessness and fell below normal values during the postflight phase. Diastolic blood pressure data were inconsistent, but pulse pressure was generally high in the weightless state. All of these "abnormalities" were considered normal physiologic responses when related to the dynamic and operational situation in which they were encountered. An unusual high heart rate accompanied by a drastic fall in blood pressure (orthostatic hypotension) was observed after landing. The last two Mercury astronauts felt "light-headed" upon egress from the capsule. Moreover, Schirra's feet were swollen and reddish-purple particularly during standing. These symptoms persisted for several days after the two longest flights.[37]

A detailed survey of the reaction of the cardiovascular system under conditions of weightlessness based primarily on the Russian flight data was given by Bayevskiy and Gażenko.[1] They analyzed the physiological changes observed on several components of the cardiovascular functions.

(a) Pulse Rate. In the early period of weightlessness, the pulse rate of the cosmonauts returned to normal from peak values produced by the preceding launch acceleration. This restoration process generally takes longer than after centrifuge runs on the ground.[36] The mechanism of the delayed adaptation of the circulatory processes under weightlessness is complex and rather difficult to assess. Apparently, the changes of the mechanoreceptoric input increase the excitability of the regulatory centers involved, and this may cause the abnormally long delay observed under low-gravity conditions. After several hours, the pulse rate slowed down below the normal values and from there on showed diurnal variations: it accelerated in the morning and decreased at night. The rates were further reduced during sleep. Moreover, significant changes occurred in the distribution of the time periods of the cardiac cycle. The change in the pulse rate of three cosmonauts in shown in Fig. 5.

(b) Time Characteristics of the ECG. As was the case with the Mercury astronauts, the atrioventricular contraction time of the Russian cosmonauts increased and showed rhythmic variations.(Fig.6) It was shorter in the morning in Bykovsky and Tereshkova, but relatively longer in Nikolayev and Popovich.[1] An analysis of the systolic index, that is the ratio of the duration of the electric systole to the duration of the entire cardiac cycle, revealed changes in different directions: it increased in the morning in Nikolayev, Popovich and Tereshkova, but it decreased in Bykovsky. The amplitude of the T-wave increased in time (Fig. 7).

(c) Cardiovascular Mechanics. The duration of the mechanical systole was determined from phono- and kinetocardiograms. In Titov, the duration of the mechanical systole before launch was 0.35 seconds. It increased to 0.47 seconds during the period from the 7th through the 13th orbit. Kinetographic studies showed that after five hours of weightlessness Titov's electromechanical lag, that is the time from the Q-wave of the ECG to the start of the mechanical systole, increased from 0.03 to 0.05 seconds during the 13th orbit.

The coordination of the contractions of the right and left halves of the heart is an important index of the state of the myocardial function. Normally, this activity is strictly defined in magnitude and time. Even a minor impairment of the existing relations reflects itself in the seismo- and phonocardiogram. Studies on Bykovsky and Tereshkova showed an increase in the duration of both cycles on the second and third day of the flight.

(d) Phase Quality of the Cardiovascular System. There are three distinct phases of the cardiovascular response to zero-G:

1. The pulse rate decreases slowly and fluctuates considerably after transition from the accelerated state into weightlessness. Changes in other characteristics are undefined.

2. There is an apparently incomplete return of the pulse rate to normal associated with an increase in the atrioventricular contraction period. The duration of the electrical systole increases slightly, while the mechanical systole shortens at first and then lengthens. Arterial pressure is persistently low with a brief rise at the end of the 10 to 12 hour period. The first cycle of the kinetocardiogram shortens. According to phonocardiographic data, the intensity of the sounds increases, and there is an appreciable

lengthening of the second sound.

3. There are distinct changes in almost all of the characteristics of the cardiovascular system in the third phase. The pulse rate stabilizes at a somewhat lower level than normal. Atrioventricular contraction time lengthens slightly. There is a distinct diurnal rhythm in atrioventricular contraction, duration of the electric systole, and systolic index.

The results obtained from American and Russian sources indicate that in weightlessness the cardiac activity is reorganized; that is, the time and amplitude correlations of the forces generated in the heart are changed. There is an "unloading" reaction of the heart which seems to be related to the decrease of mechanical stress. The changes in systolic and diastolic blood pressure, pulse rate, and in the mechanical and electrical systoles are closely related to the reduction in the minute volume of the heart. Apparently, the decreased energy consumption in muscular activity under the condition of weightlessness results in fewer demands of the organism on the cardiovascular system.

After return to Earth, the Russian cosmonauts suffered from the decrease in arterial blood pressure as well as in the systolic and minute blood volume. The Russian scientists call this syndrome "cardiovascular deconditioning" and attribute it to weightlessness. The orthostatic tests taken several days after flight revealed the persistence of this syndrome.

General Metabolism, Energy, and Physical Strength

The significance of lack of physical stress and exercise for the maintenance of various metabolic and vegetative functions has been demonstrated in laboratory experiments and in flight. In experiments conducted in zero-G parabolas, the muscle strength of the hand was measured by Yuganov and co-workers.[40] They assumed that the reduction in strength found in almost all cases was caused by a change in the tonic tension of the muscles and by functional changes in the CNS caused by weightlessness. Dynamometric data obtained from Nikolayev and Popovich during orbital flight showed that the strength of the forearm and wrist muscles was lower by 6 to 8 kg for the right hand, and by 4 to 7 kg for the left hand, respectively. In this connection it is interesting to note that the prolonged sustaining of a certain posture and the restricted mobility resulted in an acute need for muscular work. Nikolayev and Popovich conducted more exercise than required by the flight plan. In the words of the cosmonauts, muscular work "removed fatigue, relaxes, lifts the spirits, and cheers the heart."[33]

Calibrated exercise was performed by the Mercury astronauts during the longer flights. A hand-held bungee cord with a 16-pound pull was used through a distance of 6 inches. Glenn exercised by pulling the cord once per second for 30 seconds. As a result, his pulse rate increased from 80 per minute to 124 per minute but returned to 84 within two minutes. The blood pressure was 129/76 before the 129/74 after work. Generally, the responses of the organism to exertion during weightlessness were within the ranges observed under 1 G conditions. Bykovsky's routine included certain isotonic exercises, which did not prevent postflight fatigue, orthostatic hypotension, and stress intolerance for several days. For example, his exercise tolerance decreased by 35 per cent. Both oxygen consumption rates and the tilt-table tests indicated the decreased muscular reserves and corroborate similar effects observed on Schirra and Cooper.

The post-flight weight loss reported for all astronauts is shown in Table 2. It does not seem to be related to the duration of the weightless period. It may reflect the re-distribution of body fluid due to the elimination of the hydrostatic component. This results in a readjustment of body fluid to the weightless condition. Upon return to normal gravity, this effect contributes to the reduced blood volume and may play a part in the observed stress tolerance of the astronauts.

The results of the urine and blood chemistry tests conducted on the Mercury astronauts are shown in Tables 3 through 5. There seems to be a mobilization of the skeletal minerals in Carpenter, but for the other pilots the data are inconsistant, although there are indications of an increased urinary potassium excretion (Table 3). There is also a trace of hypercalcemia (Table 4), and peripheral blood changes, of which the increase in hematocrit and monocytes may be related to weightlessness (Table 5). Enzyme activity data are rather inconclusive. The peripheral blood values including electrolytes reveal that blood calcium was maximal in the immediate postflight period but returned to the preflight levels in less than one day. Such changes are only suggestive because of their low magnitude, and they may have been caused by a variety of factors including dehydration, hyperthermia, loss of weight, immobilization, situational stress, and even laboratory variations. Post-flight hypercalcuria never exceeded preflight variations under both normal and under stress conditions.

The study of certain metabolic indices in the Russian cosmonauts was also made by means of blood and urine analyses at various occasions several days prior to and after the flights.[3] During the prelaunch period, the pilots showed changes in the enzyme activity and blood composition which are typical of physical and emotional stress. The symptoms declined during the rest period.

Post-flight analyses showed an increase in the protein content of the blood and also a slight elevation of the level of the serum mucoids. Moreover, the steroid level in the urine of the cosmonauts increased to the upper normal level, whereas the DNA activity decreased. All the biochemical and metabolic alterations in the state of the organism after flight could be interpreted as a generalized stress response. A survey of some of the peripheral blood data of one American and two Russian astronauts is given in Table 6. This table shows consistent increases in leucocytes, neutrophils, monocytes, and elevated erythrocyte sedimentation rate (ESR). In contrast, thrombocytes and lymphocytes are found in decreasing numbers after the flights. The values were obtained shortly before and two days after the exposure.

The dependence of muscle mass and strength on gravitational and physical stress is also well established. Low gravity states and lack of exercise can cause hypokinesia, that is soft, weak and flabby muscles.[25]

The dependence of muscle mass and strength on gravitational and physical stress is also well established. Low gravity states and lack of exercise can cause hypokinesia, that is soft, weak and flabby muscles.[25] Moreover, the maintenance of normal skeletal metabolism depends on mechanical forces such as those produced by weightbearing and muscle tension. The absence of strain in support of the body coupled with the enforced inactivity of flight may very well result in disuse atrophy of the musculoskeletal system and a lowered metabolic rate. Therefore, nitrogen and mineral balance can be disturbed. If the hypercalcuria is severe, osteoporosis and stone formation in the urinary tract may occur.

Following seven days of water immersion, Graveline and co-workers found a marked decrease in work capacity, subjective weakness, and increased nitrogen excretion in human subjects. There also was an increased mobilization of calcium, phosphor, sulfur, and potassium.[14-16] These experimental findings started a whole series of simulation studies of weightlessness.

A consistent potassium and calcium loss was reported as a result of the longer Mercury flights.[12] Russian data on this subject are scarce. According to the latest reports, Parin seems to be quite concerned about the possibility of physical deconditioning and bone demineralization during longer flights.[26] He now suggests programmed physical exercise as a possible remedy. Yazdovskiy believes that artificial gravity may be the most effective but drastic means for prophylaxis. Extensive experiments and investigations are planned to solve this problem and to protect the astronauts against the harmful effects of long-term weightlessness.

Reentry Stress Tolerance

The adaptations which occur during low gravity states will probably be quite appropriate to these conditions and may not impair the functional integrity of the organism until it returns to the terrestrial or another gravitational environment. In particular, major concern has been voiced about the effect of weightlessness on the physiological tolerance to the high accelerations which occur during the reentry of the spacecraft into the atmosphere of the Earth. From the operational point of view, the principal question is whether to permit low-gravity adaptation of the organism or take measures to prevent it. As to the sensory and psychological functions, a zero-G adjustment appears to be desirable. Physiologically, the adaptation may be a threat. If the recent reports from Russia are correct, the Soviet scientists are alarmed about the difficulties the cosmonauts experienced during readaptation to the terrestrial force field. Potentially irreversible effects of zero-G, which could occur after long-term exposure, may involve syncope or cardiovascular collapse produced by a high acceleration pulse.

In order to estimate the effects of weightlessness on reentry tolerance, the changes in heart rate and respiration rate caused by weightlessness and reentry stress were plotted as a function of the length of the weightless exposure. Figure 8 shows the percentage differences between inflight values and their maxima recorded during reentry. Although the data were not obtained under identical conditions - for instance, the magnitude and duration of the accelerations differ considerably - they show an increase of the vital functions with increasing flight durations of the Mercury astronauts. The correlations are not clearly established for the two functions measured. Only the heart rate increases continually, while this may be due to the fact that the pilot tends to hold his breath under high acceleration stress, whereas he cannot control his heart rate. Both stress functions have not leveled off yet. As long as the final plateau has not been established, the physiological implications warrant serious consideration.

In a similar way, the Russian scientists have tried to determine the effect of reentry stress on the heart rate of their cosmonauts after increasing periods of weightlessness. In Table 7, the mean values of the pulse rates are given for Titov, Nikolayev and Popovich during maximum acceleration associated with launch and reentry. They are compared with the values obtained during the last few minutes of weightlessness, and the percentage differences are contained in the last column of this table. An inspection of the data shows the relationship between the time spent in the weightless condition and the pulse rate: the longer the period of weightlessness, the more pronounced is the increase in pulse rate during the reentry acceleration. Thus, Titov's pulse rate increased by 2 per cent, Nikolayev's by 23 per cent, and Popovich's by 72 per cent. At reentry, Bykovsky's heart rate was given as 160, Tereshkova's 178 beats per minute, amounting to an increase of 150 and 140 per cent over the zero-G values, respectively. Their respiratory rates also reached maximum values. These data supplement our Mercury findings and emphasize the importance of a very careful appraisal of the problem.

Summary

An analysis of the data obtained from manned exposures to low-gravity states shows that certain neurophysiological and physiological functions of the American and Russian space fliers were affected by the zero-G conditions (see Tables 8 - 10). However, it must be pointed out that no changes in their state of health was noted during the inflight periods. There seems to occur a certain adaptation of the major vital functions to the weightless condition, which is generally characterized by a state of reduced metabolism and an associated state of decreased pulmonary and cardiac activity. This adaptation, which may be functionally adequate to the low gravity state, was found to be transient and of different physiological significance for the individuals involved. No essential differences in the tolerance of the zero-G condition seem to exist between astronauts of different sex. It thus seems rather difficult to predict the direction of further functional shifts during flights of longer durations and their effects on the physiology of the weightless man.

The clinical and medical data obtained through postflight examinations showed generalized stress responses of the central nervous system, the cardiovascular system, and the metabolic system. They were such as to be associated with common symptoms of fatigue, emotional and

vascular lability, weight loss, changes in bactericidal properties of the skin, and biochemical or hormonal alterations of blood and urine. So far, these symptoms were transient in nature and could be related to the unavoidable strain produced by the prolonged and demanding flights. Certain symptoms were clearly produced by weightlessness or - at least - seemed to be very closely associated with the duration of exposure to the weightless state. The physiological disturbances observed - in particular, orthostatic hypotension, cardiovascular deconditioning, and demineralization of the body - receded after a few days and later disappeared completely. However, their occurrence after the Mercury and Vostok flights, which were of relatively short durations, and their apparent dependence on the length of the low-gravity period are a matter of grave concern for future long-term mission planning.

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Table 1

METHODS OF RECORDING OF PHYSIOLOGICAL PARAMETERS DURING FLIGHTS OF SOVIET AND AMERICAN SPACESHIPS

ASTRONAUTS	PHYSIOLOGICAL PARAMETERS								
	ECG	PNEUMOGRAM	KINETOCARDIOGRAM	EEG	PGR	EOG	SCG	ARTERIAL BLOOD PRESSURE	BODY TEMPERATURE
J. GLENN	+	+	-	-	-	-	-	+	+
M. S. CARPENTER	+	+	-	-	-	-	-	+	+
W. SHIRRA	+	+	-	-	-	-	-	+	+
G. COOPER	+	+	-	-	-	-	-	+	+
YU. GAGARIN	+	+	-	-	-	-	-	-	-
G. TITOV	+	+	+	-	-	-	-	-	-
A. NIKOLAYEV	+	+	-	+	+	+	-	-	-
P. POPOVICH	+	+	-	+	+	+	-	-	-
V. BYKOVSKY	+	+	-	+	+	+	+	-	-
V. TERESHKOVA	+	+	-	+	+	+	+	-	-

Table 2

CHANGES IN THE WEIGHT OF THE ASTRONAUTS AFTER SPACE FLIGHTS

ASTRONAUT	FLIGHT DURATION	WEIGHT BEFORE FLIGHT (KG)	WEIGHT CHANGE AFTER FLIGHT	
			ABSOLUTE DIFFERENCE (KG)	DECREASE (PERCENT)
YU. GAGARIN	1 HR 48 MIN	69.5	-0.5	0.7
M. S. CARPENTER	4 HR 44 MIN	69.7	-2.7	3.9
J. GLENN	4 HR 56 MIN	77.7	-2.4	3.1
W. SCHIRRA	9 HR 13 MIN		-2.0	
G. TITOV	25 HR 18 MIN	62.6	-1.8	2.6
G. COOPER	34 HR 20 MIN	66.6	-3.5	5.2
P. POPOVICH	70 HR 57 MIN	74.8	-2.1	2.8
V. TERESHKOVA	71 HR	58.0	-1.9	3.3
A. NIKOLAYEV	94 HR 22 MIN	68.0	-1.8	2.6
V. BYKOVSKY	119 HR	66.6	-2.4	3.6

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RESULTS OF URINE TESTS

Table 3

	MR-3	MR-4	MA-6	MA-7	MA-8	MA-9	Remarks
Specific gravity	–	–	–	–	0	0	Inconsistent
Albumin	0	0	0	Trace	0	0	No Change (?)
Glucose	0	0	0	0	0	0	No Change
Ketones	0	0	0	0	0	0	No Change
Bile	0	0	0	0	?	0	No Change
pH	0	–	–	–	–	–	Decrease
Na	+	–	–	+	–	–	Decrease (?)
K	–	–	–	+	+	+**	Increase
Ca	+	?	–	+	–	+	Inconsistent
Cl	–	+	–	+	–	–	Decrease (?)

+ Increase 0 No Change ? No data available
– Decrease ** Based on mean of 3 preflight values

BLOOD CHEMISTRY

Table 4

	MR-3	MR-4	MA-6	MA-7	MA-8	MA-9	Remarks
Na (serum)	0	–	–	–	–	+	Inconsistent
K (serum)	+	–	–	+	+	0	Inconsistent
Ca (serum)	+	?	0	–	+	+	Increase (?)
Cl (serum)	+	–	+	–	+	0	Inconsistent
Proteine (total)	+	–	+	–	0	–	Inconsistent
Albumin (serum)	0	+	0	–	?	?	Inconsistent
Alb/Glob (serum)	+	–	–	–	?	?	Inconsistent
N urea (serum)	–	?	–	?	?	?	Inconclusive
Glucose	?	+	–	?	?	?	Inconsistent
Epinephrine	0	0	0	0	?	?	Inconclusive
Norepinephrine	+	+	?	?	?	?	Inconclusive
P	?	?	?	?	?	+	Inconclusive

+ Increase 0 No Change
– Decrease ? No data

CONSISTENT BIOMEDICAL CHANGES

Table 5

Postflight

Index	MR-3	MR-4	MA-6	MA-7	MA-8	MA-9	Result
White blood cells	+	+	+	+	+	+	Increase
Hemoglobin	+	+	+	+	?	+	Increase
Hematocrit	–	–	+	+	+	+	Increase
Monocytes	–	–	0	+	+	+	Increase
Calcium (serum)	+	?	0	–	+	+	Increase
Isomerase (phosphohexose)	+	+	+	+	–	?	Increase
Body weight	–	–	–	–	–	–	Decrease

Table 6

INDICES OF THE PERIPHERAL BLOOD OF THE ASTRONAUTS BEFORE THE FLIGHT AND DURING THE FIRST TWO DAYS AFTER IT

BLOOD INDEX	G. COOPER		V. BYKOVSKY		V. TERESHKOVA	
	1	2	1	2	1	2
HEMOGLOBIN, g/100 ml	15.0	16.5	14.4	14.6	13.0	12.5
ERYTHROCYTES, thousand/mm^3	4790	4800	5090	5080	4020	4100
THROMBOCYTES, thousand/mm^3	314	230	370	294	249	238
LEUCOCYTES, thousand/mm^3	6.5	9.2	6.3	8.5	7.3	11.6
NEUTROPHILS, %	60	75	55	63	66	71.5
LYMPHOCYTES, %	36	20	37	28	26	18
MONOCYTES, %	3	5	8	8.5	7	10
EOSINOPHILS, %	1	0	0	0.5	1	0.5
ESR, mm/hr	-	-	2	4	5	13

NOTE: COLUMN 1 CONTAINS THE DATA BEFORE THE FLIGHT, COLUMN 2 CONTAINS THOSE AFTER THE FLIGHT.

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Table 7

CHANGE IN THE PULSE RATE OF THE COSMONAUTS DURING THE PERIOD OF THE SHIP'S GOING INTO ORBIT (PERIOD A) COMPARED WITH THE DATA OF AN EXAMINATION BEFORE LAUNCHING (PERIOD BL) AND DURING DESCENT OF THE SHIP (PERIOD C) COMPARED WITH THE RESULTS OF EXAMINATION IN THE LAST FEW MINUTES OF THE STATE OF WEIGHTLESSNESS (PERIOD N-K)

COSMONAUT	PERIOD BL	PERIOD A	INCREASE OF PERIOD A WITH RESPECT TO PERIOD BL		PERIOD N-K	PERIOD C	INCREASE IN PERIOD C WITH RESPECT TO PERIOD N-K	
			ABSOLUTE FIGURE	%			ABSOLUTE FIGURE	%
G. S. TITOV	107	112	5	5	105	107	2	2
A. G. NIKOLAYEV	112	119	7	6	75	92	17	23
P. R. POPOVICH	117	120	3	3	83	143	60	72

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Table 8

METHODS	SHORT-TERM EFFECTS FREE-FALL, FRICTIONLESS DEVICES, KEPLERIAN TRAJECTORY, MERCURY BALLISTIC FLIGHTS	ORBITAL [illegible] PROJECT MERCURY (MA-9) VOSTOK FLIGHTS (V1, V2)	SUBMERSION EFFECTS HEAD-OUT SUBMERSION (HOS) COMPLETE SUBMERSION (CS)	BED-REST EFFECTS NORMAL SUBJECTS
SENSATIONS				
FALLING	INDUCED BY PRIOR G; ABSENT WHEN SURFACE-FREE (K)	NOT EXPERIENCED	—	—
MOTION SICKNESS	RELATED TO G-TRANSITION (K)	ONE SUBJECT (TITOV)	—	—
ORIENTATION	ORIENTATION DECAYS IN DARK AND TACTILE SENSATIONS BECOME IMPORTANT; ANY SURFACE CAN BECOME FLOOR FOR THE INDIVIDUAL	PERCEIVES EARTH OR VEHICLE RELATIVE TO SELF.	OTOLITHIC SENSITIVITY DECREASED IN CERTAIN POSTURES.	—
ILLUSIONS	"OCULOAGRAVIC" ILLUSION OBSERVED (K); NO SIGNIFICANT DIFFERENCE IN SEMI-CIRCULAR CANAL SENSITIVITY AT G COMPARED TO 1 G (OCULOGYRAL ILLUSION) (K)	CHANGE IN APPARENT POSITION OF OBJECTS IN PERIPHERAL VISUAL FIELDS; HEAD MOTION DISORIENTING.	ILLUSIONS RELATED TO SENSORY MONOTONY	—
VISION	SMALL DECREMENT IN VISUAL ACUITY (K).	SIGHTINGS INDICATE IMPORTANCE OF PATTERN VISION; NO APPARENT DECREMENT IN ACUITY, COLOR VISION OR LIGHT SENSITIVITY.	—	—
PERFORMANCE				
MASS DISCRIMINATION	DIFFERENCE THRESHOLD TWICE AS LARGE FOR MASSES AS COMPARED TO WEIGHTS.	—	—	—
MOTOR	BODY RESTRAINT, HAND-HOLDS TETHERS AND ADHESIVE FOOTGEAR REQUIRED FOR EFFECTIVE PERFORMANCE, CLOSED FORCE TOOLS RECOMMENDED; EYE-HAND COORDINATION AND OBJECT POSITIONING SHOWS OVERSHOOTING, SLIGHT DECREMENT IN SWITCH OPERATION; RAPID ADAPTATION TO ALTERED MOTOR REQUIREMENTS	NO OPERATIONAL DECREMENT IN RESTRAINED SUBJECT AS EVIDENCED BY REENTRY PERFORMANCE	VIGILANCE DISCRIMINATIVE REACTION TIME AND COMPLEX TASK PERFORMANCE SHOW SMALL DECREMENTS (HOS); OVERSHOOTING AND APPLIED FORCE CHANGES RELATED TO WATER DISPLACED (CS)	—
SLEEP	DISORIENTATION ON SUDDEN AWAKENING	FREQUENT DOZING; ORIENTED RAPIDLY ON AWAKENING	DIMINISHED REQUIREMENT	—

Table 9

METHODS	SHORT-TERM EFFECTS FREE-FALL, FRICTIONLESS DEVICES, KEPLERIAN TRAJECTORY, MERCURY BALLISTIC FLIGHTS	ORBITAL FLIGHT DATA PROJECT MERCURY (MA-9) VOSTOK FLIGHTS (V1, V2)	SUBMERSION EFFECTS HEAD-OUT SUBMERSION (HOS) COMPLETE SUBMERSIONS (CS)	BED-REST EFFECTS NORMAL SUBJECTS
CARDIOVASCULAR SYSTEM				
RESTING RESPONSES				
PULSE	INFLUENCED BY PRIOR G (K)	NORMAL VALUES AT REST, WORK & SLEEP.		+0.5 BEATS/MIN/DAY.
PRESSURE	INFLUENCED BY PRIOR G; RESTING VALUE DECREASED IN 0 G (K)	NORMAL VALUES AT REST, WORK AND SLEEP		INCREASE
STROKE VOLUME	—	—	—	PROBABLE DECREASE
CARDIAC OUTPUT	—	—	—	NO MAJOR CHANGE
PERIPHERAL RESISTANCE	—	—	—	NO MARKED CHANGE
BLOOD VOLUME	—	—	PLETHORA ELEVATED HEMATOCRIT	-9.3%
TILT-TABLE RESPONSE	ABRUPT DECREASE IN HEART RATE ON TRANSITION TO 0 G (K)	TRANSIENT FAINTNESS DUE TO ORTHOSTASIS ON CAPSULE EGRESS WITH ELEVATED HEART RATE (188); CONFIRMED BY TILT-TABLE TEST POST-FLIGHT	DETERIORATION	DETERIORATION
ACCELERATION TOLERANCE	NO CHANGE	NO APPARENT EFFECT, GOOD PERFORMANCE DURING RE-ENTRY	DECREASED (SMALL BUT SIGNIFICANT)	—
EXERCISE TOLERANCE				
WORK CAPACITY	—	MAINTAINED WORK SUBJECTIVELY EASIER; PULSE RATE RESPONSE SLIGHTLY SLOWER IN RETURN TO NORMAL	DECREASED	DECREASED BUT CAPACITY CAN BE MAINTAINED BY SUPINE EXERCISE
VASOMOTOR ACTIVITY	—	—	—	RESPONSE TO SUPINE EXERCISE INDICATES EFFECTIVE ARTERIAL VASOMOTOR TONE
MECHANICAL EFFECTS				
DEGLUTITION	NO PROBLEM WITH PROPER FOOD CONTAINERS AND TRAINING (K)	NO PROBLEM WITH PROPER FOOD CONTAINERS AND TRAINING	—	—
MICTURITION	NO PROBLEM	NO PROBLEM; BLADDER SENSATION NORMAL	—	—
FREE OBJECTS	DUST, DROPLET AND FOOD CRUMB PROBLEM (K)	DUST, DROPLET AND FOOD CRUMB PROBLEM	—	—

Table 10

METHODS	SHORT-TERM EFFECTS FREE-FALL, FRICTIONLESS DEVICES, KEPLERIAN TRAJECTORY, MERCURY BALLISTIC FLIGHTS	ORBITAL FLIGHT DATA PROJECT MERCURY (MA-9) VOSTOK FLIGHTS (V1, V2)	SUBMERSION EFFECTS HEAD-OUT SUBMERSION (HOS) COMPLETE SUBMERSION (CS)	BED-REST EFFECTS NORMAL SUBJECTS
GENERAL METABOLISM				
METABOLIC RATE	—	LOW-RESIDUE BALANCED DIET PRE-FLIGHT; LOW-CALORIC INTAKE INFLIGHT	DECREASED	DECREASE [illegible]
BODY WEIGHT	—	OBSERVED LOSSES DUE TO LOW-CALORIC INTAKE AND DEHYDRATION (-7 3/4 LBS)	VARIABLE	VARIANT DEPENDING ON CALORIC BALANCE
BODY TEMPERATURE	—	ELEVATED DUE TO THERMAL STRESS	DEPENDS ON WATER TEMPERATURE	NO EFFECT
WATER BALANCE	—	INTAKE>1500 CC; OUTPUT ~950 CC DEHYDRATION WITH ELEVATED HEMATOCRIT.	DIURESIS MARKED WITH HOS	[illegible]
ELECTROLYTE BALANCE	—	POST-FLIGHT NA⁺ AND CL⁻ RETENTION WITH REHYDRATION	NA⁺ [illegible]	[illegible]
MUSCULOSKELETAL SYSTEM				
NITROGEN BALANCE	—	NOT MEASURED	EQUILIBRIUM OR NEGATIVE	[illegible] DEPENDING ON [illegible]
MUSCLE GIRTH & STRENGTH	—	NO CHANGE	LITTLE OR NO CHANGE	[illegible]
CALCIUM EXCRETION	—	NO INCREASED EXCRETION	—	SUSTAINED [illegible] SUPINE [illegible]

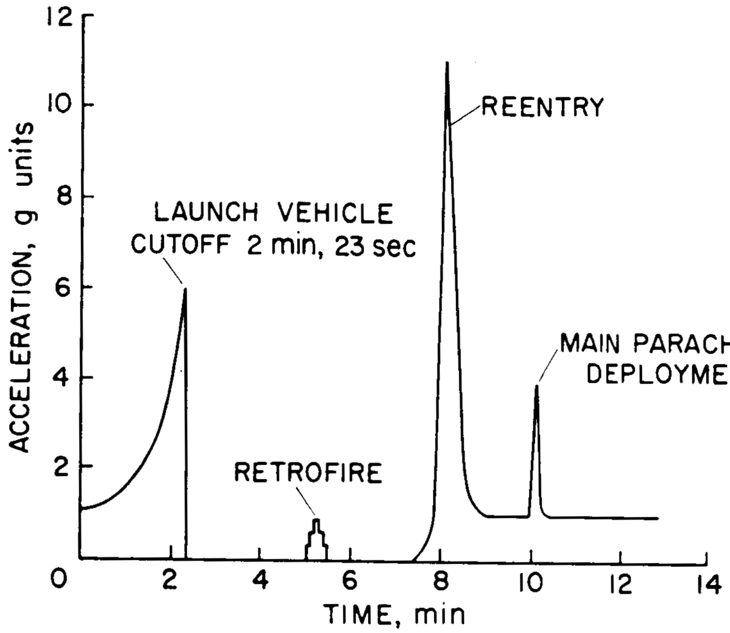
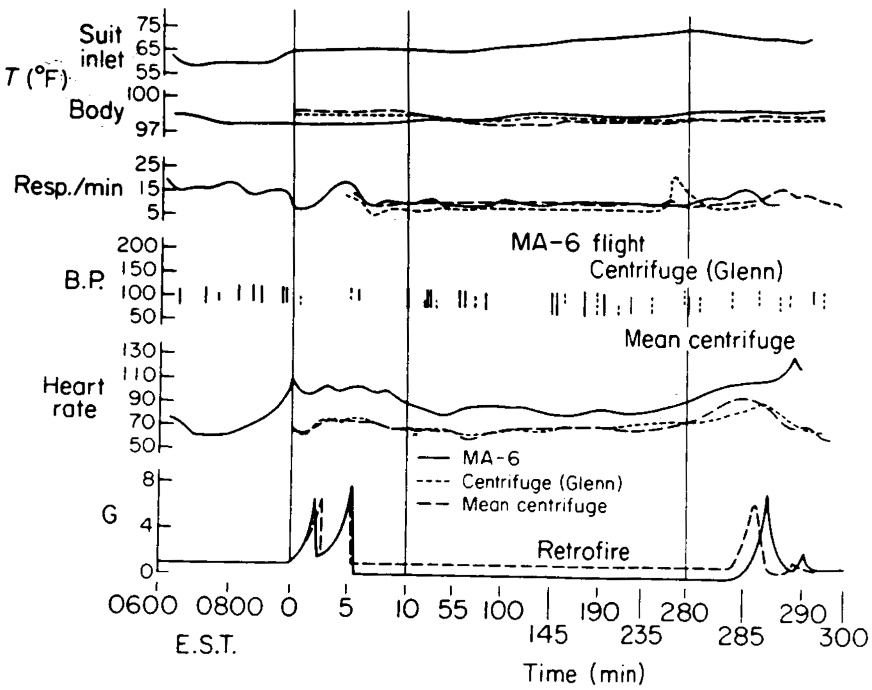


Figure 2



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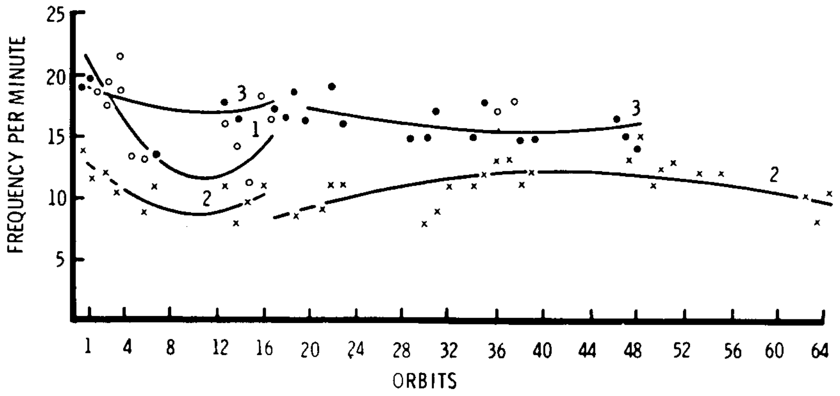
CHANGE IN THE RESPIRATORY RATE UNDER CONDITIONS OF WEIGHTLESSNESS



CHANGE IN THE RESPIRATORY RATE OF G. S. TITOV (1), A. G. NIKOLAYEV (2) AND P. R. POPOVICH (3) UNDER CONDITIONS OF WEIGHTLESSNESS.

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Figure 4

BIOINSTRUMENTATION IN FLIGHT

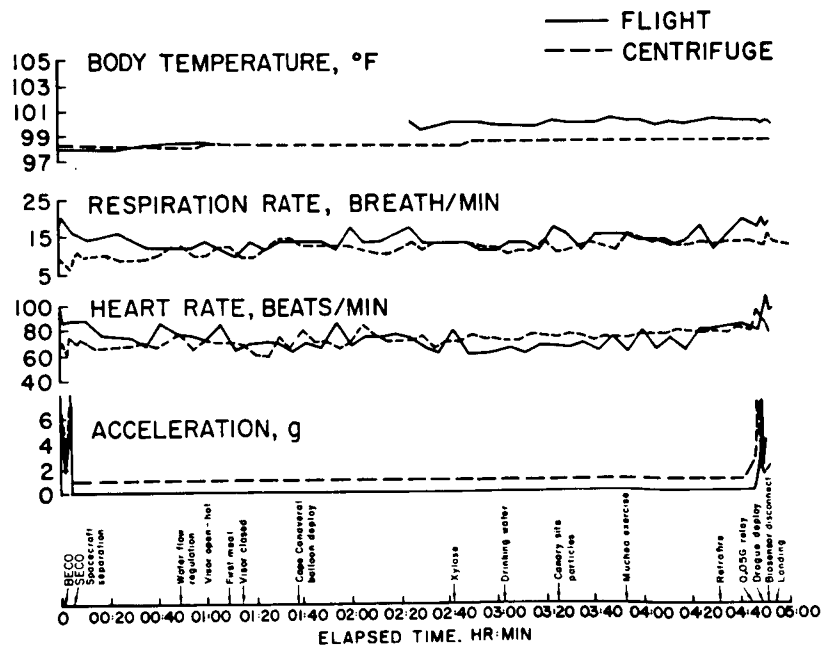

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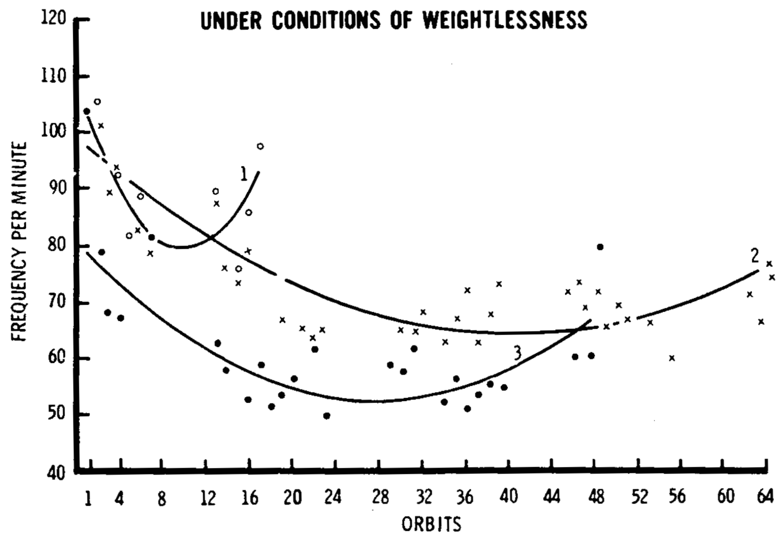
Figure 5

CHANGE IN THE PULSE RATE UNDER CONDITIONS OF WEIGHTLESSNESS



CHANGE IN THE PULSE RATE OF G. S. TITOV (1), A. G. NIKOLAYEV (2) AND P. R. POPOVICH (3) UNDER CONDITIONS OF WEIGHTLESSNESS. THE BLACK DOTS, CIRCLES AND CROSSES ARE THE AVERAGE FIGURES OF THE INDICES STUDIED FOR ONE REVOLUTION IN P. R. POPOVICH, G. S. TITOV, A. G. NILOLAYEV RESPECTIVELY; THE SOLID LINES ARE THE DIRECTION OF THE CHANGES.

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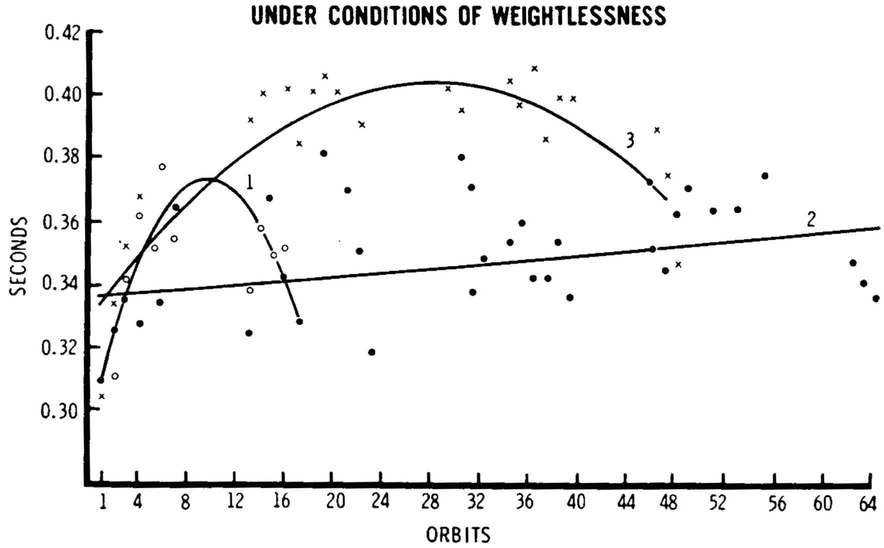
Figure 6

CHANGE IN THE QT INTERVALS ON THE EKG UNDER CONDITIONS OF WEIGHTLESSNESS



CHANGE IN THE QT INTERVALS ON THE EKG IN G. S. TITOV (1), A. G. NIKOLAYEV (2) AND P. R. POPOVICH (3) UNDER CONDITIONS OF WEIGHT-LESSNESS.

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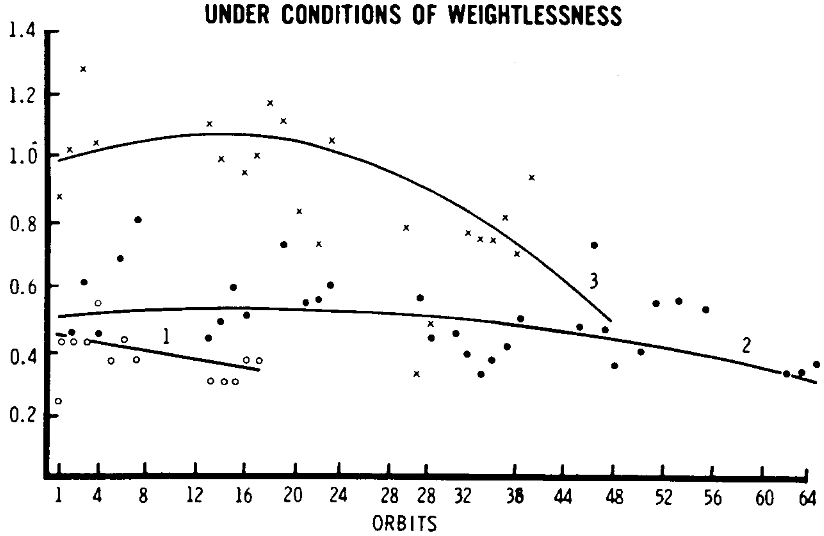
Figure 7

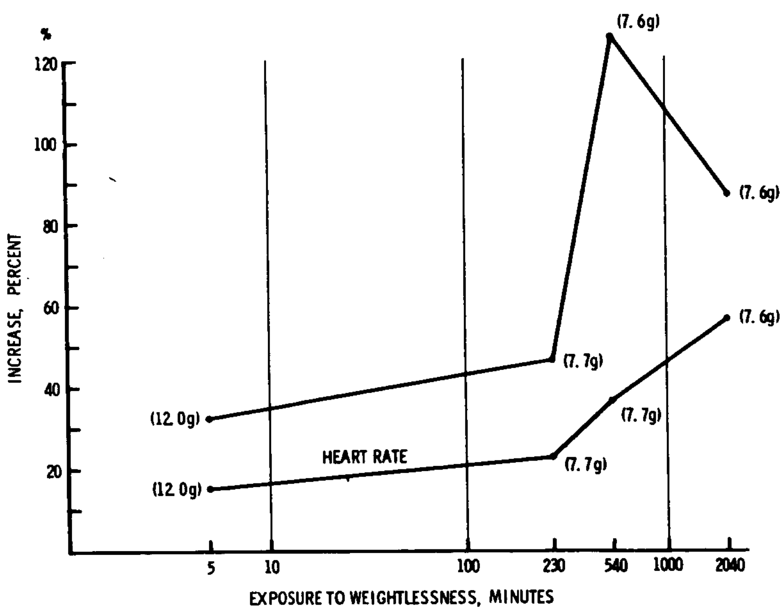
CHANGE IN THE AMPLITUDE OF THE T ON THE EKG UNDER CONDITIONS OF WEIGHTLESSNESS



CHANGE IN THE AMPLITUDE OF THE T ON THE EKG IN G. S. TITOV (1), A. G. NIKOLAYEV (2) AND P. R. POPOVICH (3) UNDER CONDITIONS OF WEIGHTLESSNESS. THE ORDINATE REPRESENTS THE SIZE OF THE WAVE IN RELATIVE FIGURES.

NASA SM64-1661

Figure 8



EFFECT OF REENTRY ACCELERATION ON RESPIRATION AND HEART RATE AFTER INCREASING PERIODS OF WEIGHTLESSNESS

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EFFECTS OF HIGH-GRAVITY ON PHYSIOLOGICAL PERFORMANCE

by

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The primary purpose of this paper is to summarize the effects of high gravity on the physiological and psychological performance capabilities of man, and to review some of the major simulation studies which have concentrated on these aspects. Many studies have been conducted to obtain data regarding the effects of high acceleration environments on the physiological and psychological capabilities of man. Some of these studies have provided highly specific data which pertained directly to manned spacecraft systems under development and test. Others provide more general scientific findings and principles which contribute to the understanding of the physiologic and psychological responses which man makes during exposure to changes in his acceleration environment. This paper concentrates on these particular findings and principles, although some mention is made of simulation studies which have attempted to provide specific information in support of Projects Mercury, Dyna-Soar, Gemini and Apollo. The scope of this paper does not permit coverage of all the different types of acceleration environments; consequently, it is necessary to limit the material primarily to problems involving high sustained linear accelerations, even though the importance of angular and impact accelerations is recognized. The early portion of this paper described the acceleration environments, and some of their effects on the psychophysiological performance of human subjects. Later in the paper recent space flight simulation and astronaut acceleration training programs are summarized. The paper concludes with 17 general principles which describe the effects of high gravity on man, and which evaluate some of the significant problems on which further research is needed.

The physiological description of acceleration used in this paper is described in Chambers (1963) and is illustrated in Figure 1.

PHYSIOLOGICAL TOLERANCE TO ACCELERATION STRESS

Physiological tolerance is one of the most important concepts in acceleration research. It is defined as the physiological ability to sustain, endure, or withstand the acceleration stress. Many different kinds of criteria are used to measure G tolerance. These include EKG abnormalities in rate or wave form, cardiovascular response survival time, chest pain, grayout, blackout, and unconsciousness.

Human tolerance to positive G($+G_z$) is usually indicated in terms of grayout, blackout, or unconsciousness. If the subject is unable to perceive objects in his peripheral field of vision, this peripheral vision loss is called grayout (see Figure 2). If he fails to respond to an illuminated central light, it is called blackout. The next stage in severity is unconsciousness.

For negative G($-G_z$), the criteria are generally: severe visual malfunctions such as extremely blurred vision, excessive pain in the eyes and head, excessive tears, redout, and retinal hemorrhage.

For positive transverse G ($+G_x$), the criteria are not as definite. The symptoms include extreme chest pain, extreme difficulty in breathing, excessive pain, or discomfort in the extremities, extreme fatigue, visual dimming or loss of peripheral vision, excessive blurring or difficulty in focusing, excessive tearing of the eyes, and petechiae on the posterior surface.

For negative transverse G ($-G_x$), the symptoms are usually: extreme pain in the eyes and extremities, visual blurring, tearing, extreme difficulty in focusing and retinal hemorrhage.

During simple tumbling maneuvers when the subject is exposed to a constant steady-state acceleration, all of these symptoms may be shown, since during tumbling the subject continually passes through the $+G_z$, $+G_x$, $-G_z$, and $-G_x$ vectors. There are excellent reviews of the physiological tolerance problem in the scientific literature, and the reader is referred to these for more exhaustive considerations of the tolerance problem (Eiband, 1959; Webb, 1961; Gauer and Zuidema, 1961).

There are many tolerance curves in the published literature which pertain to the results of specific experiments. Figure 3 presents a set of physiological tolerance curves which have been extrapolated from approximately 20 experiments. The figure shows some of the most important relationships for magnitude of acceleration and duration time for positive acceleration ($+G_z$), negative acceleration ($-G_z$), transverse supine acceleration ($+G_x$), and transverse prone acceleration ($-G_x$). The figure represents averages, not necessarily maximum tolerance levels, and shows that the acceleration load which a subject can sustain for any given duration is higher for transverse supine ($+G_x$) acceleration than for the remainder of the acceleration vectors. The primary limiting factor for positive transverse acceleration is respiration difficulties and fatigue. Transverse prone acceleration ($-G_x$) is next, and the primary limiting factors are visual decrement and periorbital pain. Positive longitudinal acceleration ($+G_z$) can be endured at lower level; and the data in this figure assume the presence of a G-suit to assist in maintaining blood flow in the trunk and head areas. Visual decrements (visual grayout and blackout) without necessarily the presence of pain, are the primary limiting factors for this acceleration load. Negative longitudinal acceleration ($-G_z$) can be sustained for only short periods of time, and for only relatively low acceleration levels. Excessive pain in the head and eyes and possible severe cardiac damage may result from negative longitudinal acceleration.

Figure 4 summarizes the results of an experiment in which a group of healthy pilots attempted to sustain relatively high $+G_x$, $-G_x$, and $+G_z$ acceleration vectors for long periods of time using the Ames restraint system, a portable, adjustable type designed for all three vectors (Smedal, et al, 1961). The system was designed to provide the pilot with not only physiological G protection, but also with minimal restriction for performing operations, providing restraints for the arms, feet and head so that these body members could be maintained secure, yet relatively free to move, during exposure to G. The criteria for these runs were: (a) medical, e.g., the medical officer decided that the runs should be terminated because of cardiac or respiratory problems, or (b) the pilot's tracking performance became unsatisfactory, as judged by a performance monitor. The figure presents some unusually outstanding time-tolerance to acceleration centrifuge runs along three different acceleration vectors. This particular figure represents results of prolonged high-G acceleration tests in which experienced pilots served as subjects. They continuously performed piloting tasks in acceleration fields during steady-state G exposures in which performance proficiency as well as physiological tolerance were used as tolerance criteria.

In Figure 5 maximum tolerable acceleration profiles are presented. These are the results of record runs to date.

PRIMARY STIMULUS VARIABLES

G-tolerance may be expressed as a function of at least five primary stimulus acceleration variables, and a complex multidimensional graph would be required to show all of the relationships, even if the complete data were available. These variables are as follows:

(a) The direction of the primary or resultant G force with respect to the axes of the body;

(b) The rate of onset and decline of G;

(c) The magnitude of peak G;

(d) The duration of peak G;

(e) The total duration of acceleration from time of onset to termination.

There are many conditions which influence a human subject's tolerance. Nine of these are as follows:

(a) The types of end points used in determining tolerance;

(b) The types of G-protection devices and body restraints used

(c) The orientation of the body with respect to the direction of force application, and the body posture assumed within the force field;

(d) Environmental conditions, such as temperature, ambient pressure, and lighting;

(e) Age of subject;

(f) Emotional factors, such as fear and anxiety, confidence in self and apparatus, willingness to tolerate discomfort and pain;

(g) Motivational factors, such as competitive attitude, desire to be selected for a particular space project, or specific pay, recognition or rewards;

(h) Previous acceleration training and accumulative effects;

(i) Techniques of breathing, straining, and muscular control.

PERFORMANCE TOLERANCE TO ACCELERATION STRESS

In addition to the physiological tolerance limits which define the end points for reliable functioning for any particular physiological system during exposure to acceleration stress, there are also performance tolerance limits which define the end points for reliable functioning of any particular overt behavior system during acceleration (Chambers and Nelson, 1961). The physiological and performance tolerance limits may be functionally related, but they are not necessarily the same. Performance tolerance limits usually indicate the G amplitude level or time during which a pilot may satisfactorily perform a given task. The specification and development of performance tolerance maps which show impairment as a function of physiological acceleration stress are dependent upon the identification and quantification of performance errors so that the amount of impairment of the particular human ability in question may be indicated.

Under conditions of moderate acceleration, experienced pilots use the motion and acceleration cues in performing their tasks, and these cues, along with reasonably high concentration and motivation, may enable pilots to perform as well under moderately high acceleration as under static (1 G) conditions.

Under conditions of high gravity, however, performance proficiency deteriorates markedly. In the case of transverse acceleration, this deterioration generally reflects impairment of vision, an inability to maintain control of the movements of his muscles sufficiently well to counteract the effects of G on his body members and/or control devices.

Results of one experiment in which endurance time for continuously performing a piloting task are shown in Fig. 6. The figure shows the relative amounts of error during exposures to $+G_x$, $-G_x$, and $+G_z$ accelerations and illustrates that different amounts of error are associated with magnitude of G, as well as direction of G.

Figure 7 shows the results of an experiment in which the amount of performance decrement was studied as a function of the magnitude of transverse G. The figure shows that at 15 G_x, there was a 78% decrement in performance. Decrement was lower for lower acceleration loads. The degree of performance decrement which could be considered as being the performance tolerance limits is somewhat arbitrary in most cases.

RELATIONSHIP BETWEEN PHYSIOLOGICAL TOLERANCE AND PERFORMANCE TOLERANCE

Physiological tolerance limits by necessity define certain performance tolerance boundaries, since the pilot who is not able to sustain acceleration physiologically is unable to continue performing a task. However, the prediction of performance tolerances from physiological tolerances is extremely unreliable. Results of our experiments to date indicate that physiological responses, such as EKG, respiration, and blood pressure, are not necessarily good predictors of pilot performance during acceleration stress. An example of this is shown in Fig. 8, in which physiological and performance measures taken on a subject during high G are compared. In this example, performance impairment appeared suddenly and completely, whereas the physiological decrement was not noticeable from the recordings. Skill decrement usually occurs prior to physiological decrement. Here, for example, in Fig. 8, EKG, pulse, respiration, blood pressure, tracking efficiency, pitch error, heading error, roll control, pitch control, and yaw control were measured. In this particular example, tracking efficiency was calculated in percentage units based on accumulated tracking error divided by the accumulated excursion of the target display which the pilot was monitoring. Pitch and roll control inputs were made with a small pencil controller, and proficiency could range on a percentage scale from 100% to-100%, as derived from the division of the actual control output by the required output. This figure clearly shows that the tracking efficiency took a very sudden and marked drop from nearly 90% to approximately -95% near the end of the run. Very little physiological change is shown except for a slight change in respiration. This record is one of the many instances which have emphasized the predictive value of performance scores for medical monitoring purposes, and it illustrates the detrimental effects of high sustained acceleration on psychomotor skill performance.

It is important to note that in an experiment just completed, a study of 36 pilots exposed to a wide range of acceleration stresses failed to show any definite correlation between oxygen saturation level in the blood and performance decrement.

A description of the physiological events which are associated with acceleration stress is necessary at this time. For the purposes of this paper, the discussion is limited to only two types of acceleration vectors: positive acceleration ($+G_z$) and transverse acceleration ($+G_x$). These events are described in the following two sections.

PHYSIOLOGICAL EFFECTS OF POSITIVE ACCELERATION ($+G_z$)

The physiological effects of acceleration are largely dependent upon the direction of the acceleration with respect to the body. In the $+G_z$ vector, the obvious physiological effects are primarily retinal and cerebral, and mechanisms are due largely to cardiovascular inadequacy.

During acceleration exposures which are of sufficient rate to produce loss of vision, there is an immediate decrease in blood pressure at the head level, a decrease in the amount of blood in the head, an increase in heart rate, a decrease in the amplitude of the arterial pulse at the level of the ear, a failure of peripheral vision, and eventually, a loss of central vision (blackout). For slow rates of acceleration (less than 1G per second), a period of compensation may become effective so that the fall in arterial pressure in the carotid sinuses may result in some recovery of blood pressure and ear pulse, due to the pressor reflexes initiated by the fall in arterial pressure.

In addition to the above effects, pooling of venous blood occurs in the blood and splanchnic region. There is an increase in hydrostatic pressure in the abdomen. The diaphragm also descends. In addition, there is a loss of venous return, which gives rise to a decrease in cardiac output. With rates of onset of about 1 G per second, subjects in the seated position and going to 4 G may expect as much as 25% decrease in cardiac output, 49% decrease in stroke volume, and an increase in heart rate of as much as 56%, a mean aortic pressure increase of as much as 27%, and an increase in vascular resistance of as much as 59%.

Of most interest, perhaps, are the hydrostatic effects on vision, and the effects which manifest themselves at levels below those affecting unconsciousness. The intraocular pressure is approximately 20 mm Hg higher than the intracerebral pressure. Consequently, blood supply to the retina fails before failure of the cerebral circulation. Lambert (1945),using a specially designed pair of suction goggles applied to the eyeballs, found that the application of 30 to 40 mm Hg negative pressure to the eyeball, raises the blackout threshold.

Duane (1954) and others have illustrated that there is a correlation between visual change and change in the fundus oculi. Associated with the subjective loss of peripheral vision is the arteriolar pulsation, i.e., recurrent exsanguination. Associated with the subjective experience of blackout is arteriolar exsanguination and collapse. Associated with the return of central and peripheral vision is the return of arteriolar pulsation and temporary venous distension.

In later work (1963), he observed that where the hydrostatic pressure was such as to cause collapse of the arteriolar vessels during diastole and recovery, in systole a pulsation of the vessels may be observed which is associated with the grayout, or reduction of the visual field to approximately 15° in all meridians. In addition, in those subjects in whom a photic drive of the EEG was observable at rest, loss of photic drive could be demonstrated at grayout levels.

The inner retinal layers are sensitive to hypoxia. It is theorized that the retinal arteriolar ischemia produced hypoxia of these layers. The critical site of hypoxia is believed to be the junction of the ganglion and bipolar cells in the retina.

While the major part of the cerebral hypoxia that ensues under positive acceleration is no doubt due to inadequacy of the blood flow, there is some evidence that prolonged positive acceleration could produce marked arterial hypoxemia. Arterial unsaturation develops during prolonged exposures to positive ($+G_z$) acceleration, despite an accompanying increase in respiratory minute volume. For example, Barr (1963a) found that arterial saturation during a 2-minute exposure to +5 G_z dropped from a mean of 96.2% to 87.4% while the alveolar oxygen tension fell to a mean of 58.0 mm Hg.

Respiration rate and tidal volume increase and vital capacity decreases during exposure to positive acceleration. The decrease in vital capacity is due in part to a limitation in inhalation imposed by downward pressure on the thorax. Overall pulmonary efficiency is lowered. In a study by Barr (1963b), it was found that human subjects exposed to +5 G_z for 1 minute (wearing G-suits), had an initial apnea for a few seconds with onset of acceleration, followed by a marked increase in respiratory rate and volume, persisting throughout the acceleration and for some time after the acceleration ceases. During exposures of +5 G_z for two minutes, expired minute volume increased from 8.6 to 20.8 liters per minute, and effective alveolar ventilation increased from 4.9 to 9.6 liters per minute. Arterial to end-tidal CO_2 difference increased by 8.0 mm Hg and was responsible for the major part of the accompanying decrement in end-tidal CO_2 tension. Oxygen uptake increased from a pre-run value of 269 to 410 ml per minute, whereas CO_2 elimination increased from 216 to 391 ml per minute, resulting in a change in the respiratory exchange ratio from 0.80 to 0.96. He relates the large arterial to end-tidal CO_2 difference to the result of ventilation of an unperfused portion of the lungs, equivalent to one-third of the total number of alveoli.

Electrocardiography has been a major area of positive acceleration research. Pulse rate progressively increases with G. At the lower acceleration levels, pulse rate for non-experienced subjects is higher than that for experienced subjects (Fitzsimons, 1957). This difference disappears at higher levels of G. Fitsimons reports that the rise in pulse rate is produced by stimulation of the carotid sinus brought about by the fall in blood pressure, and also by an adrenal medullary response, brought about by apprehension. This latter aspect is supported by the fact that the increase begins before the onset of acceleration, while the maximum drop in blood pressure is reached several seconds after onset.

Major changes occur in the electrical axis. These appear to be among the primary changes. In addition, there are some S-T segment and some non-specific T-wave changes. They are indicative of cardiac strain and are most likely to occur 10 to 20 seconds before visual disturbance. The P-R interval shortens concomitantly with the pulse rate. Under high positive G stress and high pulse rate (190/min), the P-wave may not be distinguishable from the S-T complex. Sometimes there are bursts of cardiac arrhythmia, bradycardia, marked sinus arrhythmia, extrasystoles, and displacement of the pacemaker. If these conditions persist, or if G increases, unconsciousness from cerebral hypoxia results. Actually, there are two types of unconsciousness which can result. One is associated with hypertension at the heart level, but inadequate tension at the eye level. The other is associated with failure of compensation, hypotension at heart level, and syncope. Convulsions may occur next. Franks, et al (1945)found that convulsions and EEG changes occurred in 52% of 230 subjects and in 40% of 591 tests producing unconsciousness. There were usually slight colonic seizures involving all or some of the extremities, face, and trunk.

PHYSIOLOGICAL EFFECTS OF TRANSVERSE ACCELERATION ($+G_x$)

During exposure to transverse acceleration, the increase in hydrostatic pressure is much less than for positive acceleration because of the shorter distance involved. During transverse acceleration, the limitations are largely respiratory in nature, although during extremely high acceleration, some hydrostatic effects are great enough in the eye and brain to be significant.

During $+G_x$, there is an elevation of the posterior half of the diaphragm, a decrease in the antero-posterior diameter of the thorax, dimunition of lung area, and an increase in radiolucency in the arterior portion of the lung (believed to be due to perfusion). The heart is displaced posteriorly. Also, the trachea is displaced posteriorly.

The respiratory rate increases almost linearly with acceleration. (See Fig. 9) Minute volume increases initially, then levels off at about 8 G. (See Fig. 10) Tidal volume appears to increase initially, but decreases with extremely high G. There is a decrease in expiratory reserve volume and in tidal volume, as well as a decrease in total lung capacity and functional residual capacity. No significant change occurs in residual volume. Vital capacity decreases as G increases, until approximately 12 G, where the vital capacity is essentially the same as tidal volume, thus indication a decrease in pulmonary reserve . If acceleration were to continue to get higher, both vital capacity and tidal volume would approach zero. These factors all point to a marked interference in pulmonary ventilation, and the severity of this interference increases as G increases. So far as the pilot is concerned, much extra work is required to maintain his breathing requirements.

It should be noted that there is also an increase in respiratory frequency, and an increase in heart rate. An example of this is shown in Fig. 11. This appears to be linear to about 12 G, after which the subject tends to hold his breath.

Watson and Cherniak (1962), using positive pressure breathing of 2 1/2 to 3 mm Hg per G, found that a 67% increase in tolerable duration of exposure to 10 G_x transverse G could be produced. This study utilized 100% oxygen, rather than normal breathing air. Oxygen uptake itself has been found to increase duration time.

It is believed that there is an increase in O_2 uptake under transverse acceleration. However, some investigators believe that there is a reduction in O_2 consumption and in increase in CO_2 retention during acceleration in the face of an adequate oxygen supply followed by a large increase in O_2 consumption immediately following acceleration. It may be that the reduction in O_2 consumption may represent dimunition of the arterial oxygen content, due to pulmonary shunting and diminishing peripheral utilization, which results in part from inadequate perfusion of portions of the usually perfused peripheral vascular bed.

There is a decrease in diffusion capacity. Its significance is not clear. Much of it may be due to the development of pulmonary edema, and some results from a decrease in the area of functional alveoli in contact with functional capillaries.

Arterial pressures are increased under G_x acceleration. At 6 G negative pressures can occur in the ventral region which begin to approach the threshold for rupture of pulmonary parenchyma.

Arterial oxygen desaturation occurs under transverse acceleration and diffusion capacity is also reduced. At the Aviation Medical Acceleration Laboratory (Alexander, et al, 1964), it was demonstrated that following an initial rise, probably due to hyperventilation, there is a rapid and almost linear fall to a minimum of about 81% at 10 G_x. (See Fig. 12) This minimum can be maintained for a short while. On cessation of acceleration, there is a rapid climb to about 93% during the first 30 seconds, followed by a prolonged recovery. (See Fig. 13) Even at 6 G, saturation falls to a little over 85%. Using 100% oxygen at 5 psi, saturation was less, and the rate of desaturation is slower. In another study using the AMAL Human Centrifuge, Reed, et al (1964) measured arterial oxygen saturation at 7, 8, 9, and 10 G_x. He found that, using air breathing, a drop of about 3 % in saturation developed in about 10 seconds; after approximately 80 seconds, the saturation was near the 60 to 70% level.

Up to 5 G_x there is little cardiac output change in man. Stroke volume appears to hold constant, at least to 5 G_x pulse rate has been found to vary some, however, and this is essential in the maintenance of cardiac output. In the G_x position, the relative change in heart rate appears to depend upon the position of the carotid baroreceptors in relation to the position of the trunk. This is presumably due to alteration produced by acceleration on the perfusion pressures in the carotid arteries.

Lindberg (1962) observed increases in mean aortic pressure, and in right arterial pressure.

Petechial hemorrhage is also one of the manifestations of hydrostatic effects. There may be some minor changes in P-wave, deviation of the electrical axis to the right, low voltage R & T in the chest leads, and an enlargement of S and Q. These may be interpreted as indicating an increased pulmonary artery pressure with high ventricular and auricular preponderance, resulting from compression of thoracic contents and a shift in the anatomical position of the heart.

G-PROTECTION

In addition to the concepts of physiological and performance G tolerance, an important concept is that of G-protection. There are many kinds of G-protection, including form-fitted contour couches, net couches, G-suits, water suits, a large variety of straps, restraints, bindings, and foams.

The standard type of G-protection for positive ($+G_z$) acceleration is the G-suit (Fig. 14). As G increases, the suit inflates around the legs and torso, and the resulting pressure thereby assists in maintaining the blood in the head region, thus assisting the pilot in maintaining vision and consciousness. Whereas this system is helpful for positive acceleration ($+G_z$), it does not provide protection from transverse accelerations ($+G_x$ and $-G_x$). Transverse supine accelerations have been used in Project Mercury, and they are planned for Project Gemini and Project Apollo, consequently, there is a major interest in protecting pilots against the effects of transverse supine ($+G_x$) accelerations.

The G-protection system which is receiving most intensive study at the present time is the form-fitted contour couch. An example of this couch, as developed through cooperative efforts between the AMAL and the NASA is shown in Fig. 15. This couch was developed for enduring high $+G_x$ acceleration forces. The subject wears a flight suit when in this couch and at his right hand position there is a small stick which is used to respond to peripheral lights during an acceleration exposure. Using this couch, one subject was able to tolerate a 40-second centrifuge run which kept him at a peak of +25 G_x for five seconds.

This particular couch, which was designed for maximum transverse G, is not practical for actual flight operational use. During the past four years, AMAL working closely with NASA, has been instrumental in developing and testing a variety of contour couches which could be used for operational use. A family of these couches in shown in Fig. 16. Each couch is individually molded for a specified person. The one at the far left was developed in cooperation with the NASA High Speed Flight Center at Edwards Air Force Base, California, and was found to be satisfactory for acceleration loads extending to +15 G_x during which time the pilot was required to fly complex two-stage booster-orbital missions. The second couch was a design developed for the Mercury Astronauts and this particular couch for Astronaut Carpenter, permitted acceleration runs to +14 G_x. Some of the astronauts who were fitted to these couches achieved runs to 19 G_x. These couches were developed in cooperation with NASA Langley Research Center.

In the center is a couch developed in cooperation with the NASA Ames Research Center. The primary feature of this couch was the the feet could be freed so as to allow the pilot to use toe pedals. Pilots have successfully used couches of this type to as high as +14 G_x without losing control of relatively complex piloting tasks. The fourth couch represents a model which was developed for permitting the use of the Mercury full-pressure suits. This model of couch was used in most of the centrifuge acceleration training projects for the Mercury Astronauts. These couches were developed in cooperation with NASA Langley Research Center and the McDonnell Company. The last couch, represents the final design used in some of the centrifuge training programs for the Mercury astronauts, showing slight additions of an inner-liner and siightly modified head support. This couch design was used in the early Mercury flights, and has been found effective for tolerating acceleration loads up to 14 G_x without losing control of a relatively complex reentry task. Comparative test data on the major G-protection systems are shown in Fig. 17.

A final approach to the G-protection problem is the use of pharmacological agents. See Figure 18, which summarizes an experiment using this approach.

DYNAMIC FLIGHT SIMULATION

Many of the physiological and performance problems expected to be encountered in flight may be studied by means of simulation techniques. By using centrigues, rocket tracks, and other acceleration devices, it is possible to produce some of the acceleration conditions of real flight. Unconstrained motion with aircraft and spacecraft involves six degrees of freedom which may be conveniently expressed in terms of six components, three of which are linear accelerations and three of which are orthogonal angular accelerations. For any given aircraft or spacecraft, some of these components are more important than others, and the ways in which they are combined determine the complexity of the pilot's acceleration environment. It is possible to express these linear and angular accelerations in terms of the amplitude, direction, rates of onset and decline, duration, and pattern of acceleration components, using the acceleration nomenclature which has been described in Chambers (1963). This permits a comprehensive description of the acceleration environment with respect to the human pilot, and many aspects of the acceleration environment can be simulated on the human centrifuge. Table 1 summarizes the 8 human centrifuges in the United States. There are also 7 others in the world.

A schematic diagram of the AMAL Human Centrifuge and some of its associated computer equipment is shown in Fig. 19. This centrifuge, which has a radius arm of 50 feet, has a 10 by 6 foot oblate spheroid gondola mounted at the end of the arm. The gondola is mounted within the double gimbal system which can continuously position a pilot within the gondola with respect to the direction of any resultant acceleration vector producing radial accelerations up to 40 G. The angular accelerations can reach 10 radians/sec^2 and angular velocities can reach 2.8 radians/sec^2. Given this power capability and the proper control, it is possible to simulate the three linear acceleration components of flight continuously and some of the angular accelerations; however, the angular accelerations of the centrifuge with only three degrees of freedom of control cannot simulate all of the possible flight accelerations.

When the responses of the pilot are included within the driving mechanism of the acceleration device so that the accelerations he receives from moment to moment vary as a function of his behavior, an interesting type of interaction effect occurs, since the pilot's behavior also varies as a function of the acceleration he experiences. A photograph of this device, including a Mercury astronaut in his pressure suit, is shown in Fig. 20. After the astronaut enters the centrifuge, the hatch is closed, and the atmospheric pressure may be regulated in order to simulate some of the environmental conditions which may be encountered during normal and emergency flight.

An astronaut, in his cockpit within the centrifuge gondola, is shown in Fig. 21. (Figure 22 shows a similar view, except the astronaut is wearing a flight suit, rather than a pressure suit, and his head is restrained).

The pilot within the gondola of the centrifuge is provided with an instrument display panel, a control device, and other piloting equipment, as may be required. The pilot operates his control devices in response to information presented on the instrument panel and cues which he receives during the acceleration. The analog computers are used to close the loop between the pilot, his displays, his controls, and the centrifuge accelerations. Thus, the control movements which the pilot makes are converted into electrical signals and fed into the analog computer, which continuously generates the flight problem and provides solutions which result in output signals. Some of the signal outputs are transformed by a coordinate conversion system into appropriate centrifuge control signals which regulate the power voltages to the arm and gimbal system of the gondola. Simultaneously, the other signal outputs are fed to the pilot's instruments.

The pilot-centrifuge-computer system described above consists basically of two closed-loop systems: one connecting the pilot's control responses with the driving system of the centrifuge, and the other connecting the pilot's control responses with the driving mechanisms of the indicators on the pilot's instrument panel. (Hardy, et al, 1959; Chambers and Doerfel, 1959; Chambers, 1962a.)

This procedure has been used in a number of projects, such as the X-15, Mercury, a number of basic research studies, and X-20.

During a typical simulation program on the AMAL centrifuge, there are from 3 to 9 duty stations at which various types of recordings are taken. These recordings include psychological, performance, medical and engineering data. Sometimes, a large analog computer system records performance error as a function of the programmed task and may, if desired, convert the analog scores to integrated error scores or to digital readouts on IBM cards. Another computer system computes means and variability for each run as the run proceeds, thereby providing detailed in-line scoring as each run progresses. In addition, there are several additional data processing systems available for special purpose analysis such as a 14-channel magnetic tape recorder. In-line data recording and data processing is provided by feeding the responses through a small analog computer system which simultaneously yields individual means and standard deviations of the subject's performance on several task components.

If programmed appropriately, the human centrifuge may be used as a dynamic simulation device in which physiology and performance of pilots, and the behavior and effectiveness of cockpit instruments, may be studied and evaluated. If programmed to simulate specific types of aerospace vehicles during definite portions of flight maneuvers, the human centrifuge may serve as a very useful tool for identifying and investigating some of the human factors problems associated with a wide variety of the acceleration aspects of flight. The effects of acceleration on pilot physiology, pilot performance and pilot ability to use specific controls, displays, and escape equipment may be investigated. In addition, if the centrifuge is instrumented with appropriate environmental conditions such as atmospheric pressure, pressure suit, oxygen and other gaseous conditions, and computer control of the behavior of both centrifuge and the panel instrument, the centrifuge serves as a very useful tool for studying the effects of combinations of conditions which a pilot may expect to encounter during any given particular acceleration phase of his flight.

Consequently, the centrifuge may serve as a very effective tool for studying the integrated performance of the pilot and many selected aspects of cockpit, displays, controls, and environmental conditions. The interaction effects may serve as convenient indications of complete man-machine systems performance. Finally, the human centrifuge is an extremely useful training device for acceleration aspects of complex flight missions.

ASTRONAUT TRAINING

The AMAL Human Centrifuge has been found to be a very useful device for astronaut training. Since 1958 it has been one of the major training devices for preparing the Mercury Astronauts for the acceleration phases of their suborbital and orbital space flights. The active Mercury-type instrument panel, Mercury-type side-arm controller, complete environmental control system, and remotely-controlled centrifuge drive system permitted extensive training on a wide variety of piloting tasks and emergency conditions during exposure to the various acceleration profiles for Redstone, Atlas, and abort maneuvers. The instrument panel, shown in Fig. 23 was used in a variety of ways to acquaint the astronaut with instrument malfunctioning, visual perception, changes during acceleration, flight problems, and the operation of his telelights, knobs, and handles. The association of telepanel indicator lights with acceleration levels and capsule events constituted a major training effort, as may be seen in Fig. 24, the acceleration profile and its associated events constituted a complex sequence of events.

During the course of five training programs at this facility, the astronauts received practice in straining in order to maintain good vision and physiological functioning under high G loads, and in developing breathing and speaking techniques during high G launch, reentry, and abort stress. Experience in tumbling and oscillations during relatively high G exposures was also provided. The astronauts were given extensive practice in controlling their simulated vehicles during reentry and other phases of their simulated flights. They became skilled in the operation of their environmental control systems and capsule communication procedures during acceleration exposure. Simultaneously, extensive physiological monitoring and performance provided continuous information on astronaut endurance and piloting skill. Figure 25 shows an example of a typical Redstone acceleration profile during which time the ability of the astronauts to track in pitch and yaw dimensions was monitored. The figure shows that there was very little effect of the acceleration on their tracking skill during these particular runs.

Complete mission simulations were presented during which early morning suiting, psychiatric testing, waiting in the gondola, launch, orbit, reentry, recovery, escape, post-flight testing, and debriefing were provided on a real-time basis. This type of simulation presented physiological and psychological conditioning and man-machine evaluations along real-time scale profiles. An additional advantage of this type of training was that the astronauts were able to experience the many subtle and elusive interactions which occur between the physiological, psychological, and engineering stress variables. Evaluations of the AMAL centrifuge as a training device have been very favorable (Slayton, 1961;

Glenn, 1961, 1962; Shepard, 1961; Grissom, 1961; Voas, 1961a; Carpenter, 1962).

Similar procedures have been used in training astronauts in support of Project Gemini, Project Apollo and Project X-20 (Dynasoar) . Figure 26 summarizes a typical Gemini profile and the associated physiological effects of this on a Gemini astronaut (See Fig. 27) Figure 28 presents an example of the installation within the centrifuge as it was used in testing astronauts on some of the high accelerations which were anticipated during design studies in support of Project Apollo. (See Fig. 29)

A summary of the centrifuge programs which have been conducted on the AMAL centrifuge in support of National space projects since the completion of Project Mercury is presented in Table II. The table suggests that the techniques of centrifuge simulation of space flight in order to study the effects of acceleration, and in order to train astronauts, are being used to obtain acceleration data in all of our National space projects.

Increments in performance proficiency in high G environments occur as a function of practice. Practice results in physiological adaptation and conditioning, as well as learning to make performance compensations for the acceleration disturbances. The pilot improves his performance by: (1) Accommodating to the sensations induced by G; (2) Learning to resist the effects of G through the use of proper straining and breathing techniques; (3) Learning or relearning the task in the context of changed muscular and sensory capacities induced by the acceleration, and (4) Learning to execute the physiological and performance aspects of the task simultaneously.

VISION

Visual disturbances occur during exposure to acceleration stress. During positive acceleration, these disturbances result primarily from ischemia, although some mechanical distortion of the eye may also occur. Generally, a period of grayout occurs before blackout. Grayout is characterized by general dimming and blurring, and total visual loss occurs approximately one G unit above grayout. Some of the major relationships among the amplitude, duration, rate of onset of positive acceleration, time to grayout, and unconsciousness are shown in Figure 30.

When the acceleration is transverse, there is much less visual decrement. At levels between 6 and 12 $+G_x$, there may be some tearing, apparent loss of peripheral vision, and some difficulty in focusing the eyes. For $-G_x$, at these levels, vision may be temporarily impaired, some pain may be experienced, and small petechiae may occur on the lower surface of the eyelids. However, no internal damage has been reported for accelerations as high as $-15\ G_x$. The problem of seeing under transverse accelerations appears to be largely a mechanical problem, due partially to mechanical pressures on the eyes and the accumulation of tears. However, in addition to amplitude and direction of acceleration, G duration is also a major importance. Endurance time to transverse acceleration is largely dependent upon the type of G-protection which is provided to the pilot. Using the AMAL centrifuge, it has been possible to achieve endurance record runs for transverse acceleration of 127 seconds at $+14\ G_x$, and 71 seconds at $-10\ G_x$. These runs were made possible largely because of a G-protection system developed by Smedal, et al (1960) and by the extremely high motivation demonstrated by the pilots who performed these runs. Moreover, the pilots were able to see a complex tracking display well enough to perform satisfactorily throughout these runs.

The pilot's ability to read instruments is influenced by acceleration. As the magnitude of G increases, visual acuity decreases. However, a given level of visual acuity may be maintained by increasing the size of the target or by increasing the amount of luminance. At high luminance, the impariment due to G is not as great as it is for the same G at lower levels of luminance. In most acceleration situations, it is important to know the amount of contrast required by the pilot in order to see at any particular acceleration level, because as acceleration increases, the amount of contrast required also increases.

At a recent study conducted at AMAL in cooperation with the Cornell Aeronautical Laboratories, it was demonstrated that the minimally acceptable (threshold) contrast was greater for positive acceleration than for transverse acceleration. Chambers, Kerr, Augerson, Morway (1962) In this particular experiment, visual brightness discrimination was studied at five levels of transverse acceleration. In this study, the subject in the centrifuge viewed a circular test patch. Each centrifuge test run provided approximately 15 responses, each of which was at peak G for 90 seconds. Using six healthy subjects with 20/20 vision, brightness discrimination thresholds were determined at transverse acceleration levels of 1, 2, 3, 5, and 7 G_x. Determinations were made at each G level with background luminance of .03, .29, 2.9, and 31.2 foot-lamberts. Figure 31 shows the obtained relationships between brightness discrimination threshold and background luminance for each of each of the five levels of transverse acceleration. This figure shows that for each of the five transverse acceleration conditions the visual contrast requirements increased as the background luminance decreased. For any given background luminance level, the higher acceleration levels required more brightness contrast. Figure 32 shows similar data for G_z accelerations.

POSITIVE PRESSURE BREATHING OF 100% O_2

Armstrong (1959) and Watson and Cherniak (1961) have suggested that providing a pilot with positive pressure breathing of 100% oxygen during acceleration stress, especially sustained transverse acceleration, increases endurance time. Watson and Cherniak (1961) have reported a 67% increase in endurance time for subjects exposed to +10 G_x when positive pressure breathing of 100% oxygen was provided. Using the same visual brightness discrimination apparatus as described in the above section, an experiment was conducted to determine whether positive pressure breathing of 100% oxygen would facilitate brightness discrimination during steady-state accelerations. The subjects operated a pressure breathing oxygen regulator manually so as to provide 0.7 inches of mercury per transverse G on the centrifuge. The subjects performed under three breathing conditions: breathing normal air, 100% oxygen, and 100% oxygen under positive pressure. Given a background luminance of .03 foot-lamberts, the subjects were required to repetitively operate a switch to maintain the target at the minimally discriminable brightness contrast level. The results are shown in Fig. 33. The contrast required for discrimination appeared to be the same for both the 100% oxygen and 100% oxygen plus positive pressure breathing. Both of these conditions were superior to the normal breathing air condition. It is interesting to note that as acceleration increased, the percentage of subjects reporting beneficial effects from the positive pressure breathing of 100% oxygen increased, as compared with the other conditions. (The details of this study are reported by Chambers, 1962).

A similar study was conducted on test pilots at much higher acceleration loads, using peak acceleration centrifuge runs of 8, 10 and 12 G's. The pilots were volunteers from the USAF Aerospace Pilot's School at Edwards Air Force Base. The pilots performed a Mercury type reentry task, with the centrifuge at a steady-state acceleration level for two minutes under each breathing condition. The centrifuge installation for this experiment is shown in Figure 34. At +12 G_x, the data showed that performance under conditions of positive pressure breathing of 100% oxygen was superior to normal atmospheric breathing of 100% oxygen. At 6, 8, and 10 G_x, however, no differences were observed. Subjectively, the pilots reported that positive pressure breathing of 100% oxygen was superior to the condition of normal breathing of 100% oxygen in terms of breathing ease and general comfort (Chambers, et al, 1962).

ORIENTATION AND VESTIBULAR FUNCTION

For providing the sensations and perceptions necessary for maintaining continuous position orientation and motion orientation, the human pilot has three primary systems of sensory input: (a) the visual system, (b) the labyrinthine system (vestibular apparatus of the inner ear), and (c) the extralabyrinthine system (peripheral pressure, muscle, and posture senses). All three systems respond to stimuli associated with linear and angular acceleration.

The vestibular (or labyrinthine) system has two distinctly different orientation functions: (a) one concerned with sensing the position of the head, and (b) one concerned with sensing changes in the rate of motion. The former is mediated primarily by the otolith organs, and the latter primarily by the crista ampullares and associated cupula of the semicircular canals.

Unusual head and body movements which are not normally encountered in locomotion provide illusions and disorienting effects. Examples of such movements consist of: (a) prolonged angular acceleration, (b) angular acceleration followed by a constant velocity rather than a deceleration, and (c) stimulation which produces excessive coriolis accelerations in the semicircular canal system.

For sensitivity to linear acceleration, it is theorized that the otoliths respond to the differential pull of gravity upon them. The otoliths within the itricle are primarily responsible for the static position sense. The effective stimulus is the pull of gravity, the sensory cells being differentially stimulated in different positions.

There are a number of illusions which are functions of certain types of acceleration exposures. Illusions may befined as false or incorrect perception of one's position and motion. An example of an illusion was described by Astronaut John Glenn in his Friendship VII Mercury Capsule during his earth-orbital space flight. When the sustainer engine cutoff occurred and acceleration suddenly dropped to zero, he experienced a sensation of being tumbled forward. During prior training on the human centrifuge, Glenn and others had experienced this same sensation of apparent tumbling forward during sudden deceleration. Glenn reported that during the firing of his retro rockets during reentry preparations in his Friendship VII Mercury Capsule, he preceived the false sensation that he was suddenly accelerating in the reverse direction (Glenn, 1962).

There are several categories of illusions which result from angular and linear accelerations. Although these are important in describing and predicting human behavior in some acceleration environments, they are described only briefly in this paper. Among the most interesting are the oculogyral illusions. They have their genesis in stimulation of the sensory receptors in the semicircular canals, and are described as false sensations in which the visual field appears to be moving or spinning around a body axis. There are many varieties of oculogyral illusions, and some of them occur when the semicircular canals are stimulated by the onset or cessation of angular accelerations. Coriolis illusions occur when the head makes secondary rotations about an axis perpendicular to the primary axis of the rotation in which a pilot is being rotated. In a rotating room, for example, the rotation of the room produces an effect attributed to the coriolis accelerations which stimulate the semicircular canals.

Vertigo is a commonly experienced illusion. It is a false sensation of rotation, or whirling around, in which the pilot feels as if the surroundings are revolving about him, or sometimes, as if he were revolving about his surroundings.

The oculogravic illusions are apparent tiltings or displacement movements which result from the stimulation of the otolith apparatus in the utricle of the inner ear. They result from linear, rather than angular, accelerations. During acceleration, a target may appear to be displaced upwards. Conversely, during acceleration, the target may appear to move downwards. On a centrifuge or rocket sled, a pilot may experience a sensation of tilting backwards as he accelerates, and forward as he decelerates. Some evidence suggests that the degree of perceived displacement corresponds to the angle between the resultant force and the normal force of gravity.

Major significance is given to illusions of motion and position, and their role in problems of spatial disorientation for space vehicles and for rotational space platforms is a matter of major controversy, (Chambers, 1963).

DISCRETE MOTOR RESPONSES

In addition to influencing the pilot's ability to perceive stimuli, acceleration modifies his ability to respond to them as well (See Fig. 35). Although it is generally agreed that acceleration influences discrimination reaction time behavior, it has not been possible to identify all of the underlying mechanisms which mediate these effects. (See Fig. 36). During acceleration, the changes observed in reaction time may be associated with pilot impairment in a variety of physical loci. Acceleration might reduce the capacity of the peripheral system to receive the stimulus, or of the central nervous system to process already received stimuli and to indicate discriminatory choice, as well as reduce the ability of the neuromuscular system to coordinate the motor components which translate the response into the manipulation of the appropriate control device. In a series of basic research studies, an attempt was made to measure the effects of steady-state transverse acceleration on discrimination time. A discrimination reaction time test apparatus was developed that consisted of four small stimulus lights, a small response handle containing four small response buttons, and a programmer device which could present a large variety of random sequences to subjects on the centrifuge (Chambers, Morway, et al, 1961). As each of the lights came on, the subjects was required to press the associated finger button with his right hand as fast as he could. Both the automatic program which activated the stimulus lights and the subject's responses were fed to an analog computer where initial data reduction was accomplished. Following pre-acceleration training to establish a stable baseline performance level, each subject received three blocks of 25 trials each while exposed to +6 G_x for five minutes. Each subject received three such acceleration trials. Since speed and accuracy were both involved in this type of response behavior, times and errors were normalized and added. The results are shown in Fig. 37, in which a highly significant effect of the acceleration on performance was demonstrated. Further, the effect persisted to the post-test period. Recent experiments have suggested that the oxygen saturation level of the blood continues to be low during this period.

Using an auditory task rather than a visual stimulus in order to avoid the problem of visual interference which accompanies acceleration, it has been possible to obtain data on auditory reaction time at grayout levels. One such task (Cope and Jensen, 1961) required the subject to add pairs of numbers which he heard via an auditory magnetic tape system and then to describe the sum by pressing the small odd and even response buttons which were mounted upon his left and right hand grips, respectively. Research with this apparatus during positive acceleration exposures to grayout levels indicated that the time required to make these responses increased during exposure to positive acceleration.

CONTINUOUS PSYCHOMOTOR RESPONSES: TRACKING BEHAVIOR

Studies of tracking performance during staging acceleration profiles, such as may be characteristic of certain two-stage and four-stage launch vehicles, have suggested that at the higher acceleration levels, pilots find it extremely difficult to concentrate on all aspects of a complex task while they are exposed to high acceleration loads, whereas at the lower acceleration levels they can perform very well. Figure 38 presents examples of this condition, in which pilots performed exactly the same tasks statically and dynamically for each of two types of booster combinations. The pilot's task was to perform the four aspects of the task continuously so as to fly the vehicle through the orbital injection "window". For both types of vehicles, it was found that the pilots made significantly more errors on the yaw quantity during dynamic conditions than during static conditions, but that they were able to maintain the other three task components very well under both dynamic and static conditions. In this particular study, the accelerations did not exceed 7 G_x for either type of vehicle.

It is interesting to compare the performance of a single astronaut who performs the same task on the centrifuge both statically and dynamically.

Figures 39 and 40 present such a comparison. The most marked difference is noted between the static and dynamic condition during which times the astronaut was performing the reentry task. Some impairment of performance is shown, and this is attributed to the acceleration.

During reentry simulations of the Atlas vehicle on the human centrifuge inadvertent control inputs are not uncommon. These inadvertent inputs often mirror the acceleration profile under which a control task is being performed. Figure 41 shows an actual record of this, illustrating inadvertent control inputs in the roll and yaw axes, using a Mercury-type controller.

In addition to inadvertent inputs which accompany accelerations, other more general effects of dynamic conditions may be observed. In general, acceleration reduces the sensitivity and timing of all controller movements. Examples of this for runs at 12 G_x are shown in Fig. 42. Impairment in tracking throughout a 16.5 G_x acceleration profile is shown in Fig. 43.

HIGHER MENTAL FUNCTIONING

It is generally accepted that exposure to high or prolonged acceleration may produce confusion, unconsciousness, disorientation, memory lapses, loss of control of voluntary movements, or prolonged vertigo. However, to date, there is very little quantitative data regarding the effects of acceleration on specific intellectual functions. At AMAL, emphasis in this area has been concentrated on immediate memory, since an astronaut or scientific observer during some phases of flight may be required to perform such tasks as monitoring, reporting, memory, and processing of information, all of which require immediate storage or memory of information.

In cooperation with Rutgers University, we developed a continuous memory testing apparatus which could be used on the AMAL centrifuge. It required the continuous and repetitive memorization of a portion of a sequency of random symbols. As each symbol occurred, the subject was required to compare it with his memory of the symbol that had been presented to him two, three, or four presentations previously. (See Fig. 44). New symbols appeared continuously, so that the subject constantly had to forget earlier symbols as he added new ones. Approximately 50 symbols were presented for each of the runs. In the earlier study, each run stayed at +5 G_x for five minutes. The data, collected on 21 subjects, indicated that the subjects could continue to perform this task just as well during exposure to +5 G as they could statically. However, subjectively, the subjects reported that their performance deteriorated under G and that they generally regarded +5 G_x for five minutes as a stressful experience. It was interesting to note, however, that subjects tested in the centrifuge gondola did more poorly than subjects tested in a regular testing room. The implication seems to be that some apprehension or anxiety may have been acting to interfere with maximum performance. The results of this experiment are shown in Fig. 45.

In a more recent study conducted on the AMAL centrifuge, we developed a task which required the subject to monitor two small display tubes which were located directly in front of his normal line of vision. The left-side tube presented numbers, and the right-side tube presented plus and minus symbols. The task was to continuously make matches for these two presentations simultaneously as the runs proceeded and to select one of two buttons to indicate whether both the number and symbol which were then appearing were the same as or different from those which had occurred on a specified number of trials previously. Acceleration loads of 1, 3, 5, 7, and 9 G's were studied. Each test was 2 minutes and 18 seconds long. The results of the experiment suggested that proficiency in immediate memory was maintained at least through 5 transverse G. However, at +7 and +9 G_x, some impairment of immediate memory was observed. The results of this experiment are shown in Fig. 46.

During prolonged exposure to acceleration, the continuous concentration necessary for performance is difficult, fatiguing and boring. For example, during an extended 2 G centrifuge run which lasted 24 hours, the subject started out with a somewhat detailed set of procedures to follow in making medical observations upon himself, recording his subjective comments, and writing and typing (Clark and Hardy, 1959). However, the subject found that, in spite of his initial high resolves, he took naps and listened to the radio and suffered primarily from boredom and fatigue. Areas of contact with the chair in which he was seated were the sources of the greatest localized discomfort. At 16 hours elapsed time, the subject reported the onset of aesthenia of the ring and little finger and outer edge of the palm of the left hand. The subject found it impossible to maintain his originally prescribed maintenance and observation schedules.

Chambers and Ross secured a subject in a Mercury-type contour couch and required him to perform the two symbol running matching memory task (previously described) every 10 minutes for four and one-half hours. The subject was able to perform this task throughout the entire period with only minor performance impairment. The results of this experiment are shown in Fig. 47.

EMOTIONAL BEHAVIOR

It is a common observation that both the anticipation and occurrence of acceleration forces contribute to anxiety and other types of emotional behavior. As far back as 1946, Hallenbeck, Wood, Lambert, and Allen found that pulse rates were approximately 10 beats faster per minute during the interval just prior to G than during the G itself. The increase in preacceleration pulse rate is a psychological effect. Brown, Ellis, Webb, and Gray (1957) have demonstrated that during a series of centrifuge runs going as high as 12 G_x the pulse rates of the subjects immediately prior to exposure to the acceleration were faster than during the acceleration run itself. This increase in pre-acceleration pulse rate was highly significant for all subjects. In the case of subjects who had had some prior experience on the centrifuge, the pulse rate varied according to the G-level which was anticipated. (One of the most consistent effects of acceleration itself is an increase in pulse rate, and there seems to be some suggestion that the increment may have been due to cardiac conditioning rather than to anxiety.)

Laboratory experience indicates that naive subjects undergo significant changes in pulse rate, blood pressure, and GSR in anticipation of the start of high G exposure. However, these changes become minimized following repeated exposures to acceleration. The question has been raised concerning the effects of high acceleration on the galvanic skin response, a measure that is frequently used as an indicator of emotional behavior. Figure 48 shows the results of one experiment in which GSR was measured from the soles of the feet during exposure to 12 G_x. The figure shows extremely unusual GSR recordings, during the period of exposure to peak G, and for several seconds following return to the original 1 G conditions. These oscillations in the GSR response suggest that some kind of emotional behavior may have been occurring during these portions of these runs.

In most instances, it is not possible to make quantitative measures of emotional behavior immediately before, during, or after these centrifuge exposures, because of the extensive number of other engineering and physiological tests which are required, and also because there are no good quantitative measures of emotionality which may be used on the centrifuge. However, variables other than the acceleration are items of major concern. Pressure points, muscle cramps and pains due to the pilot's restraint system, uncomfortable temperature, failure of the urinary bag, discomfort due to the biomedical sensors or special flight gear, and long-term delay in planning testing due to equipment malfunction, have created extremely aggravating and sometimes emotionally disturbing conditions. However, all available data seem to indicate that nearly all of the emotional aspects are highly susceptible to training and experience. It appears that the well-trained subject is capable of compensating for and overcoming many psychological problems which he may encounter before, during or following high-g acceleration exposures.

CHARACTERISTICS OF PERFORMANCE DECREMENT AND ERROR

During the hundreds of acceleration tests conducted on astronauts, test pilots and other volunteer subjects, rather specific characteristics of piloting performance impairment have been observed under high transverse G conditions. These are as follows:

a. Increase in error amplitude as G duration and amplitude increase

b. Lapses, or increasing unevenness and irregularity of performing the task.

c. Performance oscillations.

d. Falling off or reduction in proficiency on some parts of a task while maintaining proficiency on other parts.

e. Changes in phasing and/or timing task components.

f. Inadvertent control inputs.

g. Failure to detect and respond to changes in the stimulus field.

h. Errors in retrieving, integrating, storing and processing information.

i. Changes in the rate of performance, such as sudden initiation of performance non-essential to the task.

j. Response lags and errors in timing. Increases in latency of response to discrimination stimuli. Also, there may be large changes in timing of component response sequences, or gross misjudgments of the passage of time.

k. Overcontrolling or undercontrolling, as during a transition phase.

l. Omission of portions of simple tasks, or of parts of complex perceptual motor tasks. These occur especially during overload when the subject may not process all of the stimulus information, such as the inputs necessary to perform the secondary parts of the task at the originally achieved level of proficiency.

m. Approximations. The pilot's behavior becomes less accurate, although the task does not increase in difficulty level. His responses become less precise, but minimally adequate to meet the required criterion of proficiency.

n. Stereotyping of responses and movements, regardless of the stimulus situation. All of the stimuli appear to have an apparent equivalence to the subject during prolonged stress, for example. Figure 49 shows a good example of this type of response at 15 G.

CONCLUSIONS

Seventeen general conclusions may be reported regarding the psychophysiological aspects of acceleration stress. These may be stated as follows:

1. Physiological tolerance. Physiological tolerance, or the ability to withstand physiologically any acceleration stress, is a function of many variables.

2. Performance tolerance. In addition to physiological tolerance limits which define the end points for reliable functioning of any particular physiological system during exposure to acceleration stress, there are also performance tolerance limits which define the end points for reliable functioning of any particular performance ability system under these same conditions of acceleration. The physiological and performance tolerance may be functionally related, but need not be the same, since both are dependent upon the criteria which are accepted.

3. Relationship between performance and physiological tolerances. Physiological tolerance limits define certain performance tolerance boundaries. However, within these boundaries, the prediction of performance tolerances from physiological tolerances is extremely unreliable. Results of our experiments indicate that within these boundaries, the relationship between performance and physiological responses is small.

4. G-protection. The type of G-protection used has a very important influence on the pilot's ability to tolerate acceleration, perform tasks, and maintain proficiency during acceleration stress.

5. For an acceleration of given rate of onset and magnitude, physiological tolerance is highest for G_x, next for $-G_x$, next for G_z, and lowest for $-G_z$, directions of force.

6. Visual Decrement. Acceleration significantly influences the ability to see. During the occurrence of all types of high acceleration, the human pilot experiences visual disturbances. These disturbances result from shifts in the availability of arterial blood to the retina; mechanical pressure on the eyes, such as "eye-balls-in"; "eye-balls-out", "eye-balls-up", and "eye-balls-down" or mechanical forces acting on the eye musculature, eyelids and associated structures; distortions of the eye anatomy; and accumulation of tears.

7. Individual Differences. Major individual differences exist among human subjects in their ability to sustain acceleration stress at high G.

8. Acceleration Training and Practice Effects. Major increments occur as a function of practice. Practice results in physiological adaptation and conditioning, as well as learning to make compensations for the acceleration disturbances. Ability to perform improves by (a) accommodating to the sensations induced by G, (b) learning to resist the effects

of G through proper straining and breathing techniques, (c) learning the task in the context of changed muscular and sensory capacities induced by the acceleration, and (d) learning to execute the physiological and performance aspects simultaneously.

9. Illusions of motion and position. Certain types of acceleration exposures produce illusions, or false perceptions, of one's position and motion.

10. Control Devices. The nature of the control device which is used in performing a task under G has a significant effect upon performance.

11. Feedback Sensitivity. Acceleration impairs the ability of the pilot to sense changes in control characteristics which may occur as a function of specific acceleration vectors. There may be direct results of the acceleration forces on the receptors; there may be an effect on the central or autonomic nervous system; or there may be an effect on circulatory and other physiological systems which indirectly affect the ability of the subject to sense changes in his hand and/or fingers.

12. Task difficulty. Changes in task characteristics which have little effect upon static performance may seriously impair performance under high G.

13. Higher Mental Functions. Intellectual skills, pilot concentration, time judgment, time perception, prediction, and immediate memory, are influenced by G.

14. Emotional Processes, Fear, and Anxiety. Anticipation of the effects of acceleration may produce emotional reactions, fear, and anxiety, which are sometimes greater than the direct effects of acceleration themselves.

15. Effects of combined stresses. Significant effects of acceleration occur as a function of combined stresses, even though, taken independently, each stress may not produce the effect.

16. Characteristics of Performance decrement and Error. During the hundreds of acceleration tests conducted on astronauts, test pilots, and volunteers, rather specific characteristics of piloting performance impairment have been observed under high transverse G conditions.

17. Combined Stresses. If, in addition to acceleration stress, the astronaut is exposed to other environmental stresses, his responses may result from the combined effects of these stresses and/or the interactions among them.

TABLE I

CENTRIFUGES IN THE UNITED STATES AVAILABLE FOR HUMAN TESTING IN 1964[1]

	AMAL, NADC Johnsville, Pennsylvania	AML, WPAFB Dayton, Ohio	ARC, NASA Moffett Field, Calif. (5 Degrees of Motion Simulator)	Grumman Engr. Co. Bethpage, N.Y.	Mayo Clinic Rochester, Minnesota	SAM, USAF Brooks AFB, Texas	SAM, USN Pensacola, Florida	Univ. of Southern California Los Angeles, California
Arm								
Length, pilot to hub	50 ft [a, d]	*19 ft [a]	30 ft [a]	20 ft [a]	14.5 ft [b]	70 ft [a]	20 ft [a]	24 ft [b]
Main Drive								
Type (AC/DC or engine)	DC motor direct coupled	*3 DC motors plus flywheel	DC motor	Hydraulic system	AC motor	DC motor, hydraulic drive	Internal combustion engine	DC motor and flywheel
Rated speed (rpm) of gondola	60.5 rpm *(110 rpm) [d]	*55 rpm (approx.)	24.3 rpm	60 rpm	60 rpm	90 rpm	60 rpm	60 rpm
Radial g								
Maximum g	40 *(100)[d]	*20 (85 g spike)	6	40	15	50	15	15
Onset rate (g/sec)	10 g/sec, 1.5g to 15g 5 g/sec, 15g to 40g	*10-12 g/sec at 2g base	2 g/sec from 2 g to 6 g	1.25 g/sec	3 g/sec	1 g/sec to 10g 3 g/sec 10-50g	1.5 g/sec	5 g/sec
Rate of decline (g/sec)	10 g/sec, 15g to 1.5g 5 g/sec, 40g to 15g	*10-12 g/sec	2 g/sec from 2 g to 6 g	3.0 g/sec	3 g/sec	Variable	1.5 g/sec	5 g/sec
Gondola								
Shape	Oblate spheroid *(sphere)	*Sphere	Cylindrical, cone-shaped ends	Platform	Rectangular	Modified "tip tank" shape	Custom constructed	Circular cab
Size	10 ft x 6 ft *(10 ft dia)	*10 ft	Cyl. 5.5 ft dia, 5 ft long Cones 10" high	--	6 x 3 x 4 ft	6 ft dia, 9 ft long	Custom constructed	6 ft dia, 8 ft high
Gondola interchangeability	No *(yes)	*Yes	Yes	No	No	Yes [f]	Yes	No
Crew capacity	1 *(2-3)	*1-2	1 (2 with severe restrictions)	1	2	1	1	3
Auxiliary cradles	Yes	*No	No	No	Yes	No	No	No
Payload								
Lb in gondola at peak g	100 lb *(1000 lb) (5000 lb)[d]	*500 lb at 20 g	500 lb	2,000 lb	500 lb	30,000 lb	450 lb	2,000 lb
Degrees of Freedom	3 *(3 with prov. for 4)	*6 (including vibration)	5	1	2	1	1	1
Gimbals	2-limited roll *(2-prov. for 3-full rotation)	*2	3	None	1	None	None	3
Mode of Control								
Manual	Yes	*Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cams	Yes	*No	No	No	No	No	No	No
Punched tape	Yes	*Yes	No	No	No	No	No	No
Computer	Yes	*Yes (digital)	Yes	No	Yes	No	No	No
Mode of Braking								
Electrical	Yes [c]	*Yes	Yes	No	Yes	No	No	No
Friction	Yes	*Yes	Yes	No [g]	No	Yes [g]	Yes	Yes
Closed Loop Operation								
Centrifuge	Yes	*No	Yes	No	Yes	No	No	No *(planned)
Instrument panel	Yes	*Yes	Yes*	Yes	Yes	No	No	Yes
Gondola Environment e								
Pressure altitude (max ft)	60,000 *(100,000)	*40,000	ambient	None	ambient	None	ambient	None
Temperature range	*(-50 F to +160 F)	*40-110 F	ventilation only	None	ambient	None	ambient	None
Humidity range (% R.H.)	ambient	*10-90% R.H.	ambient	None	ambient	None	ambient	None
Env. control during rotation	*(Proposed)	*Yes	No	No	No	No	chamber air conditioned	No
Vibration Capability								
Frequency range (cps)	*(Proposed)	*1-15 cps to 9" ampl. or 15 g	No	None*	No	None	None	Under construction
Amplitude range (inches)	*(Proposed)	*±12"(Z-axis); ±3-4"(X and Y)	No	None*	No	None	None	Under construction
Slip Rings	70 *(104 +124 to gondola, 144 to hub)	*625	30 physiological; 150 instrumentation and project	50	60 two-lead channels	200	72	100
Visual Displays	*(Proposed)	*Yes	No	None*	No	None	Yes	No
Present/Future Training or Research	Basic research in physiology. Space flight simulation and astronaut training. Shoulder harness, restraint systems, anti-g suits. Controls and displays.	*Tolerance and performance studies with regard to interaction of environmental variables, and hardware and testing.	Basic research in physiology and psychology. Space flight simulation.	Disorientation and flight simulation. Equipment testing.	Cardiopulmonary effects of acceleration.	25% training and indoctrination, 25% clinical evaluation, 50% human and animal experiments on tolerance, etc.	Effects of continuous slow rotation and vestibular disorientation.	Sensitivity of carotid sinus mechanism and effect of acceleration on blood lymph circulation and fluid balance in extremities. Also performance studies.

* Approved or under construction.
a Single-ended
b Double-ended
c Regenerative
d 22-ft arm (section removable)
e Part of payload
f Second gondola not available
g Hydraulic pressure

1 Other facilities planned or under construction to be operational after 1964:
Ames Research Center, NASA, Moffett Field, California - Man-carrying motion generator.
Manned Spacecraft Center, NASA, Houston 1, Texas
Goddard Space Flight Center, NASA, Greenbelt, Maryland
Minneapolis Honeywell Regulator Company, Minneapolis, Minnesota

TABLE II

Summary of Centrifuge Programs Conducted on the AMAL Centrifuge in Support of National Space Projects Since Project Mercury

Centrifuge Program	Dyna-Soar	Military Astronaut Training Program II	Military Astronaut Training Program III	Gemini Phase I	NASA Basic Physiological Study	Military Astronaut Training Program IV	Apollo Phase I
Centrifuge Operational Dates	11 June 7 Sept'62	1 Dec 19 Dec'62	26 Feb 6 Mar'63	29 June 1 Aug'63	1 Aug 2 Oct'63	26 Aug 30 Sept 30 Aug 4 Oct	23 Oct 6 Dec'63
Coordinating Agency	USAF SPO	EAFB HSTPS	EAFB HSTPS	NASA MSC	MSC, Crew Systems Div.	EAFB HSTPS	NASA APO-MSC
Unmanned Dynamic Runs	47	193	91	54		10	54
Manned Static Astro. & Pilot	202	31	31	121	94	60	115
Manned Dynamic Astro. & Pilot	141	102	137	162	219	77	169
Total Dyn.& Stat.	343	133	168	276	313	137	284
Number of Astro. & Pilot	11	12	12	16	27	16	6
Manned Static Other	250 Approx.	32	0	17	0	0	20
Manned Dynamic Other	45	78	5	19	0	0	46
Total Dynamic & Stat.	45	110	5	36	0	0	66
Number of Other	4	10	1	6	0	0	7
Total All Subj.	15	22	13	22	27	16	13
All Dyn. - Stat. Runs	638 Approx.	243	173	312	313	137	350

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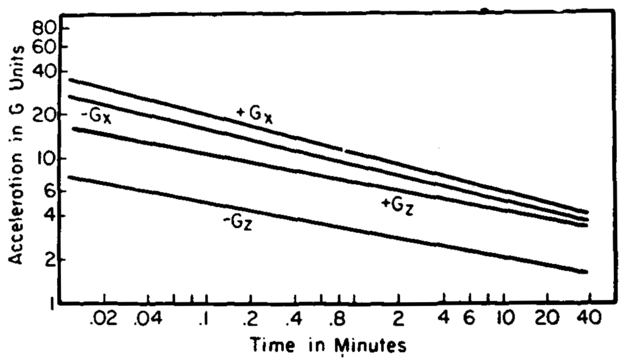

Figure 3: Average acceleration tolerances for transverse supine acceleration ($+G_x$), transverse prone acceleration ($-G_x$), positive acceleration ($+G_z$), and negative acceleration ($-G_z$).

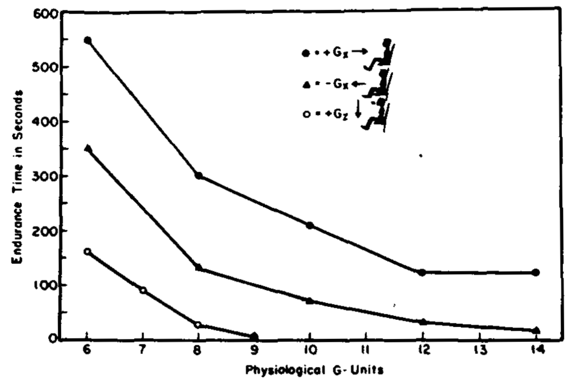

Figure 4: Endurance time in seconds vs. physiological G units for a group of highly motivated pilots.

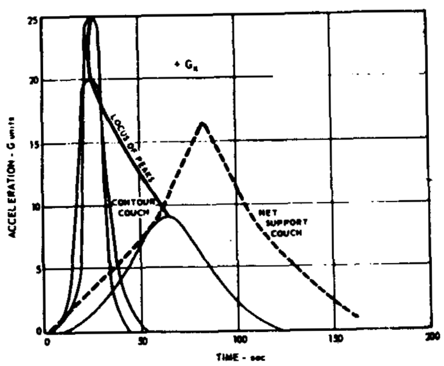

Figure 5: Maximum tolerable acceleration profiles. The figure shows the greatest acceleration time histories that have been tolerated on centrifuges, using both special acceleration protection devices and positioning. The solid lines show three curves which define about the same area of $+G_x$ times time. A heavy line connects the peaks of these three curves, and locates the peaks of other curves enclosing the same area. The dashed line encloses a number of possible acceleration profiles which are related to space flight, all of which are tolerable.

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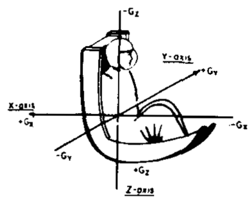
PHYSIOLOGICAL DESCRIPTION OF ACCELERATION



(Directions Are Those of Heart Displacement, With Respect to the Skeletc

Linear Acceleration Modes

Description of Heart Motion

Actual	Other Descriptions			
Towards spine	Eye-balls-in	Chest-to-back	Forward facing	$+G_x$
Towards sternum	Eye-balls-out	Back-to-chest	Backward facing	$-G_x$
Towards feet	Eye-balls-down	Head-to-foot	Headward	$+G_z$
Towards head	Eye-balls-up	Foot-to-head	Footward	$-G_z$
Towards left	Eye-balls-left	—	Rightward	$+G_y$
Towards right	Eye-balls-right	—	Leftward	$-G_y$

Figure 1: Physiological description of acceleration

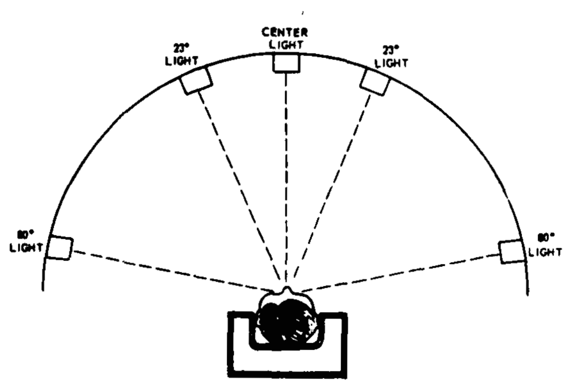


Figure 2: Procedure for measuring the positive acceleration value at which grayout and blackout occur. As G increases, the subject attends the center light, and responds to the random presentations of the peripheral lights by operating a small switch to turn off each light as rapidly as he can as it is continuously turned on by the illumination stimulus programmer. Many variations in the position of the peripheral lights have been studied. This figure illustrates the two extreme positions which have been used frequently. As G increases, ability to detect the peripheral lights decreases until the subject fails to respond. This is called grayout. If G continues to increase, a point is soon reached at which the subject also loses central vision. This is called blackout, and is expressed in terms of the G-level at which vision is completely lost (after Zarriello et al, 1958)

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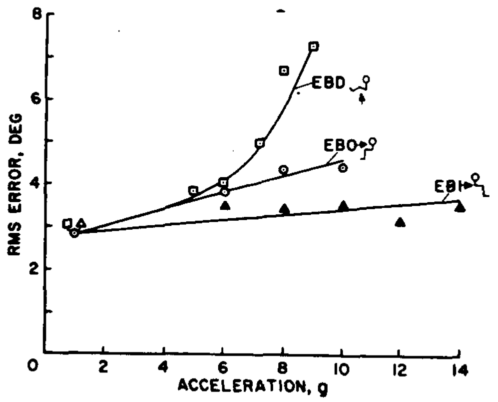

Figure 6: Results of one experiment conducted on the AMAL Human Centrifuge showing root mean square error for continuously performing a piloting task during exposure to accelerations varying in direction and magnitude. It was found that different amounts of error were associated with the magnitude of G and also with the direction of G (after Creer, et al, 1962).

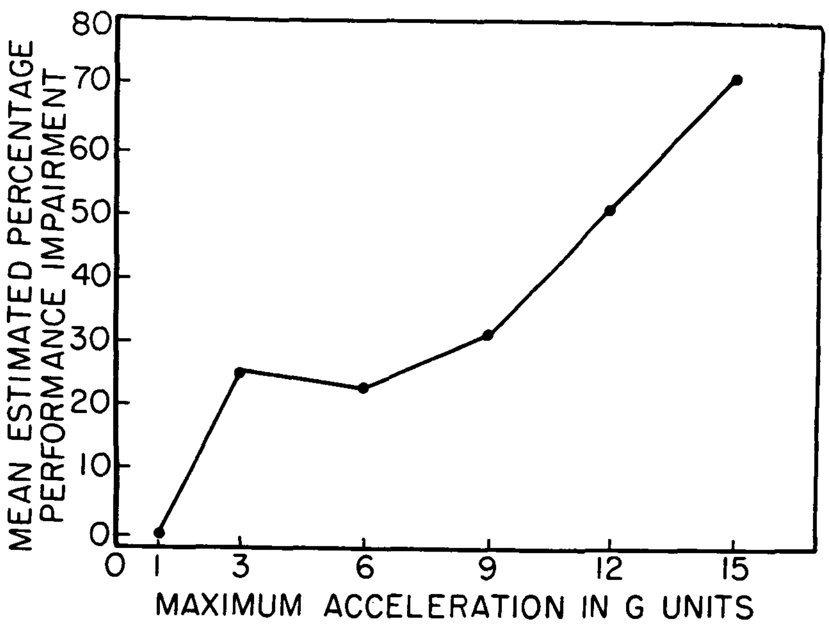

Figure 7: Average estimated performance decrements by pilots who performed complex launch and insertion maneuvers through peak accelerations of 1, 3, 6, 9, 12, and 15 G_x. (Chambers and Hitchcock, 1963.)

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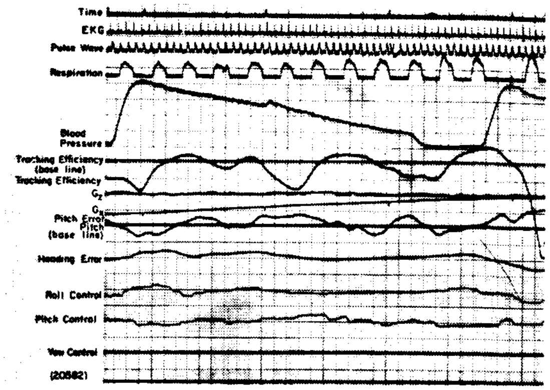

Figure 8: Comparison of physiological and performance measures recorded under acceleration stress.

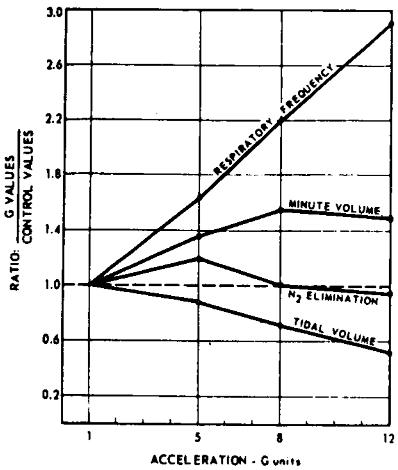

Figure 9: Effects of G_x on respiratory frequency, tidal volume, minute volume, and nitrogen elimination. (after Zechman, et. al., 1960).

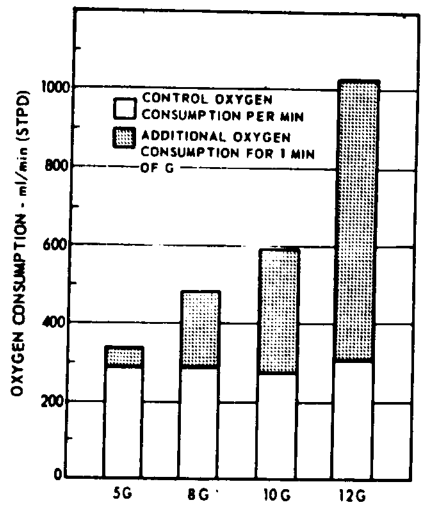

Figure 10: Oxygen consumption during transverse accelerations at 5, 8, 10, and 12 G_x. (From Zechman, et. al., 1960.)

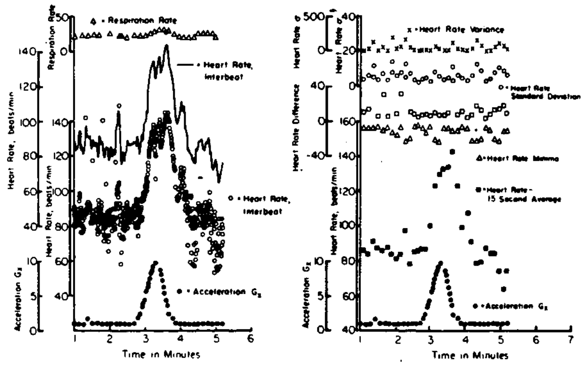

Figure 11: Example of data collected from the AMAL Human Centrifuge in which a subject was exposed to a transverse acceleration profile as heart rate and respiration rate were recorded on magnetic tape and later analyzed.

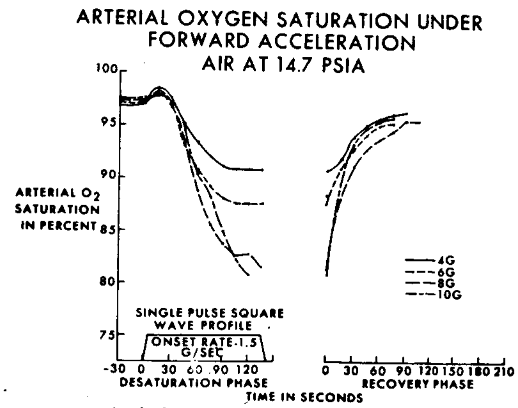

Figure 12: Effects of 4, 6, 8, and 10 G_x on the oxygen saturation of the arterial blood of 25 pilots in a supine position on the AMAL Human Centrifuge. An ear oximeter was used to measure oxygen saturation throughout each of the acceleration profiles.

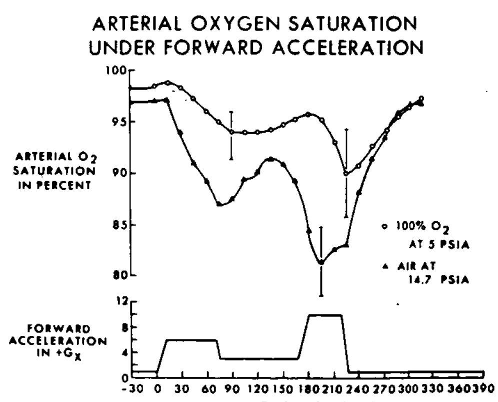

Figure 13: Effects of transverse acceleration on arterial oxygen saturation level.

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Figure 14: Pilot wearing G-suit for protection against positive acceleratio

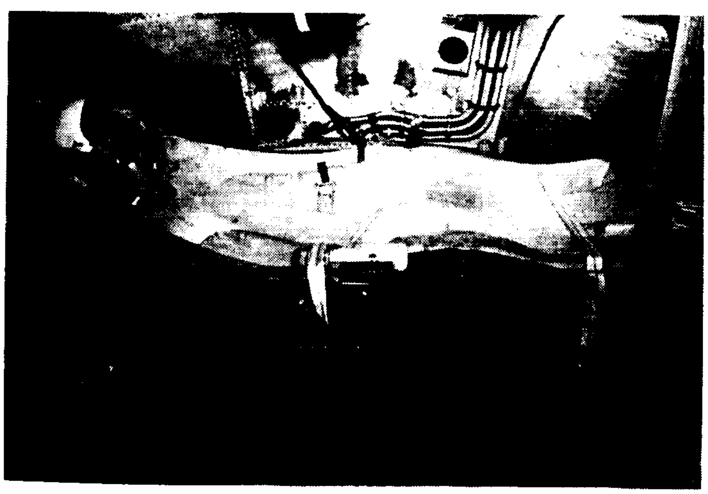

Figure 15: Example of early model of contour couch developed for sustaining high transverse supine ($+G_x$) acceleration forces.

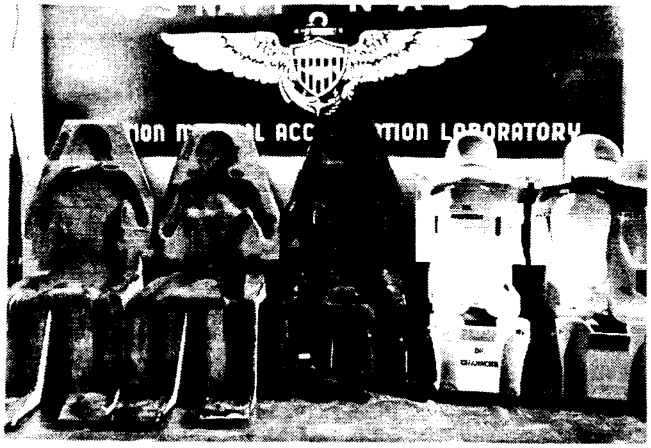

Figure 16: Examples of individually molded contour couches used in pilot performance studies during exposure to transverse G stress environments.

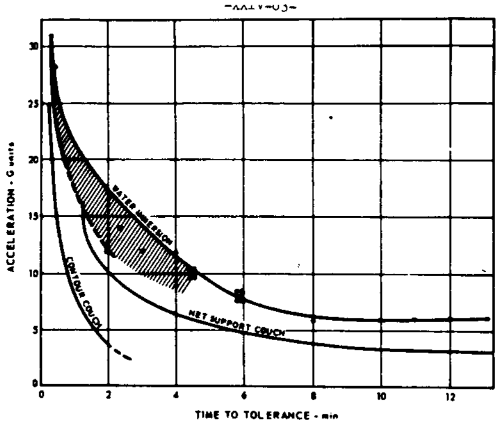

Figure 17: Comparison of maximum protection against the effects of transverse acceleration ($+G_x$) under conditions of optimal positioning in three types of restraint systems: Contour couch, net support couch, and water immersion.

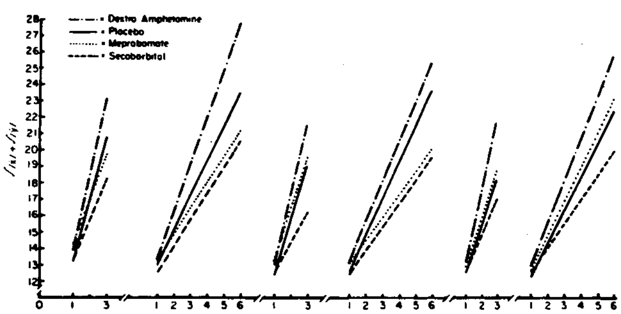

Figure 18: Relative amounts of tracking rate error in four groups of subjects following administrations of dextro-amphetamine (10 mgs), meprobamate (400 mgs), seco-barbital (3/4 grain), and placebo (control). It is postulated that acceleration protection may be provided by certain types of pharmacological agents.

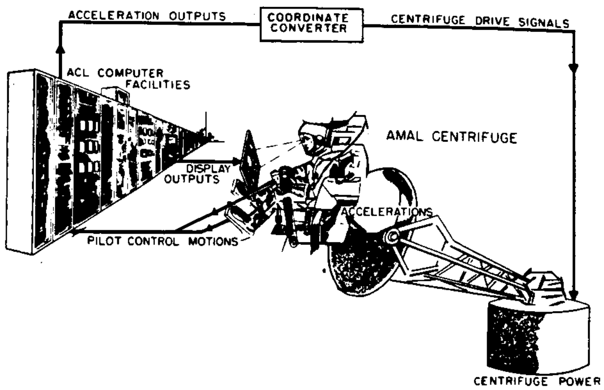

Figure 19: Diagram of the human centrifuge and associated computer facilities to provide closed-loop flight simulation of space vehicle environments.

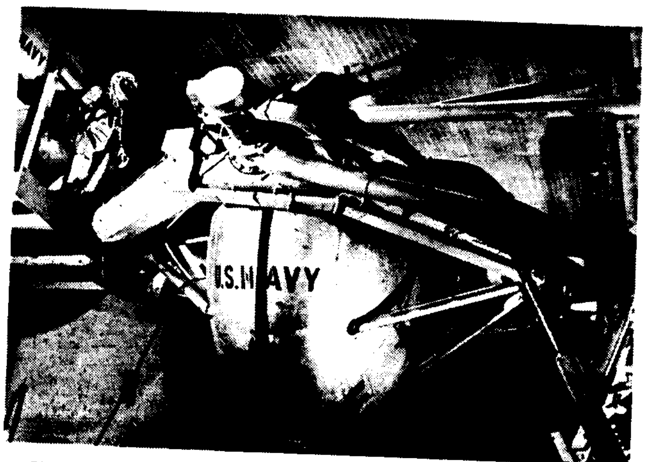

Figure 20: Mercury Astronaut entering the two-gimbaled gondola at the end of the 50-foot arm of the AMAL Human Centrifuge.

Figure 21: Mercury Astronaut performing a capsule attitude control maneuver during a simulated space flight, during early centrifuge simulations of Mercury flights.

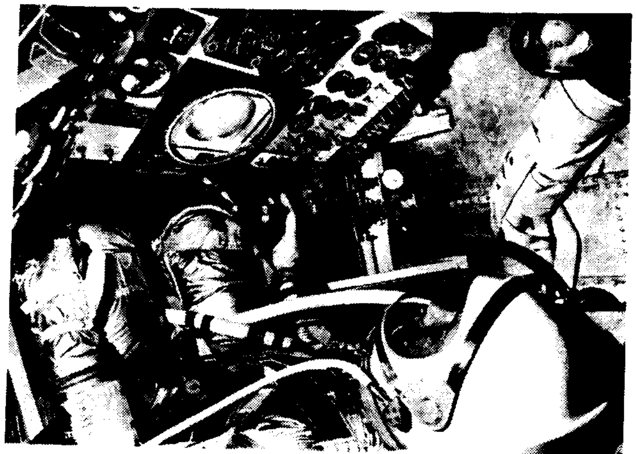

Figure 22: Project Mercury astronaut performing a capsule attitude control maneuver during a simulated space flight in the AMAL human Centrifuge.

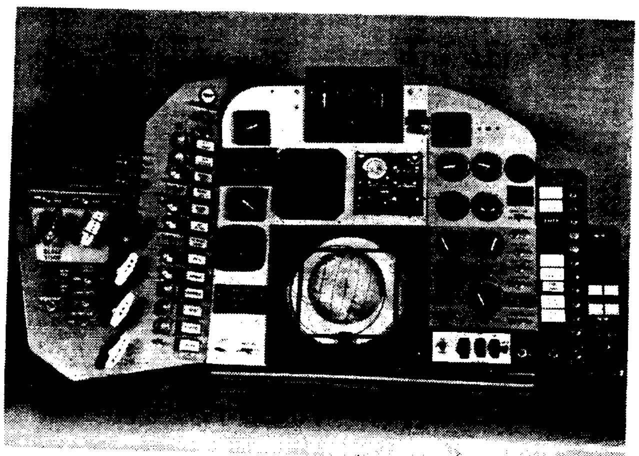

Figure 23: Mercury type instrument panel used in centrifuge simulations of Project Mercury flights.

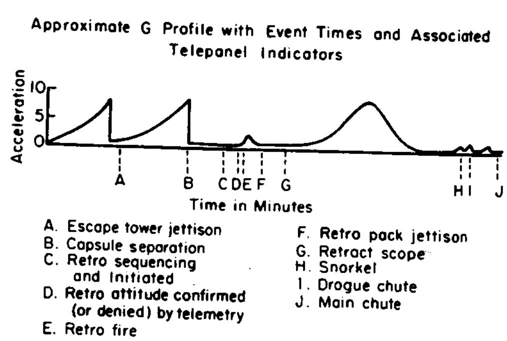

Figure 24: Approximate G profile with event times and associated telepanel indicators used in centrifuge simulations and astronaut training in support of Project Mercury.

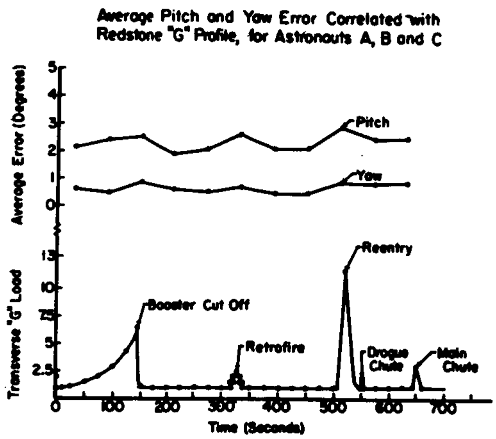

Figure 25: Redstone-Mercury acceleration profile, as simulated on the AMAL Human Centrifuge. Pitch and yaw scores in the upper part of the graph were based on tracking performance independent of the Mercury flight task.

Figure 26: Cockpit installation used for early training of Gemini astronauts on the AMAL Human Centrifuge and for simulating manned Gemini flight acceleration profiles.

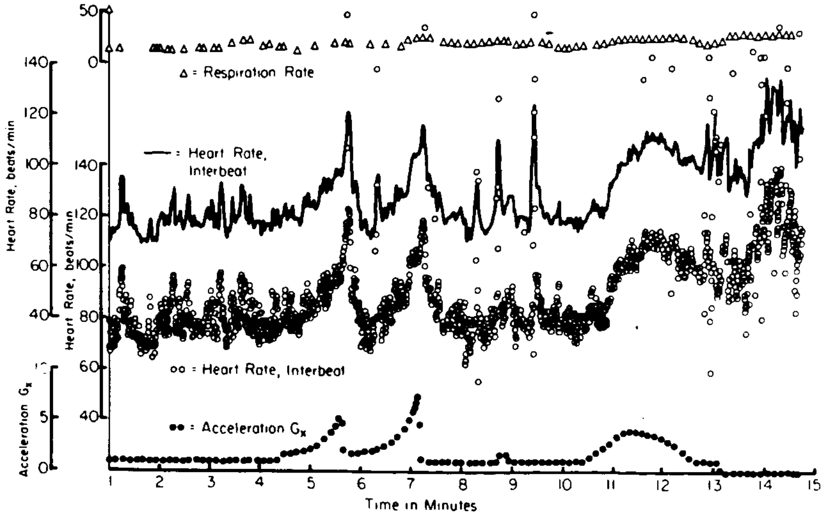

Figure 27: Example of physiological responses to a centrifuge simulation of a Gemini acceleration profile. The acceleration profile and the resulting electrocardiographic and respiratory data are examples of that obtained from the AMAL Human Centrifuge in support of Project Gemini astronaut training.

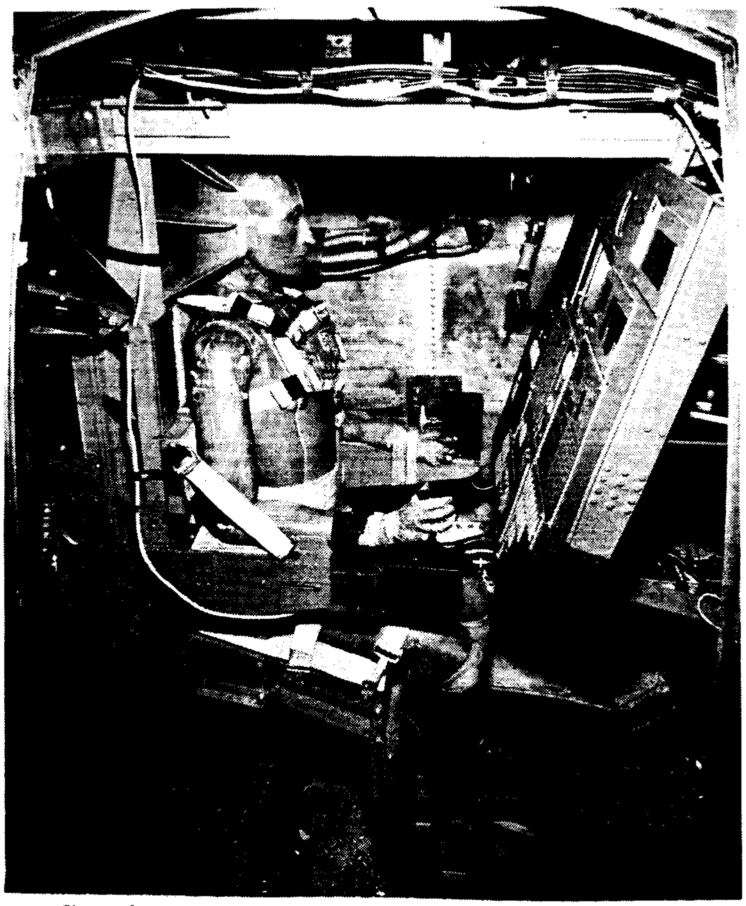

Figure 28: Anthropometric dummy and associated cockpit equipment used in centrifuge simulations in support of Project Apollo. Following acceleration tests with the anthropometric dummy, volunteer pilots and astronauts were tested, and cockpit instrumentation was evaluated.

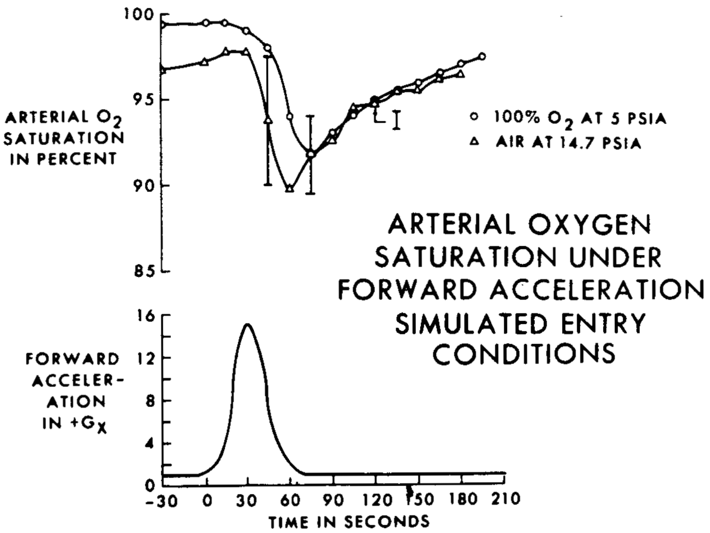

Figure 29: Arterial oxygen saturation under G_x entry conditions simulated on the AMAL Human Centrifuge. The acceleration profile shown in this figure is representative of a group of profiles which were simulated.

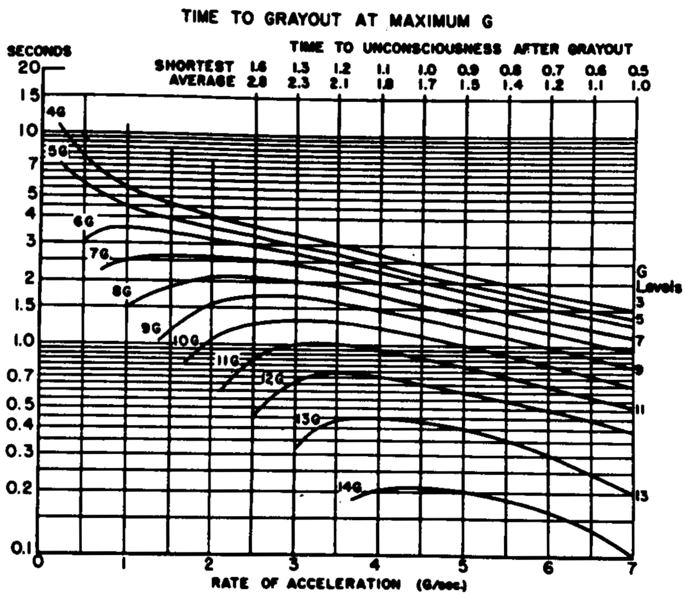

Figure 30: Relationships among amplitude, duration, and rate of onset of positive acceleration for grayout (Stoll, 1956).

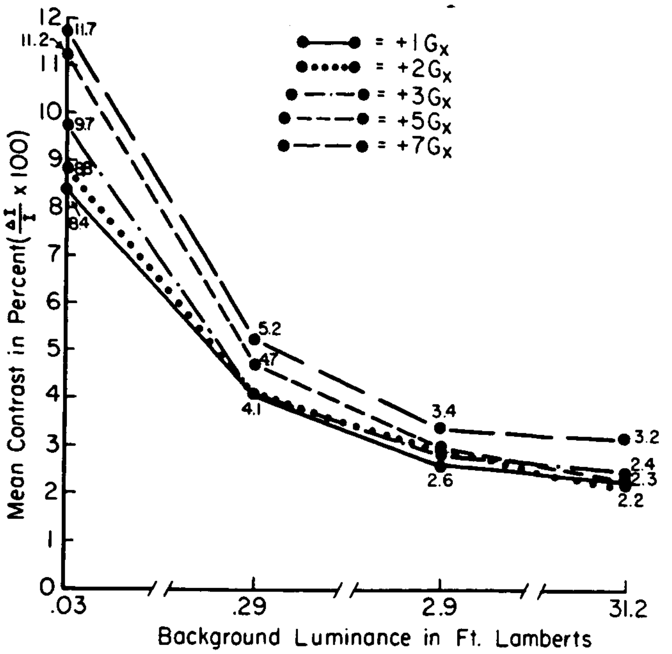

Figure 31: Relationships between brightness discrimination thresholds and background luminance for each of five levels of transverse acceleration, as measured on the AMAL Human Centrifuge.

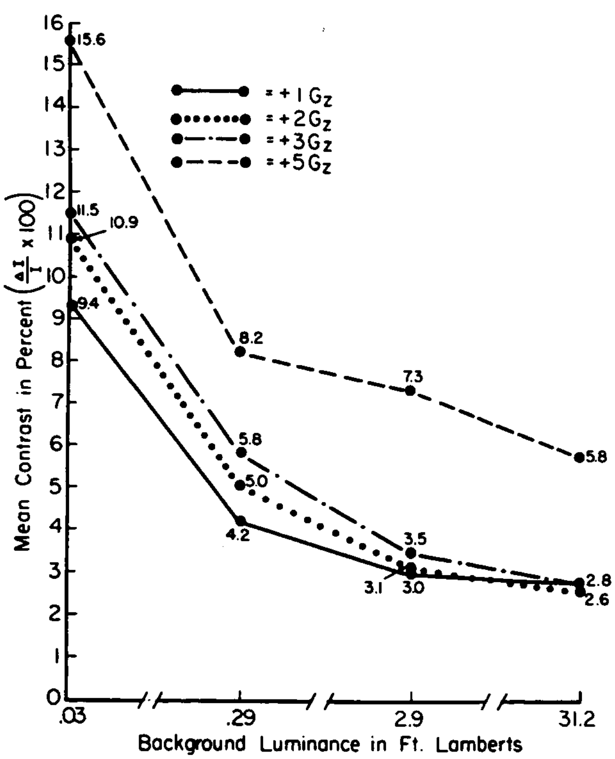

Figure 32: Results of experiment showing relationship between brightness discrimination threshold and background luminance for four levels of positive acceleration.

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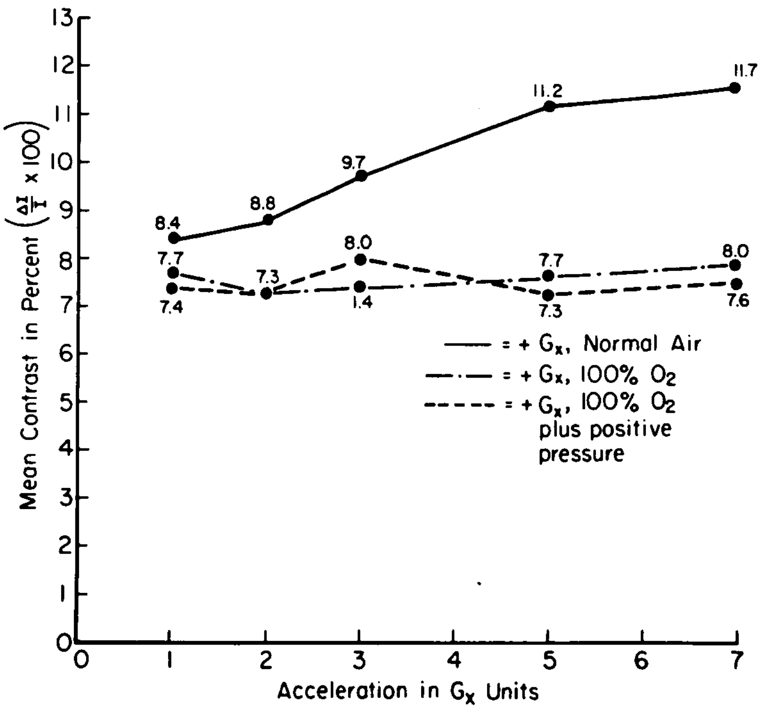

Figure 33: Comparison of effects of breathing normal air, 100% oxygen, and 100% oxygen plus positive pressure, on brightness contrast requirements, as measured on the AMAL Human Centrifuge.

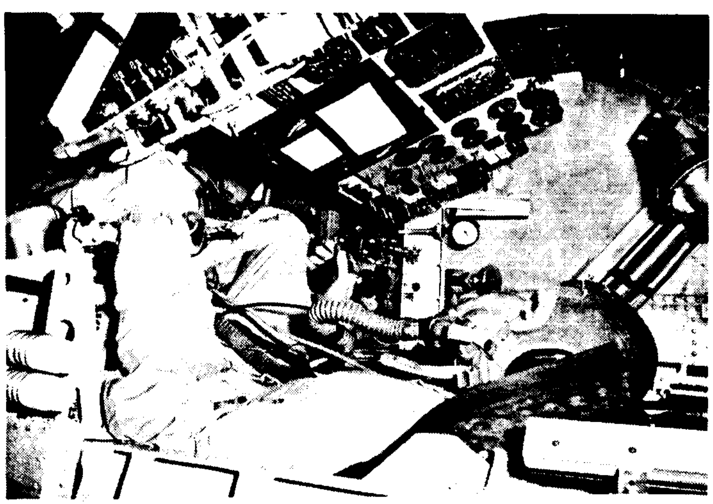

Figure 34: Pilot, mask, restraint system, three-axis side-arm controller, and instrument display panel used in positive pressure breathing experiment.

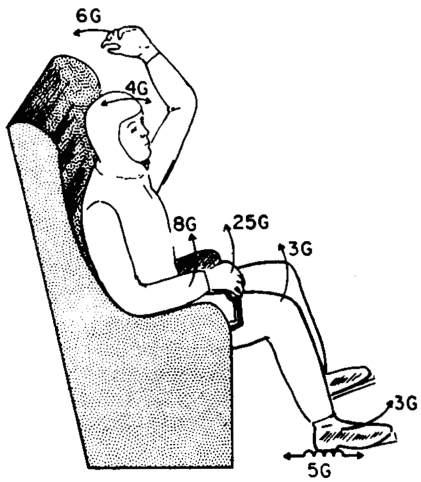

Figure 35: Movements just possible under conditions of vehicle accelerations.

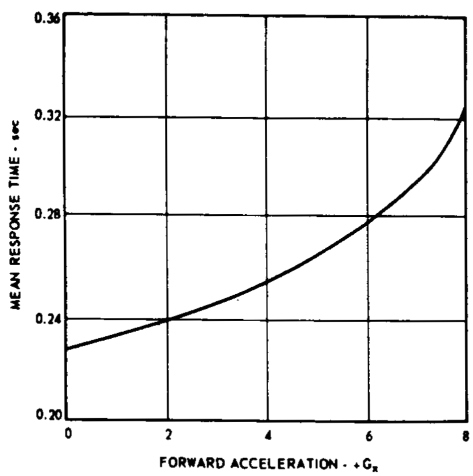

Figure 36: Mean response times obtained in more than 900 tests during exposure to transverse G_x accelerations. (after Kaehler and Meehan, 1960).

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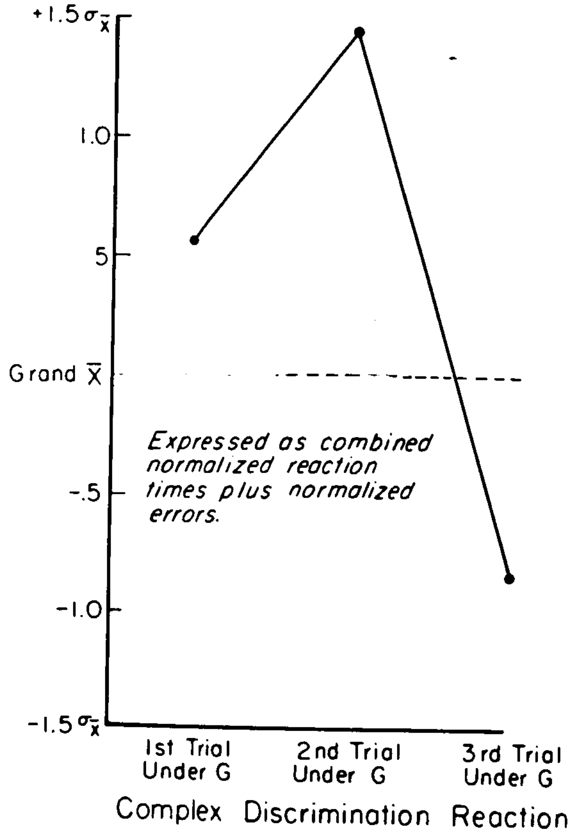


Figure 37: Complex discrimination reaction time performance during exposure to 6 G_x for 5 minutes per run.

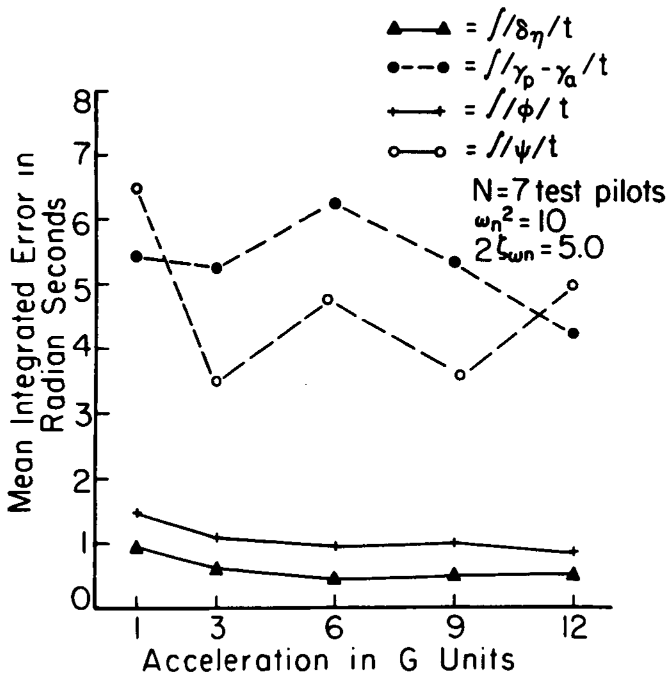


Figure 38: Static vs. dynamic pilot performance for 3-stage and 4-stage vehicles, as simulated on the AMAL centrifuge, in which the pilot's task was to perform complete launch maneuvers.

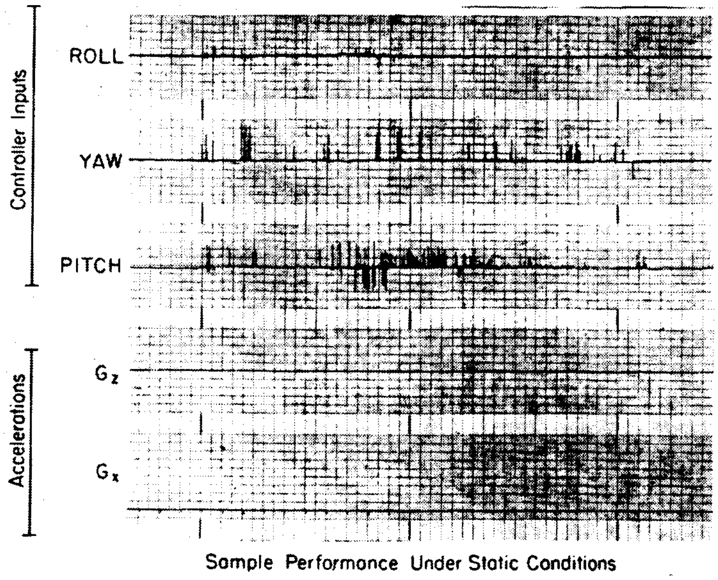


Figure 39: Recording of sample performance under static conditions.

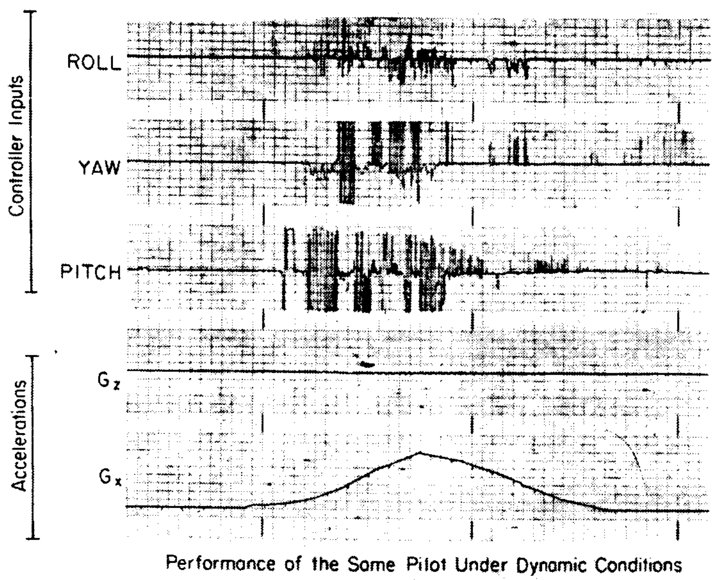
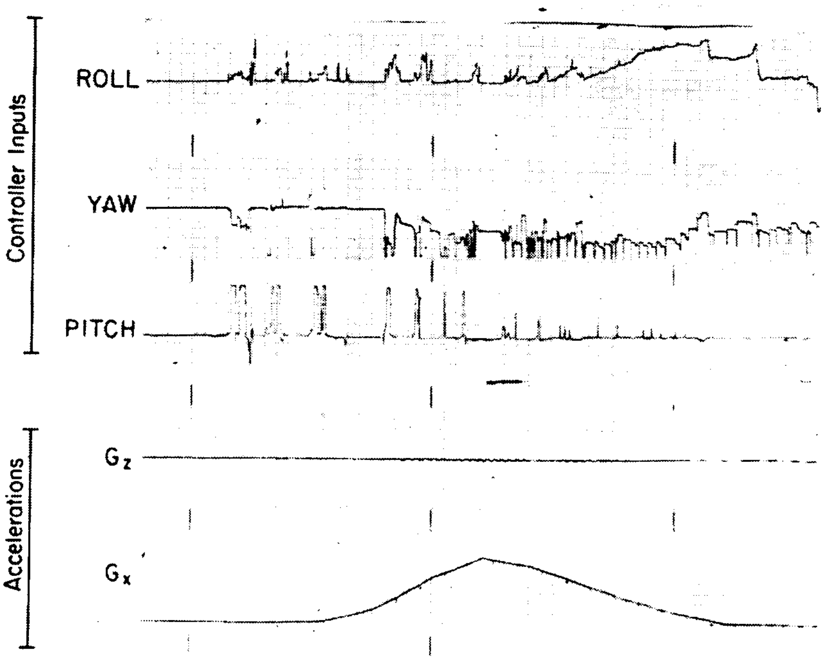


Figure 40: Recording of performance of the same pilot (as shown in Fig. 39) under dynamic centrifuge simulation conditions reaching 8 G_x.



Simultaneous Inadvertant Inputs in the Roll and Yaw Axes

Figure 41: Recording of simultaneous inadvertent control stick inputs in the roll and yaw axes during exposure to an 8 G_x profile.

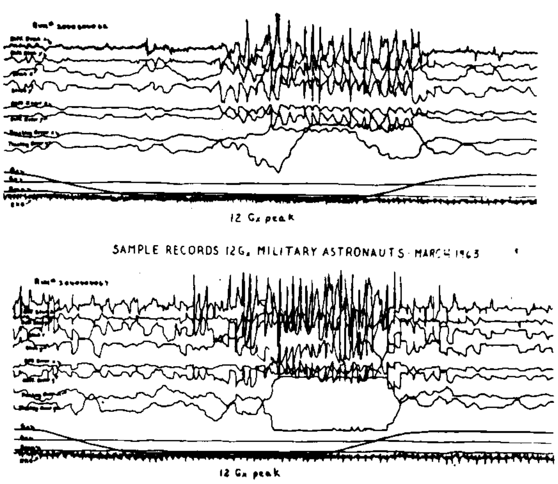


Figure 42: Sample recordings of piloting performance during exposure to 12 G_x on the human centrifuge.

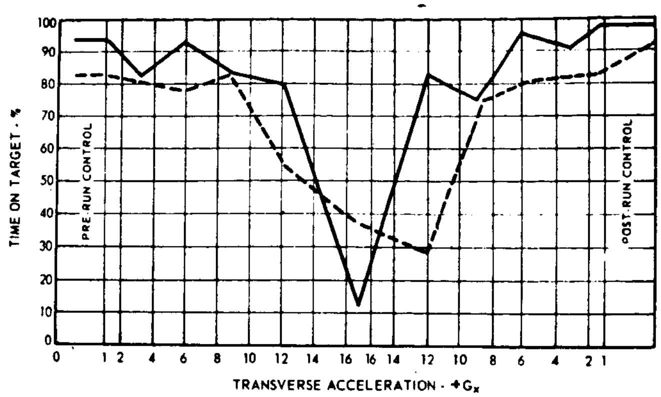


Figure 43: Example of decrement in tracking performance during exposure to a 16 G_x profile. A 3.5 mm target was used in a dual pursuit task by each of the two subjects. (Clarke, et al, 1959)

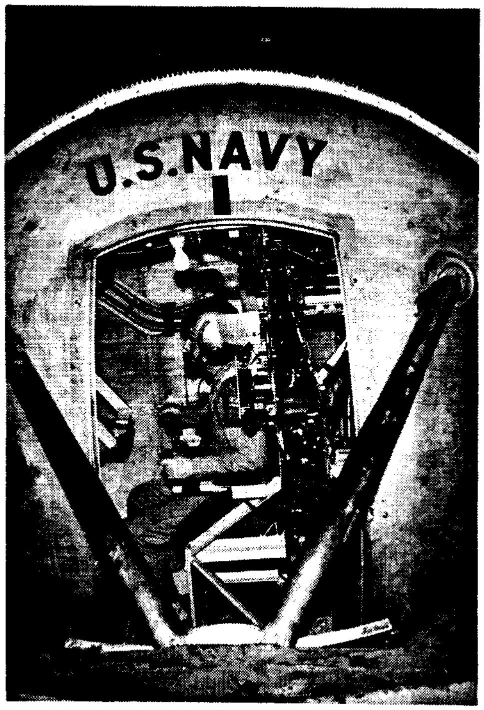


Figure 44: Running matching memory indicator tubes and subject's response trigger handle as mounted in the human centrifuge in study of higher mental abilities during exposure to acceleration stress. (Ross, Chambers and Thompson, 1963)

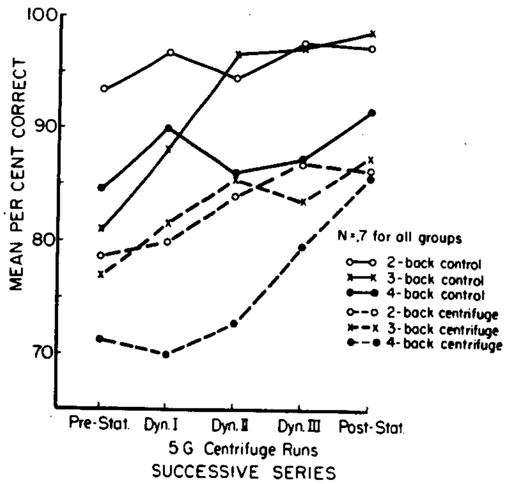


Figure 45: Mean percent correct responses for static, 5 G, and post-test runs, control versus experimental group, on 2-back, 3-back, and 4-back immediate memory task.

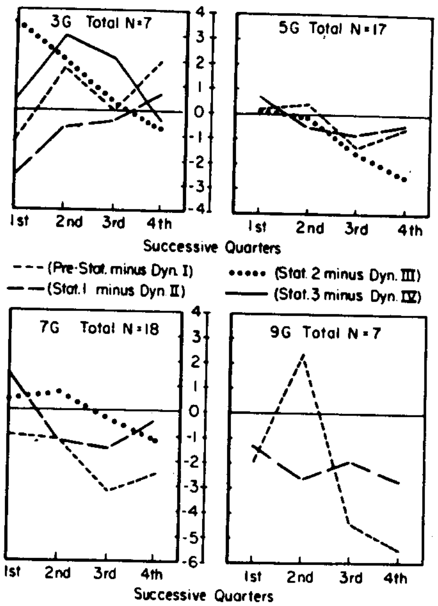


Figure 46: Successive quarters scores for 3, 5, 7 and 9 G_x, showing performance on immediate memory task. (Ross, Chambers and Thompson, 1963)

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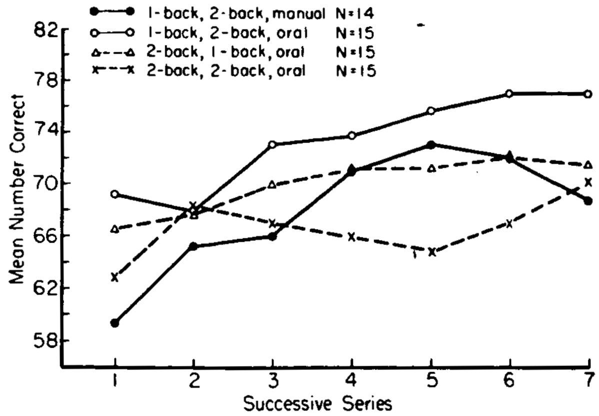


Figure 47: Mean number correct as a function of successive four-series blocks for 1-back and 20-back immediate memory task responses during a 4 1/2 hour centrifuge run at 2 G_x.

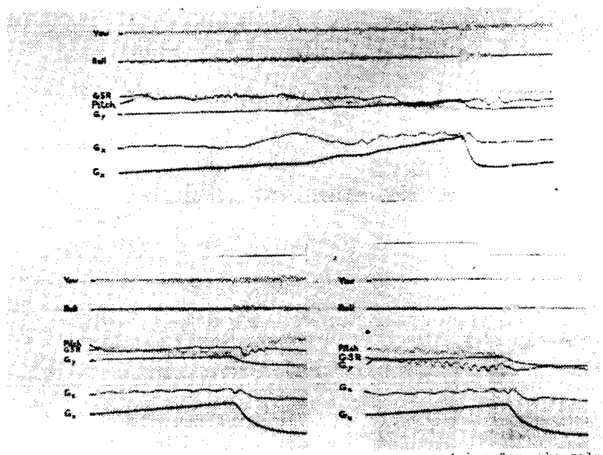


Figure 48: Example of galvanic skin response measures taken from the sole of the foot of a human subject during exposure to 12 G_x on the AMAL Human Centrifuge. Shown also are the pitch, roll, and yaw performance of the subject.

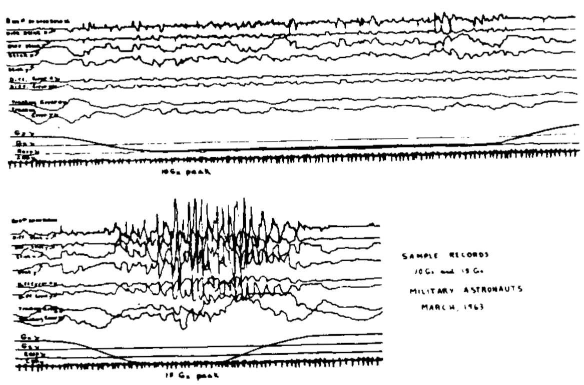
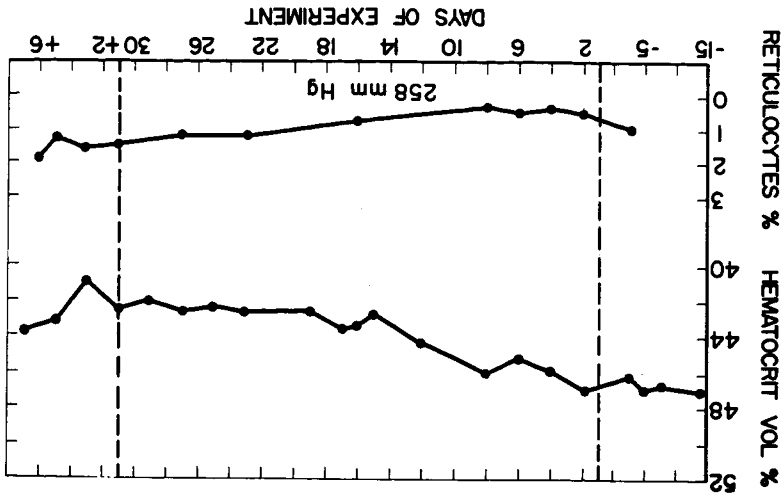


Figure 49: Sample recordings of piloting performance during exposure to 10 G_x and to 15 G_x on the human centrifuge.

Figure 22 Average Hematocrit and Reticulocytes at 258 mm Hg
Brooks 30 Day Experiment



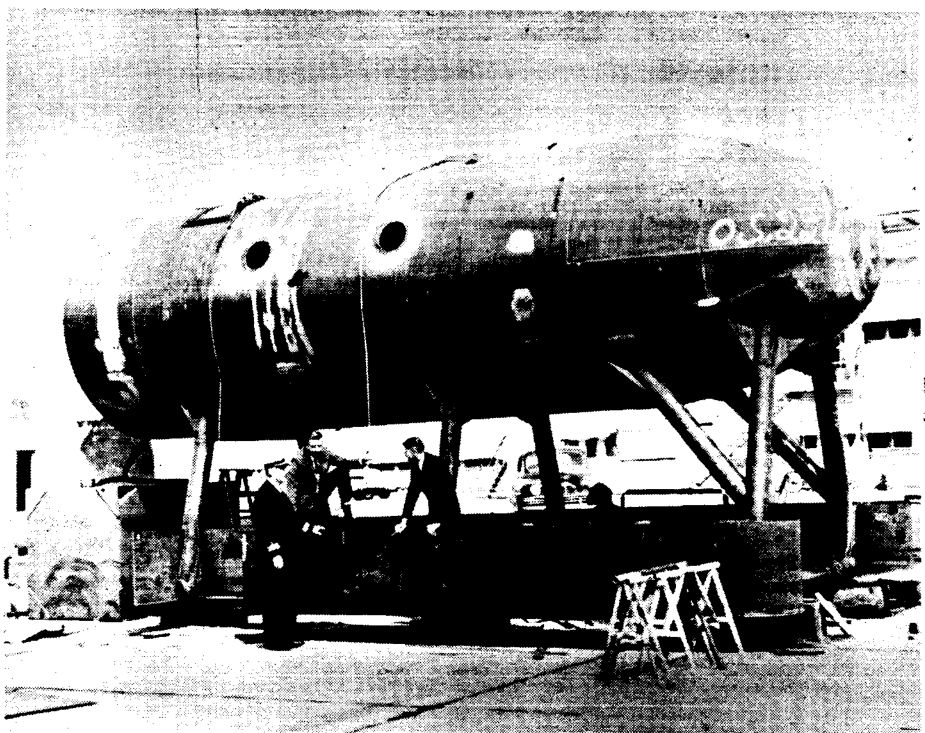


Figure 24 Project Sea Lab I

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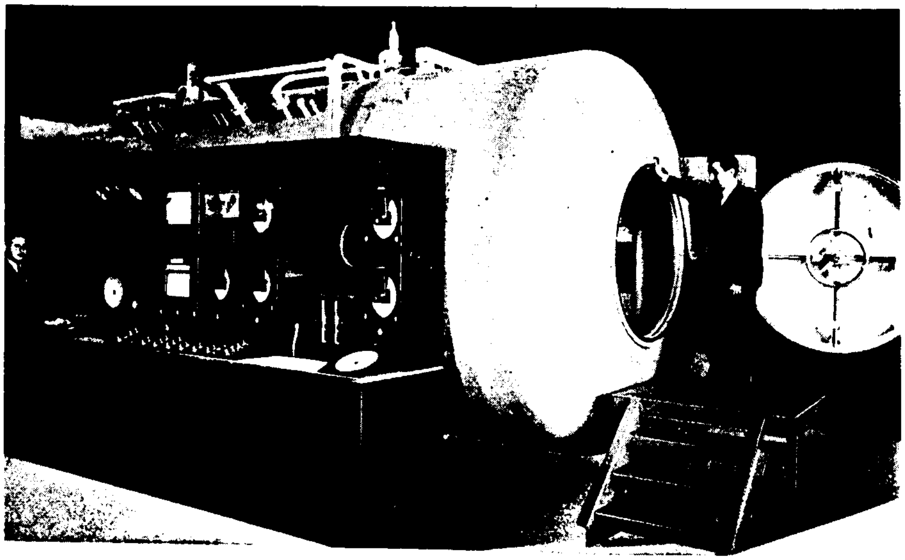

Figure 23 Project Genesis I

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CLOSED ATMOSPHERES

by

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INTRODUCTION

The role of simulation in "closed atmospheres" is to elucidate and resolve the physiological and engineering problems associated with a closed environment and to derive and test the life support system design requirements for future manned space systems. Simulation studies are necessary to (1) determine man's physiological tolerance, (2) develop, test, and qualify the life support system and subsystems, and (3) establish that man can survive and perform as a man-machine integrator of the manned space system. Previous programs have determined procedures for obtaining these goals (e.g., Project Mercury, Gemini atmosphere validation program, subsystems and component flight qualification procedures, and final acceptance testing of the man-system in space simulation facilities). Governmental and industrial simulation facilities are being expanded to permit these procedures for the Gemini and Apollo programs.

The fidelity of the space simulation required versus its cost and practicality has to be resolved on the individual requirements of the simulation and the objectives of the test program. Is simulation of the complete solar spectrum required for thermal balance or solar panels studies? What is the effect of absence of convective currents in weightlessness on the ventilation and thermal requirements for the "closed atmosphere"? Should procedural ground trainers or simulators duplicate the "closed atmosphere"? Should physical stress (e.g., vibration, noise, acceleration, etc.) be simulated? The effects of combined stress on man, machine, and the man-machine system must be evaluated and, where critical interactions occur, these should be included in the space simulation test program. Unfortunately, all of the stresses of the space environment can not be simulated in ground-based studies (e.g., weightlessness, radiation, etc.).

In a NASA study program, Republic studied "The Biomedical and Human Factors Requirements For A Manned Earth Orbiting Station"(1). The Phase 1 BIOSTAT report determined which biomedical and human factors measurements should be made aboard a space station to ensure adequate evaluation of the astronaut's health and performance during prolonged space flight. The major environmental factors or stresses from launch to re-entry and return to earth from an orbit inclined approximately 30° to the equator at an altitude of 200-300 nautical miles were categorized as weightlessness, dynamic factors, ionizing radiation, cabin atmosphere, contaminants, thermal environment, circadian rhythms, and psychophysiological factors (Fig. 1 and Fig.2). One of the recommendations of this report was that "extensive ground based studies be conducted to evaluate the effects of variables other than weightlessness (e.g., cabin atmosphere, contaminants, circadian rhythms, small radii centrifugation, radiation)."

Circadial rhythmicity may exert a vital role in the control of endocrine glands(2). Possibly the alteration of rhythmic metabolic activity may cause an increase in the adrenal glands' production of cortisone. Hypercortosonemia produces profound changes in the body's physiology, some of which might be falsely attributed to the effects of weightlessness (e.g., negative calcium and nitrogen balance, electrolyte and fluid shift, and psychic changes).

Initial concern about the effects of the space environment center around the effects of weightlessness on the cardiovascular and neuromuscular-skeletal systems. The subacute, latent, and chronic effects of space flight center more around the hematopoietic, pulmonary, and metabolic systems and genetic changes from exposure to "closed atmospheres" and ionizing radiation. The long-term effects of artificial atmospheres and the interactions of ionizing radiation, increased partial pressure of oxygen, and contaminants are unknown.

Ground simulation studies in "closed atmospheres" will provide guidelines to establish the design requirements for development of "closed atmosphere" systems. Where significant penalties are incurred in meeting these requirements, extensive simulation studies may permit a relaxation of standards or necessitate the development of an alternate approach. Unfortunately, there is poor agreement in the biological community even on the partial pressures of oxygen that is toxic, or the role of inert gases, let along potable water standards or the level of contaminants permissible for continuous long-term exposure. While the environmental variables appear infinite and biological responses are complex, progress can be made by studying classes of stresses and biological system responses. However, the major emphasis in simulation studies should be operationally oriented to resolve system design problems and provide an optimal system that compromises neither man nor the system and is realistic in terms of operational constraints.

FACILITY REQUIREMENTS

The successful development of closed life support systems suitable for space flight will require the pooling of governmental, industrial, and university talents and resources. Facility requirements for the research development and test programs will vary with the vehicle, system, subsystem, or component being tested. Basic research in understanding human physiological effects of artificial environments will include animal research, especially toxicity studies. However, in the final analysis, man must be the test subject requiring the use of man-rated facilities. Elaborate man-rated facilities have and are being constructed both at NASA centers and by major NASA contractors.

For the Gemini program, McDonnell Aircraft Corporation has installed ten cylindrical vacuum-thermal chambers having diameters of 2-1/2, 5-1/2, 8, 18, and 32 feet equipped with cold walls maintained at liquid nitrogen temperatures for the thermal-vacuum testing of Gemini components and systems and manned tests of the Gemini spacecraft with human subjects.

The space environment simulation chambers under construction at the Manned Spacecraft Center, Houston, Texas, comprise two large man-rated chambers. The large chamber (Fig. 3) consists of a 65-foot diameter vertical cylinder, 80 feet in height[3]. The chamber can handle a spacecraft of up to approximately 75 feet in height and 25 feet in diameter. The smaller chamber is 35 feet in diameter and 42 feet high. In addition to the chambers, the facility includes vacuum pumping systems, liquid nitrogen and gaseous helium refrigeration, and the necessary control instrumentation.

Man-rating a simulation facility adds significantly to its complexity and cost requiring personnel air locks, an emergency recompression system, an environmental life support system, visual, auditory, and electronic monitoring systems, and medical facilities.

The Aerospace Research and Testing Committee of the Aerospace Industries Association has recently published ARTC Report No. ARTC-41, "Recommended Safety Practices for Manned Space Chambers"[4]. This report presents recommended safety practices for the construction and operation of manned space chambers as developed by AIA member companies. Medical problems of man-rating a space environment simulator include hypoxia, rapid or explosive decompression, rapid recompression, dysbarism, logistics, and accidents caused by cryogenic slippage or contact with thermal devices or cryogenic surfaces, and exposure to fire[5].

Hypoxia is the state of oxygen deficiency resulting from the reduced partial pressure of oxygen in inspired air at simulated altitudes. Because inspired air is quickly saturated with water vapor at body temperature, the partial pressure of oxygen in the trachea is reduced from 160 mm Hg to 149 mm Hg under normal sea level conditions. With the reduction of barometric pressure at simulated altitudes, the water vapor, being dependent only on body temperature and not total pressure, encroaches upon the other gases present until at an ambient pressure of 47 mm Hg (63,000 ft. equivalent) there is theoretically room for only water vapor in the respiratory tract.

The breathing of 100% oxygen at 34,000 feet is the equivalent of breathing room air at sea level. When breathing 100% oxygen, at 37,000 feet and 40,000 feet simulated altitude, the concentration of oxygen in the blood is the same as 5,000 feet and 10,00 feet altitude. Above 40,000 feet, breathing 100% oxygen under positive pressure up to 30 mm Hg can raise man's physiological altitude ceiling to 50,000 feet. Higher positive pressures are not effective in raising the ceiling because of the increasing reduction of partial pressure of O_2 and the mechanical effects of the positive pressure on venous return and cardiac output. Therefore, in order to perform at higher altitudes in a space simulator, man must be enclosed in a pressure vessel, either a capsule or pressure suit.

Failure of the space suit or pressurized vessels in the simulator will result in a rapid decompression affecting the absolute pressure in the lungs within fractions of a second. Depending on the size of the perforation and the pressure differential, this sudden decompression may reach violent and explosive-like proportions. The effects on the body of decompression are the possibility of being physically blown through or against the opening and internal trauma by the sudden expansion of gas in the body, especially the lungs. Secondary effects after the decompression are the result of acute hypoxia and, at the lower barometric pressures, the formation of water vapor bubbles in the blood and other body fluids and tissues. With closed airways (breath-holding, swallowing, closed glottis), severe and even fatal damage may result during relatively slow decompressions of one second or longer. With the airway closed, at the end of the normal exhalation, a decompression from sea level to 30,000 feet altitude may result in dangerously high intrapulmonic pressures. When the lungs and thorax are expanded by relatively static-intrapulmonic pressures of more than 80 mm Hg, air bubbles are actually forced into the pleural spaces and can result in generalized air embolism to the brain.

Unless adequate pressurized garments are immediately activated or recompression to a lower altitude is initiated promptly, after sudden decompression altitudes in excess of 63,000 feet (47 mm Hg), serious cardiopulmonary and neurologic damage, and even fatal results, may occur if the exposure is prolonged for much more than one to two minutes. Following rapid decompressions to altitudes above 52,000 feet, loss of consciousness is unavoidable if the exposure time before recompression exceeds 5 to 6 seconds.

Rapid recompression is a necessity to rescue a man after sudden decompression during testing of a space capsule or space suit. Of initial concern during recompression is the blast, noise, vibration, and thermal effects from the inrush of air at sonic velocity. Direct blast effect on the man is of minor consideration compared with the hurling of the man against the internal structure of the simulator, or from flying equipment and debris. Noise, vibration, and thermal effect must not exceed the acute tolerance levels for man.

The required speed for emergency recompression is not known. Animal studies being conducted under the NASA sponsorship suggest that exposures of 90-120 seconds at 100,000 feet may be tolerated with full physiological recovery(6). If possible, the recompression rate should be able to return the subject to a minimum altitude of 40,000 feet and assistance available from a "buddy" with adequate means of delivering oxygen to the subject within 15 seconds because of the possibility of unavoidable unconsciousness in that time period. Further recompression at a rate of 1 psi/sec. may be performed without incident except for minor aerotitis.

Decompression sickness may occur on exposure to altitudes above 17,000 feet. The basic underlying pathologic process in decompression sickness or "bends" is the local formation of bubbles in body tissues, both intravascular and extravascular. The resulting symptoms vary widely in their nature and their intensity, depending on the location and size of these bubbles. Bubbles tend to form in any tissue whenever the surrounding atmospheric pressure is reduced to the point where there is a "steep" pressure gradient driving the gas out of solution. Under such conditions, the rate of diffusion of the gas from the tissues into the expired air via the blood and the lungs is too slow to cope with the volume of nitrogen evolved. Hence, the gas comes out of solution locally in the tissues as bubbles. These bubbles usually result in deep and poorly localized pain, most commonly in the knees and shoulders. Pruritus, hot and cold sensations, and a type of formication, as though a small compact colony of ants were moving over the surface of the body, may occur.

Respiratory symptoms (the "chokes") are characterized by substernal distress, with a burning or gnawing or lancinating pain, and are aggravated by attempts to take a deep breath. "Chokes" is probably the result of the circulation of miliary gas emboli in the pulmonary circulation. As in the case of "bends" severe "chokes" may lead to secondary reactions, such as pallor, sweating, fainting, and unconsciousness. Syncope may occur accompanied by bradycardia and hypertension and, if prolonged, may lead to secondary shock from hemoconcentration. Neurologic symptoms, including temporary paralysis, may occur, but most common are visual disturbances, such as blurring of vision, diplopia, blindness, and visual field defects.

There is a wide individual variation in susceptibility to the "bends". "Bends" does not occur on ascents from sea level to below 17,000 feet, but it occurs with increasing frequency at higher altitudes. Obesity, physiological aging, and general poor physical condition increase the incidence of "bends". Exercise while at altitude is an important factor in lowering the threshold altitude for the development of "bends". It increases both the incidence and severity of "bends", decreases the time of onset of symptoms, and greatly reduces the number of individuals who will be protected by symptom regression. This is important operationally considering the metabolic load required to perform effectively when encumbered in a space suit.

Breathing 100% O_2 at ground level prior to a simulated flight (denitrogenation) is the most efficient means of removing nitrogen from the body and reducing the incidence of "bends". The incidence of "bends" during 2 hours at 38,000 feet is 6% after sea level denitrogenation. The practical advantage of prolonged periods of denitrogenation is unknown, and when heavy exercise is carried out even after 4 hours of denitrogenation, a high incidence (18%) of "bends" may still occur. Studies are currently being conducted at the USAF School of Aviation Medicine to determine the denitrogenation required to permit safe extravehicular operations in a 3.5 psi space suit[7].

Recent experience in Republic simulation experiments has shown a high incidence (50%) of mild "bends" and one case of early neurocirculatory collapse on ascent to 33,000 feet even after 2-1/2 to 3 hours of denitrogenation. This high incidence was attributed to cold exposure during the denitrogenation period in the personnel entry lock which was being flushed with 100% liquid oxygen.

Medical and logistic problems of prolonged chamber missions involve considerations of toxicology, personal hygiene and subsistence, and psychological factors. Reduced barometric pressure will likely increase evaporation of volatile substances. Functioning equipment may generate toxic substances such as ozone or carbon monoxide. Toluene and benzene are constituents of certain plastics which may break down in an increased oxygen pressure environment. Supply of food and water and waste removal or storage for multi-crew members should be provided at the start, or procedures and facilities should be established for the transferring of these materials without interrupting the test program. Personal hygiene is important for comfort and prevention of infection. An unsuspected contagious disease in one of the test subjects may spread and cause an expensive test program to be terminated before test objectives are achieved. Psychological stress factors of confinement, isolation, and hazardous surroundings should be evaluated and considered in determining the overall medical well-being of the test subjects.

Industrial-type accidents may occur within the space simulator because of the presence of extreme hot and cold surfaces, heights, narrow passageways, and heavy test equipment. The fire hazard in the presence of 100% oxygen is of real concern as demonstrated by several unfortunate fires in the Gemini atmosphere validation program and other simulation studies.

In addition to the specialized facilities and reliability considerations required for man-rating a space simulator, chamber personnel and auxillary staff must be experienced in operational and emergency procedures to ensure the safety of the chamber occupants. Essential automatic chamber controls should be provided with manual overrides. "Fail safe" devices may not be safe if double failures occur. Automatic versus manual initiation of the emergency recompression system should be carefully evaluated for each specific test program. Inadvertent automatic initiation of the emergency recompression system is costly in terms of test schedules, money, and the well-being and morale of test subjects. Automatic systems which are designed to operate safely at normal operating conditions may be unsafe during transition phases.

An incident occurred with Republic space simulator during the Gemini atmosphere validation program which illustrates this point.

EMERGENCY RECOMPRESSION INCIDENT

The Republic space simulator is a stainless steel cylinder 13 feet in diameter and 30 feet long (Fig. 4). It is divided into two sections: a main chamber 18 feet long and an entry lock 8 feet long. The two chambers are connected by a personnel door, and another personnel door provides access to the entry lock from the laboratory floor. Observation of the subjects within the chamber is accomplished through seven 24-inch diameter viewing ports.

Three control consoles are provided for the operation of the facility. The main console consists of a communications segment, an alarm and schematic segment, an atmosphere supply segment and two pressure control segments -- one for the main chamber and one for the entry lock. Smaller control consoles which operate the various components of the pumping system are provided immediately adjacent to chamber viewing ports for the entry lock and for the main chamber. A schematic display (Fig. 5) is presented on the main console. Each component is represented by an illuminated indicator, the color of which indicates the status of the component. Blue indicates closed or inoperative, white indicates changing, amber indicates operating, and red indicates failure.

The components on the left side of the schematic diagram represent the emergency recompression system. The oval area on the left represents a recompression air storage tank. This tank is connected to the main chamber through a silencer and a frangible disc which can be pierced by a spring-loaded spear. The tank is connected to the entry lock through a silencer and a check valve and to the ambient atmosphere through redundant recompression vent valves and a larger silencer.

Normal operation of this sytem can best be described by considering a typical test situation. A subject is suited in a full pressure suit occupying the main chamber which is at high vacuum. The entry lock pressure is at the equivalent of 27,000 feet altitude, and is occupied by an observer in "shirt sleeves" equipped with an oxygen mask. Upon initiation of operation of the emergency recompression system, either automatically or by pushing any one of seven "panic" buttons located around the chamber, the spring-loaded spear pierces the frangible disc and compressed air from the recompression tank flows into the main chamber. When the pressure in the recompression tank is equal to that of the entry lock, the check valve opens and the three vessels reach a common pressure as air rushes from the entry lock into the main chamber. An equivalent altitude of 40,000 feet is reached in 5-1/2 seconds. At this time the personnel door between the main chamber and the entry lock may be opened by the inside observer, who can then enter the main chamber. The two recompression vent valves, whose operation is controlled by a cam-operated programmer, allow ambient atmosphere to enter the system and recompress the chamber to sea level in an additional 16 seconds.

During the Gemini atmosphere validation program, an emergency recompression occurred because of a momentary loss of electrical power which actuated the emergency recompression system. Six subjects has just been locked in the personnel entry lock and the main chamber was under a vacuum of 10^{-4} Torr in preparation for back-filling with oxygen to establish a nitrogen-free environment of 5 psi pure oxygen. Normally, an observer in the entry lock would have been decompressed from 27,000 to 40,000 and then returned to sea level at .7 psi/sec. These subjects were at sea level initially, were decompressed to 25,000 feet in 7 seconds at a maximum ascent rate of 5,000 feet/sec., remained at 25,000 feet for 4 seconds and then were recompressed to sea level in 7.5 seconds with a maximum rate of descent of 7,000 feet/sec. (Fig. 6). This incident resulted in termination of the subjects' participation in the experiment. Five of the six subjects had bilateral aero-otitis including several with injected blood vessels on the posterior pharynx and inner aspects of the external ear canal. Only one subject reported a sensation of air rushing out of his lungs during the episode. All subjects made an uneventful recovery with conservative treatment.

An alteration in procedure (back-filling the main chamber with oxygen before occupying the entry lock) or increasing the relay time before loss of electrical power would actuate the emergency recompression system could have prevented this incidence. However, in future test programs requiring the main chamber to be under high vacuum and the rotation of inside observers to minimize fatigue the entry lock would again be at sea level for a short time during the transfer procedure.

ATMOSPHERE SELECTION

The selection of the cabin atmosphere is one of the most critical environmental factors in the design of manned space vehicles. A near sea level "air" environment and one-third atmosphere oxygen environment represent two current approaches which have apparently been satisfactory for current missions. Other combinations and pressures may be useful for future space missions, but will require extensive ground-based experiments and mission simulation prior to the use in space flight.

The most important single constituent in the gaseous atmospheres is oxygen. In a pure O_2 environment, the oxygen available to the body; i.e., alveolar partial pressure, may be calculated from the following equation:

$$P_{A_{O_2}} = P_B - (P_{A_{CO_2}} + P_{A_{H_2O}})$$

where P_B is the barometer pressure, $P_{A_{CO_2}}$ is the alveolar partial pressure of carbon dioxide, and $P_{A_{H_2O}}$ is the alveolar partial pressure of water. Assuming a normal $P_{A_{O_2}}$ of 100 mm Hg,

$$P_B = 100 + 40 + 47 = 187 \text{ mm Hg.}$$

Hence, this should be considered the minimum total pressure for design purposes if no inert gas is present in the atmosphere.

No minimum total pressure above the hypoxic level has been established for space missions from two to twelve months. Sea level to 10,000 feet altitude equivalent total pressures should have minimal pressure effects, but may not be practical for design reasons and certainly with a single gas atmosphere would result in oxygen toxicity.

The explosiveness of a decompression or, under less catastrophic conditions, the leak rate, is directly related to cabin pressure, It has been demonstrated that with higher pressures and a small penetration, effecting a decompression over a number of seconds or minutes, there is a longer period of useful consciousness for emergency action such as suit donning(8). However, in the event of a major decompression occurring in fractions of a second up to one or two seconds, the dangers of damage to the crew due to relative gas expansion in the gas filled organs is considerably greater with higher pressures. Dysbarism will be a negligible problem with a 100% oxygen system. Even with decompression of the capsule at launch, "Bends" can be averted with denitrogenation for three to four hours prior to launch. With two gas systems decompression to 1/2 the initial cabin pressure is considered within safe limits.

Specific experiments conducted to determine the preoxygenation and equilibration necessary to avoid "bends" following decompression from 1/2 atmosphere (50% oxygen, 50% nitrogen) to 1/4 atmosphere have been conducted by the U. S. Navy(9). These studies indicate three hours of preoxygenation at sea level prior to such a decompression will effectively prevent "bends". It was also noted that without pre-oxygenation 18 hours in the 1/2 atmosphere environment described, provided adequate denitrogenation from the previous sea level air environment to decompress to 1/4 atmosphere safely. Finally, a combination of two hours denitrogenation at sea level followed by 12 hours at 1/2 atmosphere provided similar protection.

Although any atmosphere capable of supporting life will support combustion, the combustion rate increased rapidly with increased oxygen partial pressure, particularly between 150 and 250 mm Hg, and is appreciably decreased with the addition of an inert gas. Consideration of the fire hazard is of paramount importance in view of the small living space and limited escape opportunities and fire fighting equipment possible in space vehicles. The magnitude of fire hazard has been assessed quantitatively by Parker and Ekberg, who performed laboratory studies to determine to what degree burning was accelerated in various gas compositions and pressure[10]. Figure 7, plotted from their data, compares the burning time of paper strips as a function of the partial pressures of oxygen. It appears that for a given quantity of material, complete combustion would occur over twice as fast at 1/2 atmosphere (50% oxygen - 50% nitrogen) compared to sea level air and three times as fast in pure O_2 at 1/3 atmosphere.

Bolstad determined the difference in ignition temperature (or time), burning rate, and the per cent of the material sample consumed on ten different materials considered for use in space vehicles. Comparative studies were conducted in air at 12.6 psi (650 mm Hg - 4,200 feet altitude) and 100% oxygen at 5 psi. The material was ignited by a coil which reached a temperature over 800°C in 100 seconds. These studies (Fig. 8) demonstrated that the samples took only two-thirds as long to ignite in oxygen (range 50-88% as long), indicating a substantial difference in temperature required for ignition. They burned approximately 2-1/2 times as long (Fig. 9) and consumed three times as much of the total sample[11] (Fig. 10). The fire hazard is estimated to be 2-4 times greater at 5 psi pure oxygen than at a 7.0 psi 50-50 oxygen-nitrogen atmospheric mixture[12].

Experience during the Gemini validation program suggests that it will be extremely difficult, if not impossible, to extinguish a fire in a 5 psi pure O_2 environment by usual means. Compartmentation of space vehicles would allow for emergency decompression as a means of extinguishing the inferno and would afford protection after meteoroid penetration. Flash blindness, burning, and over pressure are increased during meteoroid puncture with increasing oxygen partial pressure, and would probably be catastrophic in a pure oxygen environment.

Parker and Ekberg[10] considered the physiological, physical, engineering, and operational aspects in recommending an atmosphere for early manned orbital space stations containing a partial pressure of oxygen between 160-175 mm Hg and a total pressure between 350-380 mm Hg with nitrogen as the diluent gas.

OXYGEN TOXICITY

Since its discovery by Priestly in 1775, there has been an intense interest in the physiological effects of pure oxygen and there has also been a great deal of disagreement and disparity among the investigators, as is evident from the available experimental data concerning the effects of pure oxygen. To quote Comroe (1945)[13], "there is no agreement whatever among clinical investigators concerning the harmful effects of oxygen on man."

Studies of the effects of oxygen on man and animals can be divided generally into those which investigated: (1) pressures greater than one atmosphere, (2) pressures of one atmosphere, and (3) pressures of less than one atmosphere. The effects of oxygen under pressures greater than atmospheric were initiated by Paul Bert[14] in 1847 and have been studied by Haldane[15] and, more recently, Behnke[16] among others. The primary effects appear to be on the central nervous system with convulsions and death occurring as a function of a sufficiently elevated partial pressure of oxygen.

Many investigators have studied the effects of varying percentages of oxygen at a total pressure of one atmosphere on both animals and man. These studies generally indicated that partial pressures of oxygen over 455 to 460 mm Hg are detrimental to most organisms as a function of time. Smith[17] in 1899, subjected birds, mice, rats, and guinea pigs to 532 to 608 mm Hg of oxygen in one atmosphere and determined that this breathing gas mixture was lethal after four days, producing hyperemia in the lungs and other organs. Stadie, Riggs, and Haugaard[18] and Bean[19] had similar results when they subjected animals to similar conditions for up to one week. Clamann[20] and Becker-Freyseng[21] working with an assortment of fifty mice, rats, guinea pigs, rabbits, cats, and dogs, exposed to 608 to 661 mm Hg of oxygen in one atmosphere for seven days, found severe lung edema in the sacrificed animals. Before the animals died, they appeared to show symptoms similar to those of hypoxia. Becker-Freyseng and Clamann subjected themselves to 684 mm Hg of oxygen in one atmosphere total pressure in a closed chamber with a volume of 40 cubic meters. The experiment was discontinued after 65 hours vecause Becker-Freyseng became ill and was vomiting and Clamann was ill. They noted paresthesia of the extremities after two days and increased feelings of fatigue as the experiment contined. A transient bronchitis which occurred in one of the experimenters disappeared within twenty-four hours after the termination of the experiment. Comroe et al[13], working with human subjects, provided pure oxygen by masks to groups of young men for periods of twenty-four hours. They found that 82% of the subjects experienced substernal distress, and vital capacity was usually decreased significantly. Almost half of the subjects developed nasal congestion or coryza during, or shortly after, the twenty-four hour experiment. Conjunctival irritation and ear discomfort (aero-otitis) occurred in about one-fourth of the subjects. Recognizing that the low tension of nitrogen, rather than the increased oxygen, might account for the observations, these investigaters placed six men in a low pressure chamber at a simulated altitude of 18,000 feet (380 mm Hg) and provided 100% oxygen by masks for twenty-four hours with no occurrence of the respiratory symptoms. Comroe thus assumed that the high pO_2, rather than a low pN_2, accounted for the symptoms. Richards and Barach[22] found no indication of pulmonary irritation when they studied the effects on two men of 343 mm Hg of oxygen in one atmosphere for seven days.

On the basis of an analytical review, Mullinax and Beischer[23] concluded that oxygen tensions less than 425 mm Hg can be breathed indefinitely with no likelihood of physical impairment. Hall and Martin[24] maintained a subject in a full pressure suit at 3.5 psi pure oxygen for seventy-two hours with no reduction in vital capacity. A pustular dermatitis and irritation of the eyes, nose, and throat were noted. A similar study by Hall and Kelly[25] subjected two men, one of whom was in a pressure suit, to 3.5 psi pure oxygen for five days with no significant decrease in vital capacity, although some irritation of the conjunctivae, nose, and throat occurred.

Michel, Langevin, and Bell[26] subjected six U. S. Navy enlisted men to 418 mm Hg of oxygen in 523 mm Hg total pressure of atmosphere for 168 hours (one week). They found some decrease in vital capacity in two men and an area of probable atelectasis in one subject. Other than some substernal tightness, there were no marked symptoms noted by the subjects. Welch, Morgan, and Ulvedal[27] studied the effects on two men in a chamber of 150 mm Hg of oxygen in a total atmosphere of 380 mm Hg over a thirty-day period and 190 mm Hg of oxygen (total pressure) over a seventeen-day period. A mild reduction in vital capacity, work capacity, orthostatic tolerance and increased myocardial irritability, and weight loss occurred in both experiments. Psychological performance generally remained at a stable level.

Unfortunately, it is likely that in the great majority of the reported studies of "pure oxygen" or "100% oxygen", actual values varied from as low as 50% when oxygen tents or loose masks were used, to 90% in prolonged studies not utilizing hermetically sealed chambers. Even in conventional altitude chambers, pure oxygen level (excluding CO_2 and water vapor) are rarely maintained since any leak represents an influx of nitrogen (air). In addition, Comroe points out that many of the oxygen experiments performed were without air breathing controls, the number of subjects was frequently very small, and the monitoring and control of the actual gaseous environment was poor. Prior to the Gemini atmospheric validation program, there have apparently been no studies reported in the literature to indicate any experiments using partial pressures of oxygen exceeding 258 mm Hg in the absence of an inert gas over a prolonged period.

GEMINI ATMOSPHERE VALIDATION PROGRAM

Although no serious impairment of human performance was anticipated during the relatively short flights of the Project Mercury mission (<34 hours), the use of a 5 psi pure oxygen environment in Project Gemini or other forthcoming man-in-space programs required reasonable assurance that subjecting man to such a deviation from his normal gaseous atmosphere for a period of two or more weeks would not create a serious hazard. Morgan et al[28] had reported that two and possibly three of eight subjects demonstrated reduced arterial oxygen saturation immediately after seventeen days exposure to oxygen at a total pressure of 190 mm Hg without x-ray evidence of pulmonary atelectasis.

Experience in high performance jet aircraft (Ernsting[29], Langdon[30], and Levy[31]) and centrifuge simulation[32] of launch and re-entry g loads demonstrated a significant incidence of atelectasis in pilots while breathing pure oxygen. Twenty per cent of reported F-100 pilots had reversible post-flight signs or symptoms of atelectasis related to 100% oxygen high g missions.

The Gemini atmospheric validation program was an excellent example of the role of simulation in the development of space technology and the cooperation of NASA, USAF, USN, and industrial resources. Under the sponsorship of the National Aeronautics and Space Administration, the School of Aviation Medicine, Brooks Air Force Base, Naval Air Engineering Center, Air Crew Equipment Laboratory, and Republic Aviation exposed human subjects to reduced pressures of "pure" oxygen environment for two-week periods. Coordinating meetings were held with the Space Science Board to select and standardize procedures to ensure comparability of results. Emphasis was placed on measurements for the detection of atelectasis and included arterial pO_2, pCO_2, pH, O_2 contents and capacities, vital capacity, maximum breathing capacities, and chest x-rays taken at the experimental condition. The Aviation Medical Acceleration Laboratory (AMAL) included the Gemini g profile before and after the two-week oxygen exposure in the ACEL study with the subjects being maintained in a sealed 5 psi pure oxygen cabin during transport from the centrifuge to the altitude simulation facility.

Fourteen-day experiments in the USAF, School of Aviation Medicine two-man space cabin simulator were conducted at a simulated altitude of 27,000 feet (258 mm Hg) to determine the physiological effects of this environment with emphasis on pulmonary studies[33]. The arterial pO_2, alveolar pO_2, estimated venous to arterial shunt, and chest x-rays were reported within physiological limits. A 2.9% decrease in vital capacity was not considered indicative of atelectasis. There was a significant slight drop in hematocrit in all the subjects. One subject had a pronounced drop from a pre-experiment high of 49 to 38%. Post-run findings on this subject indicated a slight anisocytosis and hypochromia, slight reticulocytosis and erythroid hyperplasia which was possibly attributed to the repeated blood sampling. Symptomology included eye irritation, aural atelectasis and substernal pain. Urinalysis during the run and on follow-up examination 3-4 months later were essentially negative. The authors concluded that "this atmosphere can be well tolerated for a fourteen-day period".

The ACEL study was to include the exposure of six aviators to two peak 7 g loads to simulate launch acceleration, chamber confinement in pure oxygen for fourteen days, and a peak of 11.2 g to simulate re-entry acceleration[34]. The occurrence of a fire with the altitude chamber ended the study prematurely so that only three subjects were exposed to the complete test program, the other three being exposed to the launch acceleration profile and 13, 12, and 11 days of pure oxygen, respectively. There were no significant physiological alterations except for temporary impairment of peripheral scotopic vision. Several subjects demonstrated a 10-30 fold decrease in sensitivity to dark adaptation. There was no significant variation in vital capacity, arterial pO_2, pCO_2, or pH or x-ray evidence of atelectasis. However, several hours elapsed after the launch acceleration and 20-30 minutes after the re-entry simulation before the chest x-rays were taken. Hematological findings reported were a significant decrease in the average hemoglobin and hematocrit values. There was no rise in bilirubin or urinary urobilinogen, a slight rise in reticulocytes, and a tendency to hypochromia and microcytosis. Similar changes were noted in two control subjects outside the chamber. An estimated 700 cc of blood loss drawn in the various blood samples was considered the main etiology for these findings. Microscopic cylindruria was not noted during the experimental exposure. Renal function was normal. The authors concluded that "no evidence was obtained to indicate that any physiological detriment of operational significance would be suffered by astronauts exposed to these conditions."

In the Republic study, a broad approach to the problems associated with pure oxygen at various barometric pressures in the absence of an inert gas was planned[35]. Four groups of six men each were selected to live in an altitude chamber for a two-week period. Three of the groups lived in an oxygen environment at total pressures of 3.8 psi, 5.0 psi, or 7.4 psi, and a fourth group served as a control in a sea level (14.7 psi) air environment. Detailed medical, physiological, hematological, biochemical, microbiological, and psychological studies were conducted on all subjects(Fig. 11).

A small transfer lock was added to Republic's space simulator to provide for the passage into and out of the chamber of foods, waste, supplies, and physiological specimens (Fig. 12). The larger compartments of the chamber provided a means of isolating the subject in the event of fire. In addition to interior portable fire extinguishers and source of water, wherever possible materials were screened for use in the chamber to reduce the fire hazard by first subjecting them to a combustion test in a 5 psia 100% oxygen bell jar. It was found that "smooth" asbestos burned fairly well because of the coating on the asbestos. Some high temperature all-weather wiring also burned brilliantly because of the all-weather paraffin coating.

The life support system was provided by continuously flushing the chamber with oxygen while the pumping system of the facility was used to maintain the simulated altitude. Six hundred to seven hundred liters of liquid oxygen per day were forced through a cold panel near the ceiling of the chamber and the oxygen, now gaseous, was introduced into the chamber. In order to insure the purity of the liquid oxygen used, two samples were analyzed (Fig. 13). The mean environmental levels in the sea level control, 5, 7.4 and 3.8 psi runs for CO_2 were 2.3, 1.1, 1.6 and .7 mm Hg; for N_2 608, .33, .49, and .55 mm Hg; for water vapor 10, 24, 22, and 21 mm Hg, respectively.

No deterioration of general mental, sensory, or motor performance was demonstrated in any of the experimental runs. Aero-otitis, substernal discomfort, coughing, and eye irritation caused minor intermittent difficulties. Biochemical and microbiological examinations were within normal limits, although some shift in the balance of skin and fecal microflora was observed.

An occasional trace of protein and casts in the urinary sediment occurred in many of the subjects during the altitude runs which persisted intermittently for several months post-run. There were no other abnormal signs or symptoms of renal damage during the experimental runs. The urinary output was good and blood urea nitrogen levels remained normal.

The etiology of the renal changes and their significance is unknown. Clinical thermometers and sling psychometers were broken during the first (sea level) and last (3.8 psi) chamber run. Between runs, the highly polished stainless steel surfaces of the chamber were carefully cleaned, including the area beneath the floorboards. This cleaning should have removed any possible accumulation of mercury in the chamber. Additionally, the flushing system resulted in oxygen entering at shoulder height and exhasuting out the bottom of the chamber below the floorboards. Since heavy mercury vapor would tend to collect below the floorboards, it should have been flushed out of the chamber instead of being inhaled by the subjects.

Twenty-four hour urine samples collected during the thirteenth day of the 7.4 psia run, which had been kept in cold storage, were analyzed for mercury by the U. S. Public Health Service, Cincinnati, Ohio using an ion-exchange method sensitive to .3 microgram/liter. The average concentration of the six subjects was 10.6 micrograms per liter compared to normal laboratory values of 2-9 micrograms per liter. Since the urinary concentration of mercury is a good indicator of the level of mercury exposure, the subjects, at least in the 7.4 psi run, were not exposed to a significant level of mercury vapor.

Pulmonary function studies including vital capacity, timed vital capacity, MBC, total lung capacity, and diffusion capacity did not show and significant changes. Arterial mean pO_2, pCO_2, and pH did not show any significant change from expected values. The mean O_2 content from the fifth to the fourteenth day in the 7.4 psi run dropped from 20.2

vol % to 17.0 vol % (Table I).* This difference was found to be significant beyond the 0.01 level. The mean O_2 capacity (18.1 vol %) was greater than the mean O_2 content (17.0 vol %) at the end of the 7.4 psi run in the presence of a mean blood pO_2 of 266 mm Hg. The low mean O_2 content coupled with the larger mean O_2 capacity at the end of the 7.4 psi run are compatible with the possibility that there was a qualitative change in the red blood cells or their constituents, affecting their ability to transport oxygen in vivo, possibly the formation of methemoglobin.

The hematological findings presented the most interesting results and were highlighted by an inadvertent inclusion of a thalassemia trait subject (number 25) in the 5 psia run. Subject 35 exhibited a normal prerun hemoglobin, hematocrit, red cell count and cellular morphology with only one target cell on his peripheral smear. A decrease in hemoglobin (15.8 gm % to 10.5 gm %), red blood cell count, and hematocrit, and an increase reticulocytosis (0.6% to 3.5%) were observed (Fig. 14 and Fig. 15). After the fourth day, stippled cells appeared with hypochromia and, subsequently, many target cells, bizarre shape and normoblasts were seen with a more marked variation in the red blood cell size (Fig. 16). On exit, his red blood cells exhibited an increased osmotic fragility.

Subject 35 was hospitalized and followed extensively at Brookhaven National Laboratories, Upton, New York, where a diagnosis of thalassemia trait was made by electrophoretic analysis of his hemoglobin types. Although previously undiagnosed, examination of both parents demonstrated

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* See Table I, page -XXV-32-

thalassemia trait in his father. His mother exhibited normal percentages of hemoglobin types. Subject 35's hemoglobin rose quickly post-run to 12.0 gm % and appears to have stabilized between 12 to 13 gm % with a 3% reticulocytosis and a 5 to 6 million red blood cell count. His morphological picture, now compatible with thalassemia trait, has remained unchanged. His white blood cell count has returned to a high normal value and the osmotic fragility of his red blood cells is now decreased from normal which is typical of thalassemia trait.

The mechanisms precipitating a hemolytic episode in a subclinical thalassemic trait subject on exposure to 100% oxygen at 5.0 psi for two weeks is unknown. Astronaut screening utilizing routine hematological studies would not have eliminated this subject. It is possible that other subtle hematological defects may cause similar and even more dramatic effects. Hence, astronauts should be given comprehensive hematological examinations including ground simulation in the selected artificial atmosphere.

The change in hemoglobin concentration and reticulocytes for the four experiment groups minus the thalassemia trait subject is shown in Fig. 17 and Fig. 18. The menatological picture of the sea level control group showed no significant change. The 5.0 psi group demonstrated a slight anemia, microcytosis, increased osmotic fragility and minimal erythroid hyperactivity. One subject had a loss of over 2.0 gm % hemoglobin and a 2.2% reticulocyte count. The group demonstrated morphological changes in the size, shape, and staining characteristics of the red blood cell.

The 7.4 psi group exhibited a fall (2-3 gm %) in hemoglobin concentration during the first 48 hours, with a rise in bilirubin and urine urobilinogen levels. Reticulocytes occurred on the third day and persisted at 3.0 to 5.5% (Fig. 19). Normoblasts, macronormoblasts, and macrocytosis appeared, indicating increased erythropoiesis. The latter was also noted in the post-run bone marrow examinations. After the fourth day, the hemoglobin concentration leveled off except for a mean one gram drop on the eleventh day. Thereafter, the hemoglobin level rose and the reticulocytosis decreased.

The hematological picture of the 3.8 psia run subjects resembled that of the 5.0 psia run subjects, except for an unexplained more marked reticulocytosis. All subjects after exposure to 100% oxygen atmospheres at reduced pressures exhibited hematological abnormalities some of which persisted for many months post-run. The etiology of these findings were considered to be due to either a high level of oxygen, the absence of nitrogen, an undetected toxicant, decreased barometric pressure or a combination of these factors. To date, the findings at 7.4 psia have not been duplicated although the results at 5.0 psia are not incompatible with the studies at the USAF School of Aviation Medicine and ACEL.

Consideration was given to the possibility that increased oxygen may have precipitated a hemolytic process similar to a drug induced anemia ("oxidative anemia"). Individual hypersusceptibility to hemolysis with primaquine-type drugs is apparently the result of a deficiency of the enzyme glucose-6-phosphate dehydrogenase. Primaquine-like drugs react with molecular oxygen to form redox intermediates between oxygen and hemoglobin and other intracellular components, thereby transmitting the high oxidation potential of oxygen to cellular components. This will result in oxidative destruction of the cellular components if the cell is unable to increase its reducing capacity. The continuous generation of reducing agents is brought about by glucose metabolism through the pentose phosphate pathway[36]. Glucose-6-phosphate dehydrogenase catalyzes the initial step in the pentose phosphate pathway of carbohydrate metabolism. It provides the mature red cell with its only oxidative apparatus and source of reduced triphosphopyridine nucleotide (TPNH). TPNH, and possibly DPNH, are involved in the reduction of methemoglobin and oxidized glutathione.

Semi-quantitative determinations of glucose-6-phosphate dehydrogenase made on the available subjects months post-run indicated a significant number of deficiencies which gradually decreased.* However, there were individual inconsistencies which are unexplained. Subsequent comprehensive hematological studies at USAF School of Aviation Medicine on 30-day exposures to increased oxygen pressure did not support an "oxidative anemia" as the etiology for hematological changes at 5.0 psia[37].

The presence of atmospheric trace contaminants must be considered in any sealed capsule experiment. The use of continuous flushing during the Republic study certainly decreases the likehood of the presence of a significant contaminant. The presence of mercury vapor has been previously described. In addition, freshly prepared lockfoams containing toluene and di-isocynate were used for insulation of the liquid-oxygen cooling pipes. Roth[38] believes that these findings

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* See Table II, page-XXV-32-

TABLE I. MEAN ARTERIAL VALUES

7.4 psi

	Pre-Run Room Air	5th Day In Chamber	Post-Run In Chamber	Post-Run Room Air
pO_2 (mm Hg)	101	254	266	105
O_2 CONTENT (Vol/%)	19.2	20.2	17.0	16.8
O_2 CAPACITY (Vol/%)	19.6	19.3	18.1	-
pCO_2 (mm Hg)	38	40	40	39
O_2 CONTENT (mM/L)	22.5	23.0	23.0	22.9
pH	7.42	7.42	7.44	7.42

TABLE II. GLUCOSE-6-PHOSPHATE-DEHYDROGENASE DEFICIENCY

POST OXYGEN EXPOSURE

Subject No.	19-25 Weeks	31-37 Weeks	43-49 Weeks
31	+	-	N. S.
32	+	+	N. S.
33	N. S.	-	+
35	-	-	-
36	+	-	-
37	+	-	-
42	-	-	N. S.
43	+	-	-
44	+	-	-
45	-	+	N. S.
46	+	-	-
52	+	-	N. S.
54	-	N. S.	-
56	+	+	N. S.
Normal Control	-	-	-
Abnormal Control	+	+	+

(N. S. = No Sample)

suggest hitherto undefined combinations of toxic factors. The relationship between toxicity from continuous exposure to 100% oxygen and atmospheric contaminants is unknown[39]. The assessment of the biological significance of this relationship must await the development of specific analytical methodology and instrumentation for the identification and measurement of the trace contaminants for comparison with performance in simulation studies.

In order to determine the importance, if any, of the relative differences in partial pressure of N_2 (0.5 mm Hg) in the Republic study and 3-5 mm Hg in the USAF, School of Aviation Medicine study and the ACEL study and to provide greater assurance that 5 psi "pure" oxygen environment was operationally safe for a 30-day period, two 30-day experiments on four experimental and two control subjects were conducted by Brooks Air Force Base in which the alveolar oxygen partial pressure ($P_{A_{O_2}}$) was maintained at approximately 170 mm Hg with the ambient atmosphere at 700 mm Hg and 258 mm Hg and the ambient nitrogen partial pressure at 436 mm Hg and 0.5 mm Hg, respectively[37]. On three occasions during the 258 mm Hg run the pN_2 increased to 9, 11 and 3 mm Hg requiring 1-3 hours of flushing before the pN_2 was reduced to 0.5 mm Hg. The significance of these deviations is unknown.

Comprehensive hematological studies included routine hemoglobin, hematocrit, red and white blood cell and differential counts, reticulocytes, osmotic fragility, Heinz body counts, fecal and urine urobilinogen excretion, serum bilirubin, red cell glutathione stability, glucose-6-phosphate dehydrogenase, sternal bone marrows, and Cr^{51} and Fe^{59} isotope studies. The only positive result was a mild reduction in hematocrit, hemoglobin, and red cell counts, while the reticulocyte counts remained low during the exposure period (Fig. 20, Fig. 20 and Fig. 22). The greater alterations occurred in the 258 mm Hg "pure O_2" experiment and is consistent with Republic's 5 psi group. However, no red blood cell morphological changes were noted. All the other studies failed to indicate increased hemolysis or an "oxidative anemic" process.

Clinically, the only consistent symptoms were aural atelectasis and nasal congestion in the "pure oxygen" group. Urinalysis, createnine clearance and osmolarity determinations were normal. Dark adaptation did not change during the experiment nor on return to ambient air. Arterial O_2 contents, O_2 capacities, and per cent saturations were within expected values. Pulmonary function studies demonstrated an increased maximum breathing capacity as a function of decreased gas density and a 3% decreased vital capacity occurring upon ascent to altitude and disappearing immediately with descent to ground level. This unexplained consistent finding appears to be endemic to Texas as it was not found in the Republic or ACEL studies. In tests conducted in Republic's simulator it has been noted that if the subject can not visually observe the change in spirometric reading or is not verbally directed to continue his exhalation effort, a false low vital capacity may be obtained as the subject loses any sensation of continual expiration before the expiration is completed. In any event, the reported decrease in vital capacity is not attributed to the effect of breathing "pure oxygen".

Recent experiments conducted at ACEL have exposed eight subjects to 100% oxygen at 27,000 feet for 72 hours to investigate the visual effects observed in their previous study[40]. Several of the subjects had the "bends" and one had definite x-ray and vital capacity evidence of atelectasis. Visual data has not been completely analyzed although there does appear to be a definite change in the ERG.

Studies by Mengel et al[41] have demonstrated severe hemolysis in both mice and men on exposure to 100% oxygen at 2-3 atmospheres of pressure. In vivo formation of lipid peroxides in erythrocytes of Vitamin B deficient mice exposed to hyperbaric oxygenation were associated with a decrease in hematocrit from 50% to 20% and marked hemoglobenemia. The erythrocytes of a 67 year old negro farmer were found to be unusually sensitive to hydrogen perioxide prior to hyperbaric oxygenation at 1-2 atmospheres pressure for 1-1/2 hours. Two days after exposure his hematocrit level fell from pre-treatment levels of 48% to 44% and six days later to 35%. The serum bilirubin rose from less than 0.5 mg % to 1.6 mg % and reticulocytes increased from 0.5% to 4%.

Erythrocytes from six patients demonstrated accelerated auto hemolysis at 37°C after in-vivo hyperoxic exposure. Three patients, exposed to hyperbaric oxygenation from 8 to 10 hours demonstrated evidence of change in erythrocyte glycolytic intermediates with a rise in the level of adenosine diphosphate, inorganic phosphate, fructose-1-6 diphosphate and a fall of adenosine triphosphate. There were no changes in erythrocyte reduced glutathione, glucose-6-phosphate dehydrogenase activity, calalase activity or methemoglobin content.

It was hypothesized by the authors that "the primary effect of hyperoxia is the formation of increased levels of lipid peroxides which may damage red cell stroma directly, or through their known inability to inhibit sulfhydryl bearing enzymes subsequently interfere with normal glycolysis in other metabolic systems."

Roth(38) in his recent review of oxygen toxicity made a survey of the effects of increased oxygen tension on intracellular enxyme systems. He reports that, in general, high oxygen tensions tend to inhibit enzymatic activity of the oxygen-dehydrogenase group (lactic, malic and succinic, and triphosphate-dehydrogenase, and cytochrome C reductase). Anything that increases activity of reducing agents protects against the oxygen effect. One aspect of the change is free radical formation similar to the effect of radiation. Increased oxygen tension appears also to inhibit hexokinase activity while nitrogen activates it(42).

What operational conclusions can be made about oxygen toxicity? Atelectasis was not detected during the Gemini atmospheric validation program in which exposure to pure oxygen for two weeks was combined with launch and re-entry g simulations on a centrifuge. Subsequent experiments for 30 days at 5 psi pure oxygen did not demonstrate atelectasis. However, the effects of pure oxygen are not known for long exposures on the pulmonary parenchyma's ability to withstand or combat infection, allergies or irritation of noxious fumes. The effect of pure oxygen atmosphere under weightlessness has not been determined for missions longer than thirty-four hours. Nevertheless, atelectasis probably will not be a significant operational problem in 100% oxygen "closed atmospheres" of space vehicles.

Hematological changes could be dramatic without proper screening and ground simulation testing of potential astronauts. Hematological "misfits" in an astronaut population should be minimal provided "sensitizers" are not present in the oxygen environment. However, the role of "sensitizers" on the biological effect of contaminants in a "pure" oxygen environment is unknown.

The possible acceleration of aging by continuous exposure to oxygen is of no operational significance. Certainly, with proper selection of personnel and control of atmospheric contaminants, there does not appear to be any overriding physiological reason why "pure" oxygen could not be used in life support systems for space missions of 30 days. Acceptability for longer missions must await additional space experience and longer ground simulation studies. However, the desirability of using 100% oxygen in future life support systems is highly questionable. The increased fire hazard and the possible increased toxicity of contaminants in a "pure" oxygen environment, coupled with the introduction of an additional variable in assessing man's performance in the space environment, dictate consideration of two-gas systems approaching a sea level environment for future "closed atmosphere" life support systems.

INERT GASES

General Electric Company recently conducted a five-man 30-day test in a simulated space station utilizing a 7-1/2 psia, 50% O_2 - 50% N_2 gaseous environment. This atmosphere was selected as optimal for early manned orbital space stations based on an excellent analysis of relevant factors by Parker and Ekberg[10]. The crew performed basic psychological tasks and more complex mission simulation tasks on a schedule representative of that which would be required in an earth-orbiting space station. A high level of performance was maintained over the entire test program and the selected atmosphere did not result in any physiological changes outside of normal clinical ranges.

The physiological importance of nitrogen or any inert gas has not been established. Experimentally it is extremely difficult to maintain a nitrogen free environment. If only a few mm Hg of nitrogen are required, experimental contamination could explain the inability to establish a physiological requirement for nitrogen. Assuming a pure source of make-up oxygen, a space vehicle without any inboard leakage of nitrogen, will have much less nitrogen contamination than earth-bound experiments.

Until recently, the consideration of using helium to replace nitrogen in respiratory gases except for medical purposes was reserved for underwater research. Helium has been shown to be more favorable than nitrogen in the protection from the development of "bends" after prolonged underwater exposure and should be morefavorable than nitrogen after space flight decompression. However, the physiological effects of exposure to helium are not completely understood.

Volskii[43] has reported that eggs incubated in air appear to fix gaseous nitrogen and that eggs incubated in atmospheres in which nitrogen was replaced by helium, argon, or xenon died between the 4th and 9th day. Boriskin et al[44] reported that they were able to hatch chicks (27% compared to 79% in air control) from eggs incubated in a helium-oxygen atmosphere. Weiss et al[45] reported results comparable to Boriskin when they obtained essentially normal chicks (although smaller and only half as many as controls) from eggs incubated in helium-oxygen. Allen[46] has reported that without at least 10% nitrogen in the atmosphere chick embryo do not develop normally during the first four days of development. He believes that "nitrogen plays an important role in the mechanism of oxygen toxicity since its exclusion from the gas phase has effects on the embryo indistinguishable from those obtained during incubation in 100% oxygen." Recent studies by Hiatt et al[47] suggest that tissues from eggs incubated in helium-oxygen mixture have a higher rate of metabolism than air incubated embryos if the tissues are transferred from incubator to Warburg flask without exposure to nitrogen. If the homogenates are allowed to stand in air, their rate of metabolism is lower than that of control embryos. This work needs verification but suggested to these investigators the hypothesis of an inhibitory affect of nitrogen. Helium may release this inhibition, but when tissues which have been in helium are then exposed to nitrogen they may be particularly vulnerable with an actual decrease in their metabolism.

The U. S. Naval Medical Research Laboratory has been involved in a series of experiments in artificial atmospheres. Initially, albino rats, guinea pigs, and squirrel monkeys were exposed to normal and artificial atmospheres in a pressure chamber maintained at 7 atmospheres for 72 hours, and 12 to 14 days[48]. The gas compositions were normal air and mixtures of 3% oxygen with either 97% nitrogen or 97% helium. White rate exposed to normal air at 7 atmosphere pressure became lethargic in 15 hours and all died in 35 hours. Histopathological examination revealed intra-alveolar hemorrhage, pheumonia, pulmonary edema, and interstitial hemorrhage in the myocardium and kidneys.

Guinea pigs and rats were exposed for 14 days to 3% oxygen in nitrogen at 7 atmospheres of pressure. The animals were lethargic and demonstrated intermittent paresis of the hind quarters during the experimental procedure. Post-run focal pulmonary atelectasis and pneumonia were noted in both rats and guinea pigs. Rats and squirrel monkeys were exposed for 14 days to 97% helium - 3% oxygen gas mixture at 7 atmospheres pressure without significant alterations. The authors concluded that "the four-fold greater density of the nitrogen-oxygen gas, as compared to the helium-oxygen atmosphere, is considered to be a limiting factor to normal alveolar ventilation, predisposing to the development of pulmonary atelectasis and pneumonia." In preparation for human studies decompression times were established using goats exposed to a helium-oxygen atmosphere at 200 feet for 72 hours, as 36 hours stops at 84 and 26 feet, respectively.

Human experimental work was conducted in Project Genesis I. Three men were exposed in a 30 cubic meter pressure chamber (Fig. 23) for 12 days under 7 atmospheres absolute pressure with a gaseous environment containing approximately 90% He, 3.8% O_2, 5.8% N_2 and .4% CO_2. The density of the ambient gas was 1.5 times the density of air. Since helium transfers heat at a rate approximately seven times greater than air,,maintenance of a thermal comfort zone required a cabin temperature of 91°F. The subjects did not experience any symptomatology or major alteration in pulmonary functions. There was "an increase in tidal volume, but a 20% decrease in VC after 4 hours (largely due to a decrease in ERV), with a return to control by the fifth day; increased airflow resistance throughout as manifested by a fall in MBC from 129% of the predicted value to 83%, a 13% decrease in one second timed VC, and a 33% reduction in peak expiratory flow rate[49]".

A current project, Sea Lab I, will provide quarters for a team of four Navy divers to live and work 192 feet under the sea for a 3-week period -- 26 miles off Bermuda, near the Argus Island installation. The Sealab (Fig. 24) is a chamber of 3/4" steel, 40 feet long by 10 feet in diameter, adapted from ten floats originally used to support mine destruction gear. It is self-contained except for electrical power which will be supplied from a surface support ship. There will be two hatches in the bottom of the chamber through which the investigators can have access to the sea since the pressure inside will be the same as the pressure of the water vehicle in the chamber. At the end of the study, decompression from this depth will require 54 hours.

Welch[50] intends in the near future to study the effects of helium on humans at reduced total pressures. The use of helium in future "closed atmospheres" will depend on a more complete understanding of its physiological effects on man and a better evaluation of "bends" risk with decompression from oxygen-nitrogen cabin atmospheres.

ATMOSPHERE CONTAMINANTS

The "closed atmosphere" requires careful consideration and laboratory investigation of the effects of atmospheric contamination. Toxicants, both chemical and biological, may be expected to build up as a function of mission duration and improvement in capsule sealing techniques. Critical selection of materials, improved monitoring and control devices, and the determination of human tolerances to trace contaminants will be required.

Human responses to the usual industrial toxicants are well known. Specific toxicants may cause pulmonary edema, impaired renal function, anemia, liver necrosis, neuromuscular dysfunction or affect central nervous system performance. However, the toxicity of the space station's atmosphere may be more subtle. The interactions of space environment factors, minute concentrations of a host of possible contaminants and individual susceptibility is unknown.

Current industrial toxicological limits prepared for a 40-hour week will not be applicable to the 168-hour week exposure time of the astronauts. Threshold limit values are not stated for some compounds (indole, skatole, etc.) and others having a variable safety factor incorporated in them. Stokinger[39] calculated threshold limits for typical contaminants in space travel as 3 to 50 times less than industrial threshold limit values. He believes that completely different toxicological effects can be predicted for capsule contaminants in a one gas (oxygen) system than in a two-gas system (oxygen-nitrogen). Oxygen toxicity may reduce the threshold limits by a factor from 2 to 4.

Thomas[51] does not believe that industrial TLV's can be used for long-term exposure criteria because physiological actions and interactions between various contaminants, which may be additive, synergistic, or antagonistic, would preclude any extrapolation. In spite of the relatively minimal restrictions in size, weight, and power requirements of monitoring equipment in the Polaris submarines, detection and identification of trace contaminants has been exceedingly difficult. Hence, even less is known about the biological significance of these atmospheric contaminants. The 6570th Aerospace Medical Research Laboratories are establishing a continuous inhalation facility capable of uninterrupted long-term exposure of large numbers of animals at various pressures and gas compositions to determine the biological effects of contaminants under simulated space flight atmospheres.

Space vehicular sanitation, especially the water supply, will be critical for the health and comfort of the astronauts. Acceptable standards for potable water have not been established. U. S. Navy Polaris submarine experience has demonstrated a marked decrease in the incidence of infectious diseases among crew members, probably due to the development of cross immunity. However, the potable water source and human waste disposal system are greatly simplified on a submarine compared to a space vehicle. Simulation studies have failed to demonstrate the development and spread of clinically significant infections. However, infection may be a problem in the testing of future "closed atmospheres" with regenerative life support systems. Republic is currently conducting microbiological evaluation of various personal hygiene routines at Wright-Patterson Air Force Base during "closed atmosphere" simulation runs.

The space environment may alter microbials by changing virulence and mutation rate. Organisms which play an essential role in digestion may be unable to fulfill this task, resulting in disturbence of digestion, absorption, excretion, and nutrition. Microbials produce noxious fumes and may have a direct corrosive effect on hardware. "It is estimated that about ten grams of microorganisms will be present after sixty days in presently planned space stations unless bactericidal agents are periodically applied to all areas of the station."[52]

The importance of ground-based simulators to check out life support systems for contaminants and to establish their biological significance was demonstrated by the initial abort in the Manned Environmental System Assessment experiment[53]. The test was aborted after 4-1/2 days because of crew nausea and subsystem equipment malfunction. An exhaustive study of the sources of contaminants was made resulting in significant modifications of the original system. Subsequently, the Boeing Company successfully completed the (MESA) program demonstrating that five men can survive for thirty days in a closed self-sustained integrated system environment. The integrated system was not optimized for a thirty-day mission or for space use, but did permit the investigation of the interaction of man and the system. The subsystems included: (1) a chemical atmosphere regulating using sodium superoxide and lithium hydroxide, (2) filtration and high-temperature catalytic oxidation for trace contaminant control, (3) outside cooled circulation glycol heat exchanger for temperature and humidity control, (4) biological activated sludge system for treating the crew waste and supplying effluent for water processing, and (5) water treatment system using high temperature catalytic oxidation and multi-filtration. This study dramatically emphasized the toxicological problems in "closed atmospheres" and the value of integration testing in establishing system design concepts and ensuring operational reliability. Contaminant control system requirements may limit the feasibility and practicality of regenerative life support systems with increasing degrees of closure of the "closed atmosphere" for the foreseeable future.

FUTURE LIFE SUPPORT SYSTEMS

Life support systems include more than the "closed atmosphere". In addition to atmospheric and thermal control, future life support systems must integrate food, water, and waste management. Prototype life support systems should make maximum utilization of spacecraft by-products and be compatible with weight, power, and volume capabilities. Longer space missions will require regenerable life support systems.

In order of increasing complexity, the development of regenerable systems for (1) CO_2 removal, (2) reclamation of humidity condensate and urine water, (3) extraction of oxygen from CO_2 and water, (4) reclamation of fecal water, and (5) food production will gradually close future life support systems. However, biological regenerative systems appear beyond the next generation of life support systems (10-15 years); water probably being the only material recovered from human wastes[54]. This outlook is based primarily on engineering reasons, although there would appear to be sufficient justification for this appraisal on consideration of the complexity of the potential contamination problem with biological systems. Additionally, reliability would have to be established as "crop failures" could be diastrous.

General Dynamics is currently fabricating for NASA, Langley, a 4-man total integrated regenerative life support system with a 90-day resupply suitable for zero g operation in space stations. It is estimated that the system would weight 1,410 pounds, use an average of 2,062 watts and require 1,433 pounds of expendables every 90 days. This system will be installed at NASA Langley Research Center for both unmanned and manned experiments to resolve systems integration problems and evaluate their performance against realistic mission requirements. With the advent of future NASA space programs, orbiting space stations, MOLAB, planetary missions, etc., the components and subsystems of space systems will change markedly. However, man, the most complex and versatile component in the space system, will change neither in design nor function since man's structural changes are measured in millennia rather than months or years of an engineering timetable. It is imperative that the methods of preserving man's health and facilitating his performance (the "closed atmosphere") keep pace with the vehicles and boosters capable of placing him in the more demanding future missions of the space age[55].

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MAJOR ENVIRONMENTAL CATEGORIES	FACTORS COMPOSING CATEGORY
WEIGHTLESSNESS	•DECREASED WEIGHT BEARING (↓ METABOLISM) •HYDROSTATIC EFFECTS •ORGAN POSITIONS WITHIN THE BODY •LOSS OF CONVECTION CURRENTS •GRAVITY ORIENTED BODILY SENSATIONS •UNKNOWN EFFECTS (E.G. CELLULAR LEVEL)
DYNAMIC FACTORS	•LINEAR ACCELERATION •ANGULAR ACCELERATION •VIBRATION AND SOUND
IONIZING RADIATION	•PROTON, ELECTRON, HEAVY NUCLEI, GAMMA, X-RAY

Figure 1 Space Environments

MAJOR ENVIRONMENTAL CATEGORIES	FACTORS COMPOSING CATEGORY
CABIN ATMOSPHERE	O_2, CO_2, N_2, H_2O, BAROMETRIC PRESSURE
CONTAMINANTS	CHEMICAL BIOLOGICAL
THERMAL ENVIRONMENT	HEAT COLD
CIRCADIAN RHYTHMS	LIGHT DARK TEMPERATURE GRAVITY-MAGNETIC FIELD
PSYCHOPHYSIOLOGICAL FACTORS	ISOLATION-CONFINEMENT INTERPERSONAL RELATIONSHIP WORK-REST CYCLE

Figure 2 Space Environments (cont.)

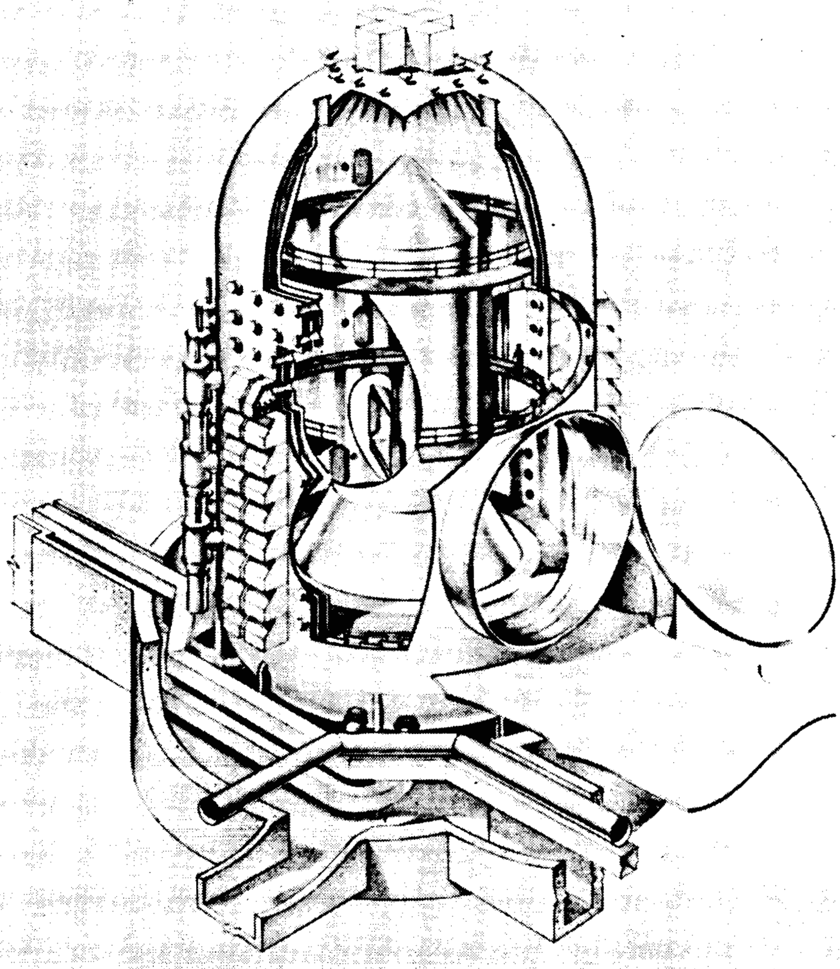

Figure 3 Artist's Conception NASA, Manned Spacecraft Center Chamber

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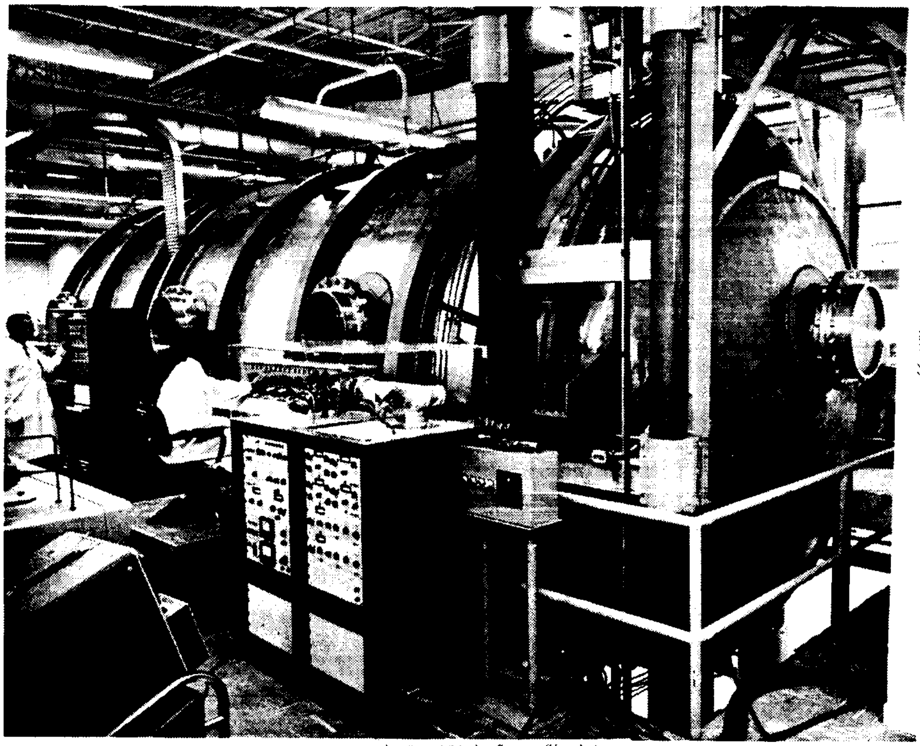

Figure 4 Republic's Space Simulator

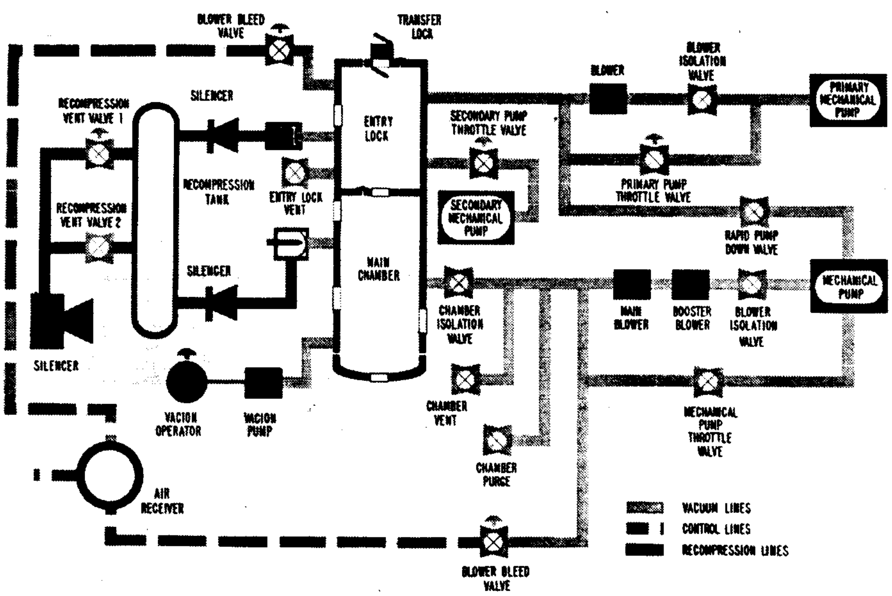

Figure 5 Main Console Schematic Display

XXV-55

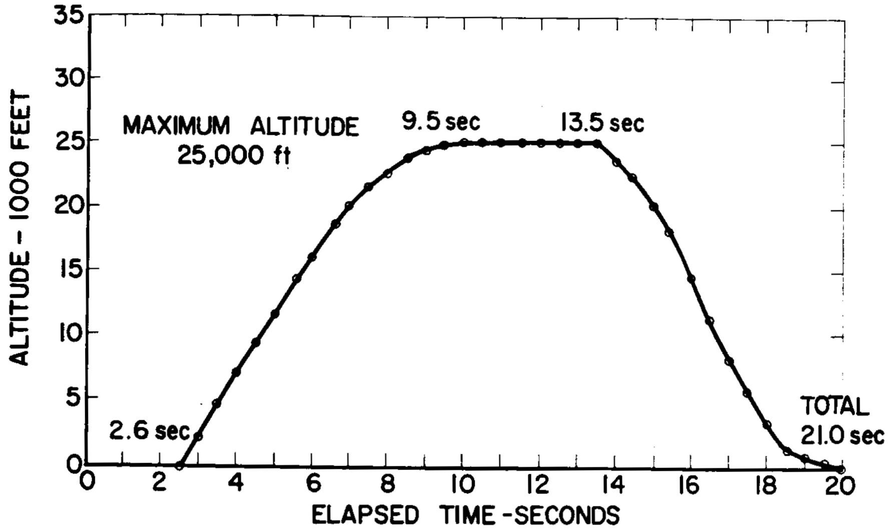

Figure 6 Emergency Recompression Incident

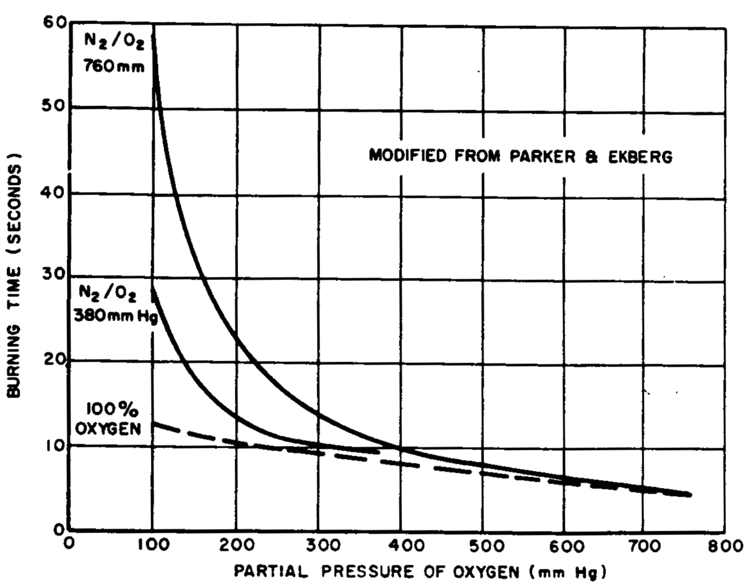

Figure 7 Burning Time

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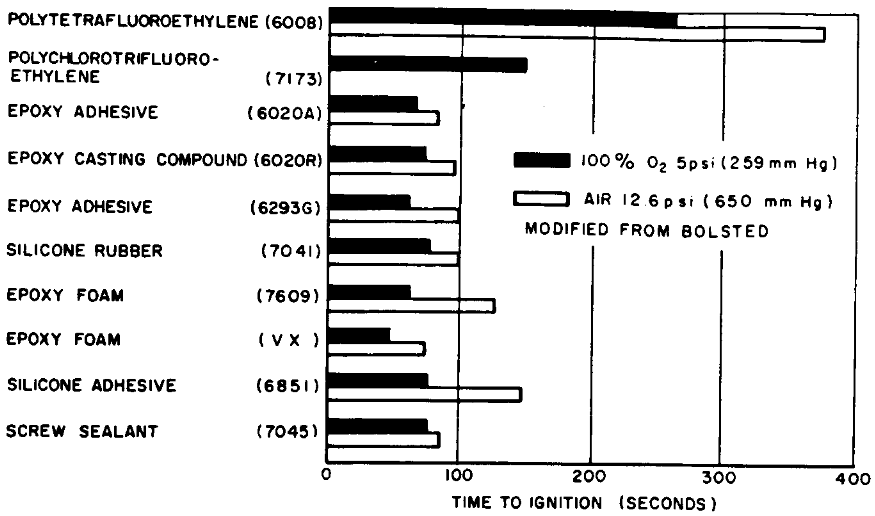

Figure 8 Ignition Time

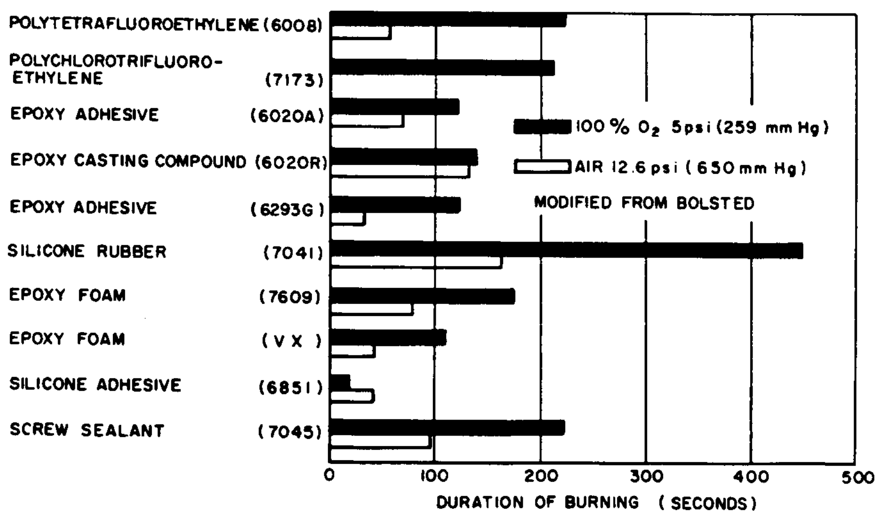

Figure 9 Material Burning Time

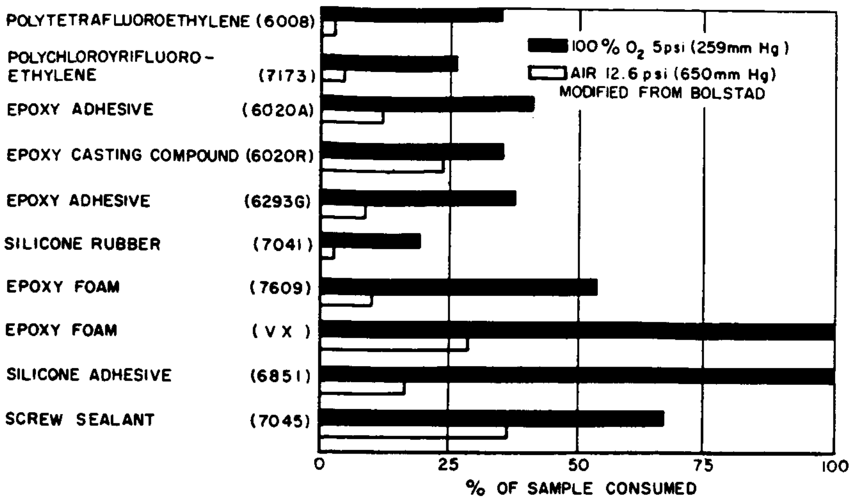

Figure 10 Extent of Material Damage

EVALUATION	Mon (Pre-run)	Tues 1	Wed 2	Thurs 3	Fri 4	Sat 5	Sun 6	Mon 7	Tues 8	Wed 9	Thurs 10	Fri 11	Sat 12	Sun 13	Mon 14	Tues (Post-run)
MEDICAL DATA																
Physical Exam	•															•
Neurological Exam	•															•
Chest X-Ray (in chamber)	•					•										•
EKG	•															•
Intake, Output		•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Body Weight	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Blood Pressure	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Pulse	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Respiratory Rate	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Body Temperature	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
MENTAL PERFORMANCE																
GATB																
Verbal Ability	•								•						•	
Numerical Ability	•								•						•	
Space Relations	•								•						•	
Clerical Ability	•								•						•	
(PANEL PERFORMANCE)																
Arithmetic Computation	•	•	•	•	•	•	•	•		•	•	•	•	•	•	
Pattern Discrimination	•	•	•	•	•	•	•	•		•	•	•	•	•	•	
Scale Position Monitoring	•	•	•	•	•	•	•	•		•	•	•	•	•	•	
Tracking	•	•	•	•	•	•	•	•		•	•	•	•	•	•	
SENSORY PERFORMANCE																
Visual Acuity	•		•		•		•		•		•		•		•	
Critical Flicker Fusion Frequency	•		•		•		•		•		•		•		•	
Dark Adaption	•		•		•		•		•		•		•		•	
Audiometry	•								•							•
MOTOR PERFORMANCE																
Reaction Time	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Fine Motor Coordination	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
Gross Motor Coordination	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
* Work Performance	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	
PULMONARY FUNCTION DATA																
Tidal Volume	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Timed Vital Capacity	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
* Max. Breathing Capacity	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Inspiratory Reserve	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Expiratory Reserve	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Alveolar Gas Analysis	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Diffusion Capacity	•															•
Total Lung Capacity	•															•
BLOOD AND SERUM																
Venous																
Plasma Volume	•															•
CBC	•		•		•			•		•		•			•	
Hemoglobin	•		•		•			•		•		•			•	
Sedimentation Rate	•		•		•			•		•		•			•	
Hematocrit	•		•		•			•		•		•			•	
Reticulocyte Count	•								•						•	
Urea	•							•							•	
Glucose	•							•							•	
Na, K, Cl	•		•		•			•		•		•			•	
Arterial																
pO_2, pCO_2, pH (Electrode)	•					•										•
O_2, CO_2 content and capacity	•					•										•
URINE																
Specific Gravity	•		•		•			•		•		•			•	
pH	•		•		•			•		•		•			•	
Protein	•		•		•			•		•		•			•	
Sugar	•		•		•			•		•		•			•	
17 OH Corticosteroids	•							•							•	
MICROBIOLOGICAL DATA																
Skin	•		•		•			•		•		•			•	
Throat	•		•		•			•		•		•			•	
Urine	•		•		•			•		•		•			•	
Feces	•		•		•			•		•		•			•	

* Only three subjects exercise and perform MBC daily

Figure 11 Schedule of Data Collections

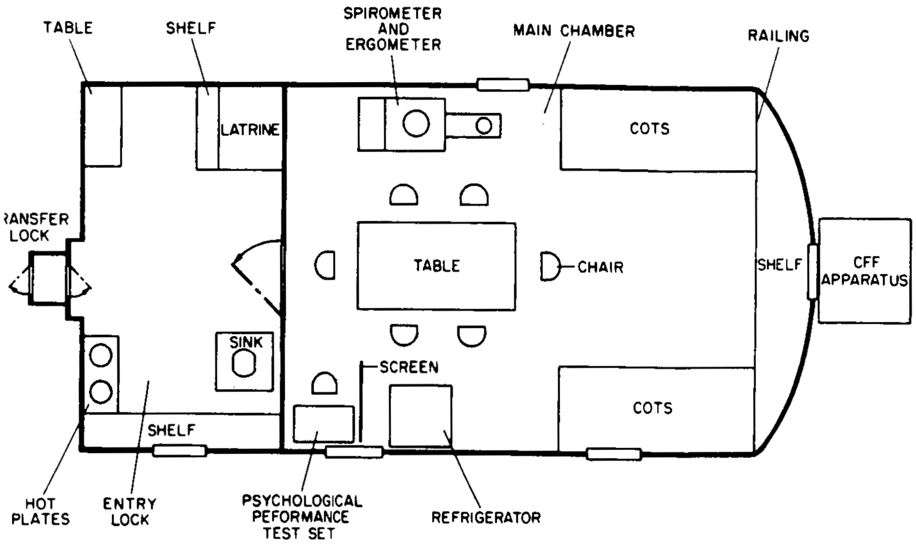

Figure 12 Schematic of Space Simulator

Analysis	Quantity V/V	
	1	2
Oxygen	99.82%	99.82%
Argon	0.1%	0.1%
Nitrogen	0.01%	0.01%
Total Hydrocarbon such as CH_4	17 ppm	16 ppm
Methane	11 ppm	10 ppm
Ethane	0.03 ppm	0.02 ppm
Carbone Dioxide	0.8 ppm	0.6 ppm
Krypton	8 ppm	9 ppm

Figure 13 Analyses of Liquid Oxygen Cylinders

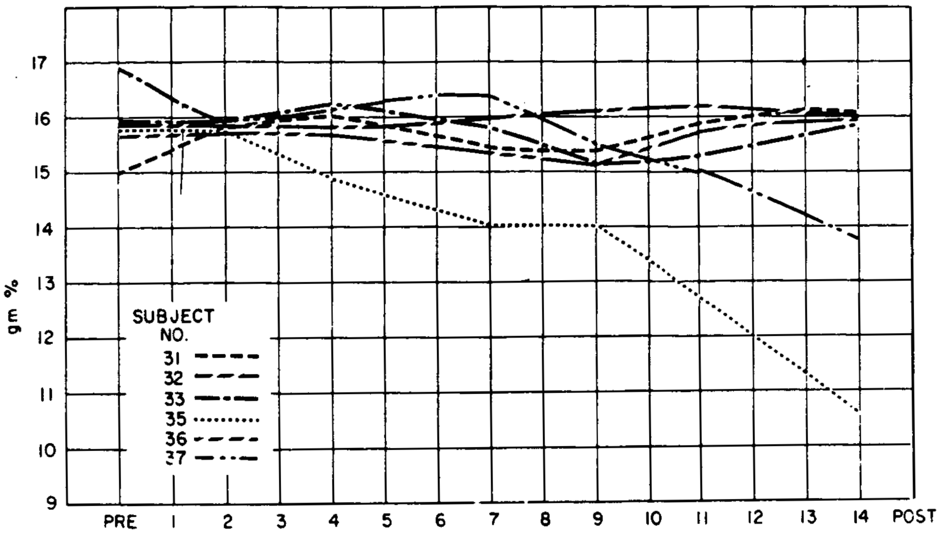

Figure 14 Hemoglobin Concentration at 5 psi

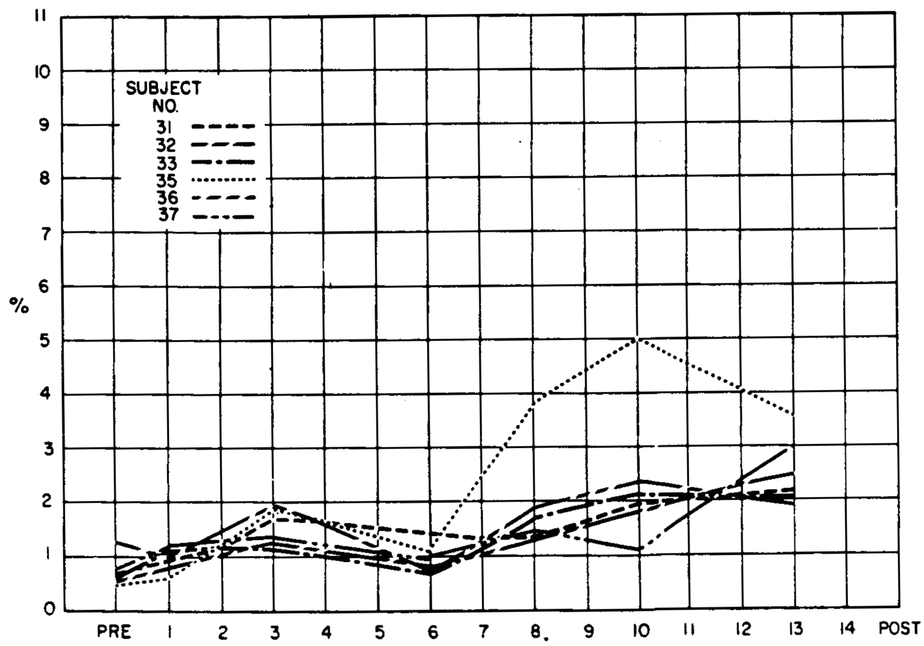

Figure 15 Reticulocytes at 5 psi

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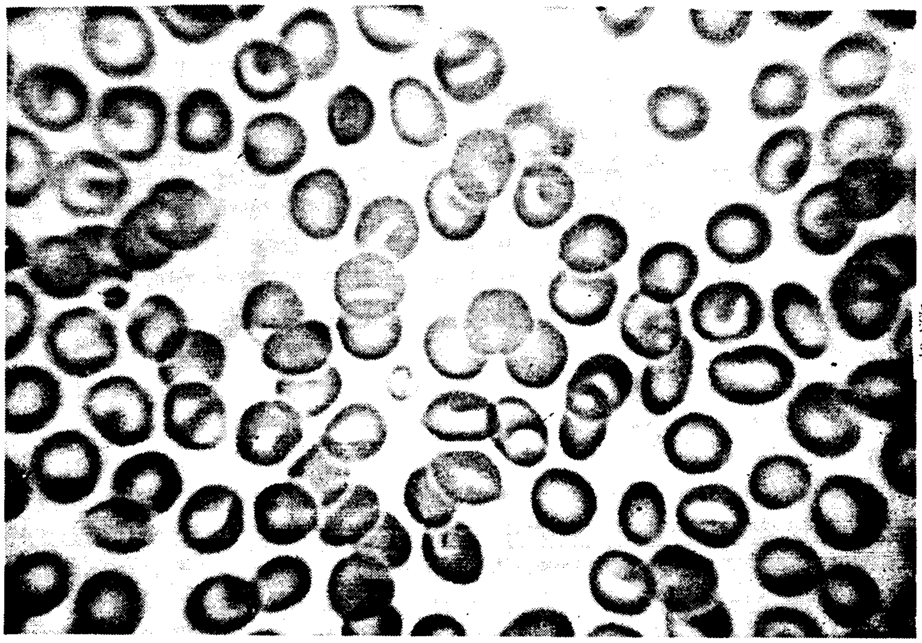

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Figure 16 Morphology of Peripheral Blood - Thalassemia Trait

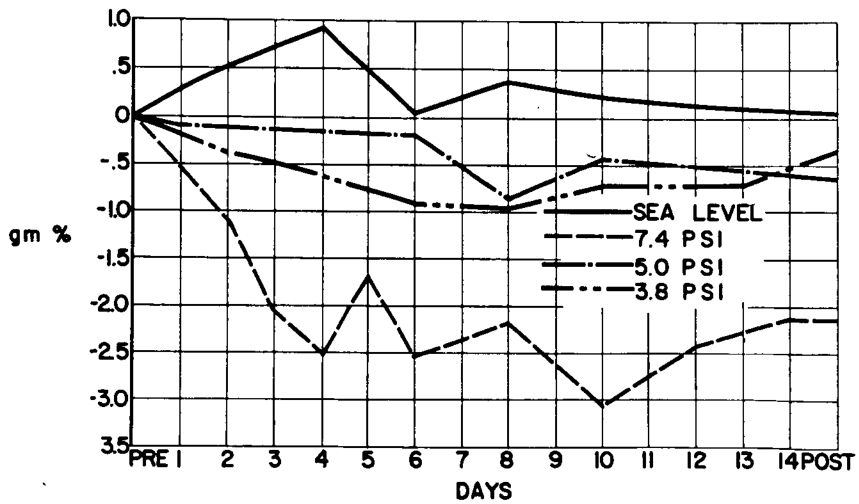

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Figure 17 Average Change in Hemoglobin Concentration

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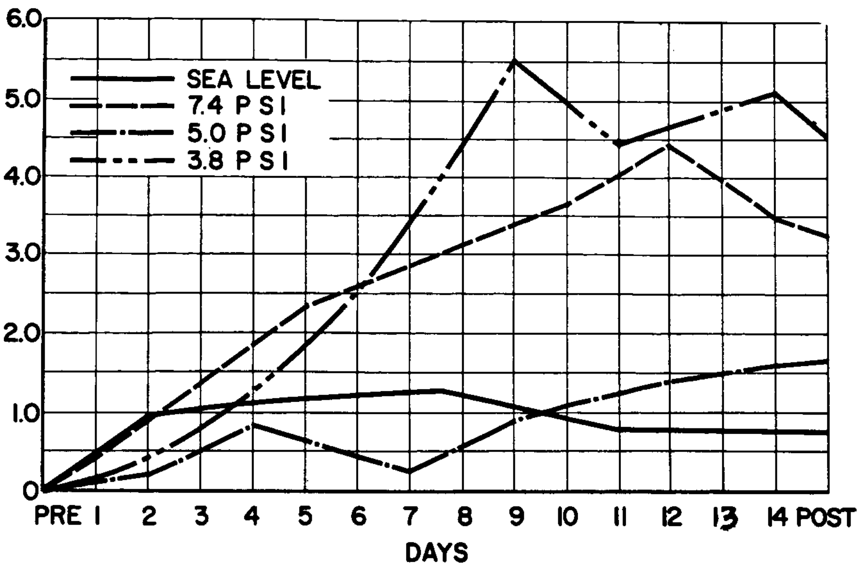

Figure 18 Average Increase in Reticulocytes

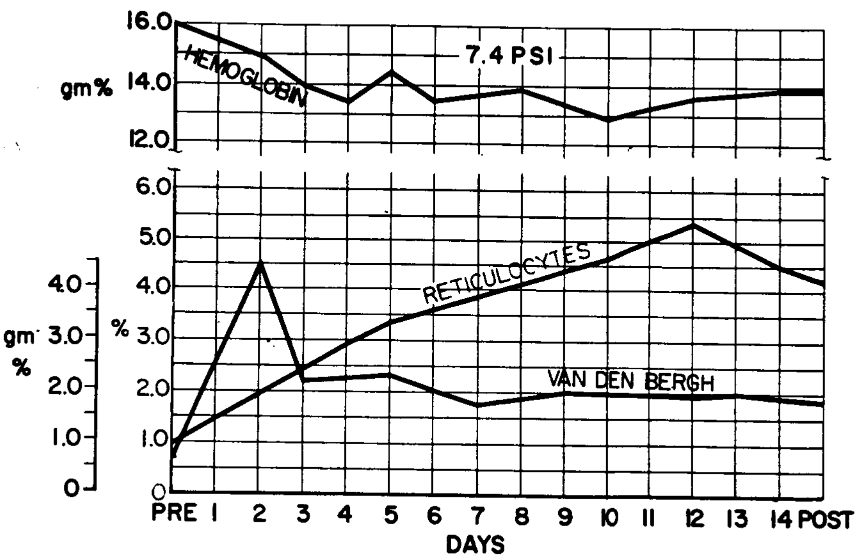

Figure 19 Average Hemoglobin Concentration, Reticulocytes and Van Den Bergh Determination

XXV-62

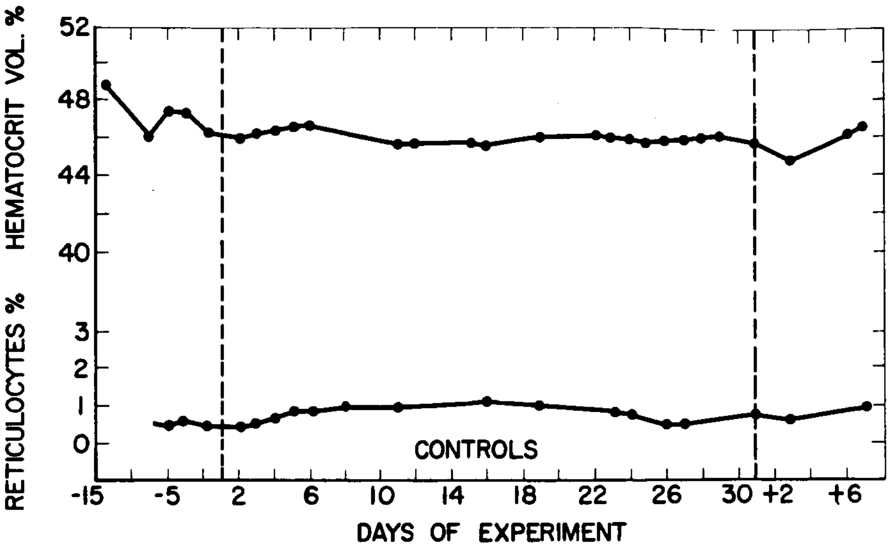

Figure 20 Average Hematocrit and Reticulocytes of Controls
Brooks 30-Day Experiment

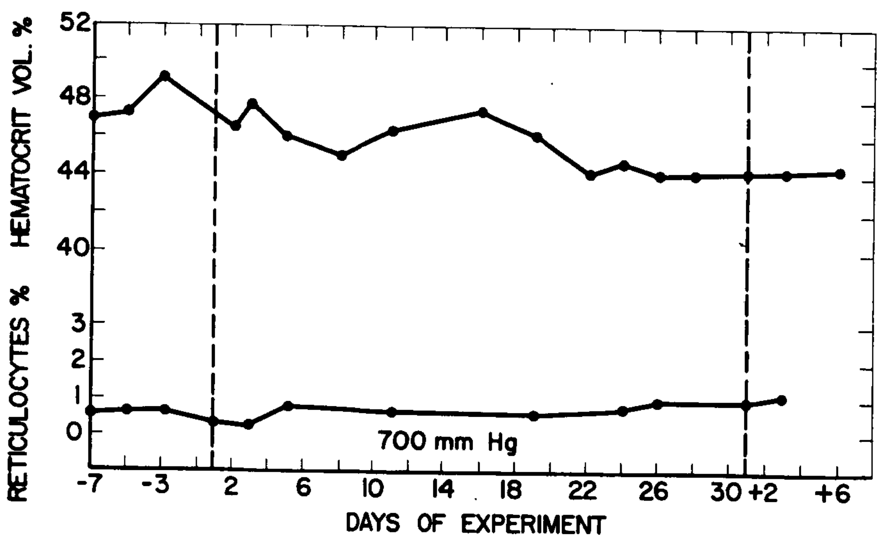

Figure 21 Average Hematocrit and Reticulocytes at 700 mm Hg
Brooks 30 Day Experiment

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VIRGINIA ENGINEERING EXPERIMENT STATION

DIRECTOR	583
Aerospace Engineering	255
Architecture (School)	243
Business (School)	440
Ceramic Engineering	548
Chemical Engineering	248
Chemistry	258
Civil Engineering	281
Electrical Engineering	409
Engineering Mechanics	245
Geological Sciences	279
Industrial Engineering	285
Mathematics	252
Mechanical Engineering	206
Metallurgical Engineering	382
Mining Engineering	380
Physics	295
Wood Construction	488