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LECTURES in AEROSPACE MEDICINE 1967

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6-9 February 1967

SIXTH SERIES

USAF SCHOOL OF AEROSPACE MEDICINE
AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS

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School of Aerospace Medicine
Brooks AFB, Texas

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*The contents of the lectures presented in this publication reflect personal views of the authors and are not to be construed as a statement of official USAF policy.

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Progress in Unmanned Space Exploration

Dr William H. Pickering

Dr. Pickering is Director of the Jet Propulsion Laboratory, California Institute of Technology. He received his B. S. degree in electrical engineering, his M. S. degree, and his Ph. D. degree in physics from California Institute of Technology. He joined the faculty of the Institute as an instructor in electrical engineering and technology, was appointed successively assistant professor, associate professor and professor in electrical engineering. Dr. Pickering was appointed to his present position in 1954. Under his direction, the U. S. lunar and planetary missions RANGER, MARINER, and SURVEYOR were planned, developed, and carried out at the Laboratory. Among the many awards he has won is the NASA Distinguished Service Medal which was presented by President Johnson.

PROGRESS IN UNMANNED SPACE EXPLORATION

William H. Pickering, Ph. D.

General Roadman, Colonel Nuttall, ladies and gentlemen, it is a pleasure to be here to help keynote your sessions in Aerospace Medicine. I must confess, however, that when I first considered the keynote address for this meeting, I wondered why we should keynote a meeting which is concerned with man in space with a discussion on instruments in space. However, it does seem to be appropriate that in considering the utilization of both manned and unmanned space flights we recognize the constraints and limitations of both. Particularly in the field of science explorations in space, a great deal has been accomplished with unmanned instrumented spacecraft, and in the future both manned and unmanned space flights will be necessary in the exploration of space.

It is just over nine years since the first U.S. satellite, Explorer I, was placed in orbit on January 31, 1958; and in this nine-year period, both the U.S. and the U.S.S.R. have devoted a large fraction of their technical resources to the exploration of space. Rockets, spacecraft, and tracking stations have been developed to gather scientific information about conditions above the Earth's atmosphere, and to explore the Moon and the nearby planets. Some flights to outer space have carried men; others have carried instruments only; and this morning I shall discuss some of our achievements in the latter area, that of unmanned instrumented space flights.

Scientific knowledge advances through quantitative observations of nature, either directly or as the result of experiments conducted within carefully prescribed constraints. Instruments, therefore, are at the core of all modern science. The development of any particular branch of science is paced by the ability to accurately measure the parameters descriptive of the phenomena and by observation. Originally, man used his own senses to make subjective measurements of the physical world around him. For example, his sense of touch told him whether an object was hot or cold. But science today replaces the sense of touch with a whole host of thermometers which not only make objective quantitative measurements, but which extend the range of measurement far beyond the biological limits of man's flesh. The existence of accurate, reproducible thermometers is the first requirement for the scientific understanding of thermal phenomena. Similarly, in all branches of exploratory or experimental science, an instrument measures the phenomenon and man records the data. Man is the planner and the observer. On the basis of prior observations and analysis, he decides which experiments to conduct and which data to collect.

In the scientific exploration of space, however, the problem becomes more complex. The planet Mars, for example, is a whole new world, nearly as big as Earth, now available for exploration. How shall man be used in this undertaking? Traditionally, man has been the explorer of new territory, first with sketch pad and notebook, and more recently with camera and tape recorder. Until half a century ago, the explorer lost all contact with his home base soon after his journey began. He was dependent solely on his own resources and ingenuity to reach his destination and return. Today, he probably carries his own radio equipment and is in regular contact with his home base. The modern explorer is likely to be the field observer for a team which includes a laboratory of experts who analyze his observations in extensive, scientific detail. However, when it becomes too difficult or too hazardous for man to explore a particular site or locality, observations may then be obtained by the use of some robot device. The effectiveness of such a robot explorer will depend, of course, upon the ingenuity of design of the device.

For many years some scientific instruments have reported their readings to observers at considerable distances. The technique, called telemetering, was first used extensively in the electrical power industry. During World War II, radio telemetering was developed so that instruments could report data many miles distant from the receiving station. After the war, the demands of burgeoning rocket and missile systems required greater sophistication of radio telemetry and, in fact, rocket and missile development could not have evolved as rapidly as it did without reliable and accurate telemetry. With the space program, radio telemetry systems of longer range were developed until any scientific instrument or measurement which can be converted into an electrical signal can now be transmitted to great distances, even the distance from Earth to Mars. Thus, the first requirement for remote scientific exploration of space has been provided.

The second requirement is the ability of a robot to respond to commands. These may be sent over a radio circuit or may be generated internally, as a result of some data which have been collected or stored previously. Both methods, commands from Earth and those generated internally, have been used successfully in unmanned space exploration so that man, the explorer, can remain on Earth to command and control his robot spacecraft as it travels to Mars and reports its findings. Obviously, the value of such an arrangement depends upon the versatility, the accuracy, and reliability of the robot spacecraft as against the scientific value of having man himself on the distant planet with his own powers of observation and intelligence. The manned flight, of course, presents more difficult technological problems and requires a larger and heavier spacecraft for both the life support system and the considerable amount of rocket fuel needed to insure the return flight. Therefore, if the scientific data can be obtained by robot spacecraft while the explorer-scientist remains in his laboratory on the Earth, the much smaller cost of the mission would argue strongly for such a choice.

Some of the recent unmanned space flights are illustrated in the following figures:

(Figure 1) This photograph of the Pacific Ocean was taken by satellite about 22,000 miles above the Earth. Almost half of the Earth's surface can be seen. In the upper right hand corner, at about two o'clock, a large portion of California shows. The photograph is an example of how well wide band data may be transmitted over considerable distances from a satellite accurately placed on a predicted orbit.

Figure 1. Pacific Ocean from Applications Technology Satellite.

(Figure 2) The use of spacecraft for meteorological observations presents some interesting possibilities for new methods of weather analysis and forecasting. This picture shows some of the satellites which are under consideration for such applications. The Nimbus series of spacecraft will carry both visual and infra-red instrumentation, for cloud cover and temperature observations of the atmosphere. With these meteorological satellites, it will be possible to gather detailed information of the atmosphere and weather processes over large areas of the Earth.

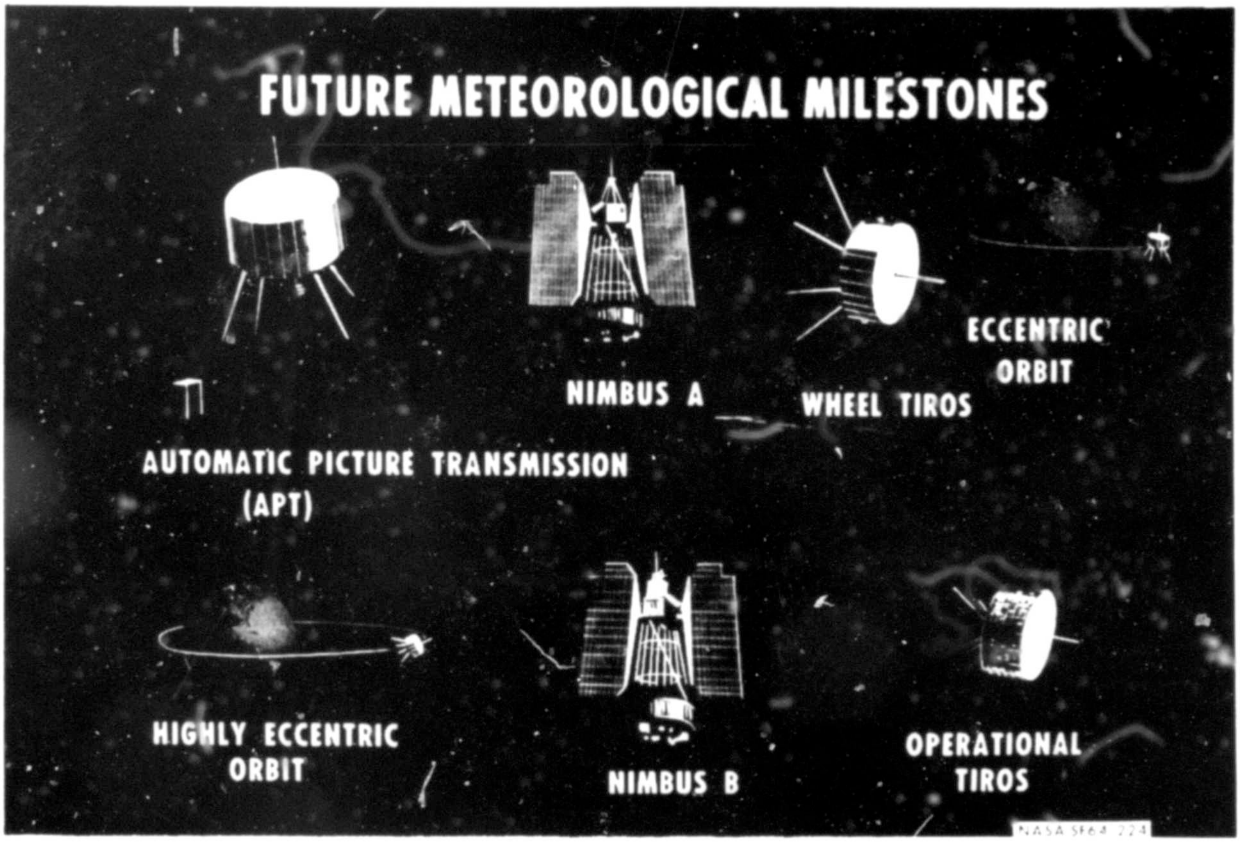


Figure 2. Future Meteorological Satellite.

(Figure 3) At the present time a Lunar Orbiter, is enroute to the Moon. The spacecraft will be flown on a precise path to the Moon and will then be placed in a precise orbit around the Moon. Orbiter III appears to be on a very good trajectory and at just about this time a mid-course maneuver is being conducted to adjust the trajectory slightly. The velocity change in the mid-course maneuver is only five meters per second. Once the spacecraft arrives at the Moon and is placed in orbit, the spacecraft will be under such precise control that the on-board cameras can be directed at specific lunar targets and, indeed, during the course of the mission, these targets can be changed and others selected.

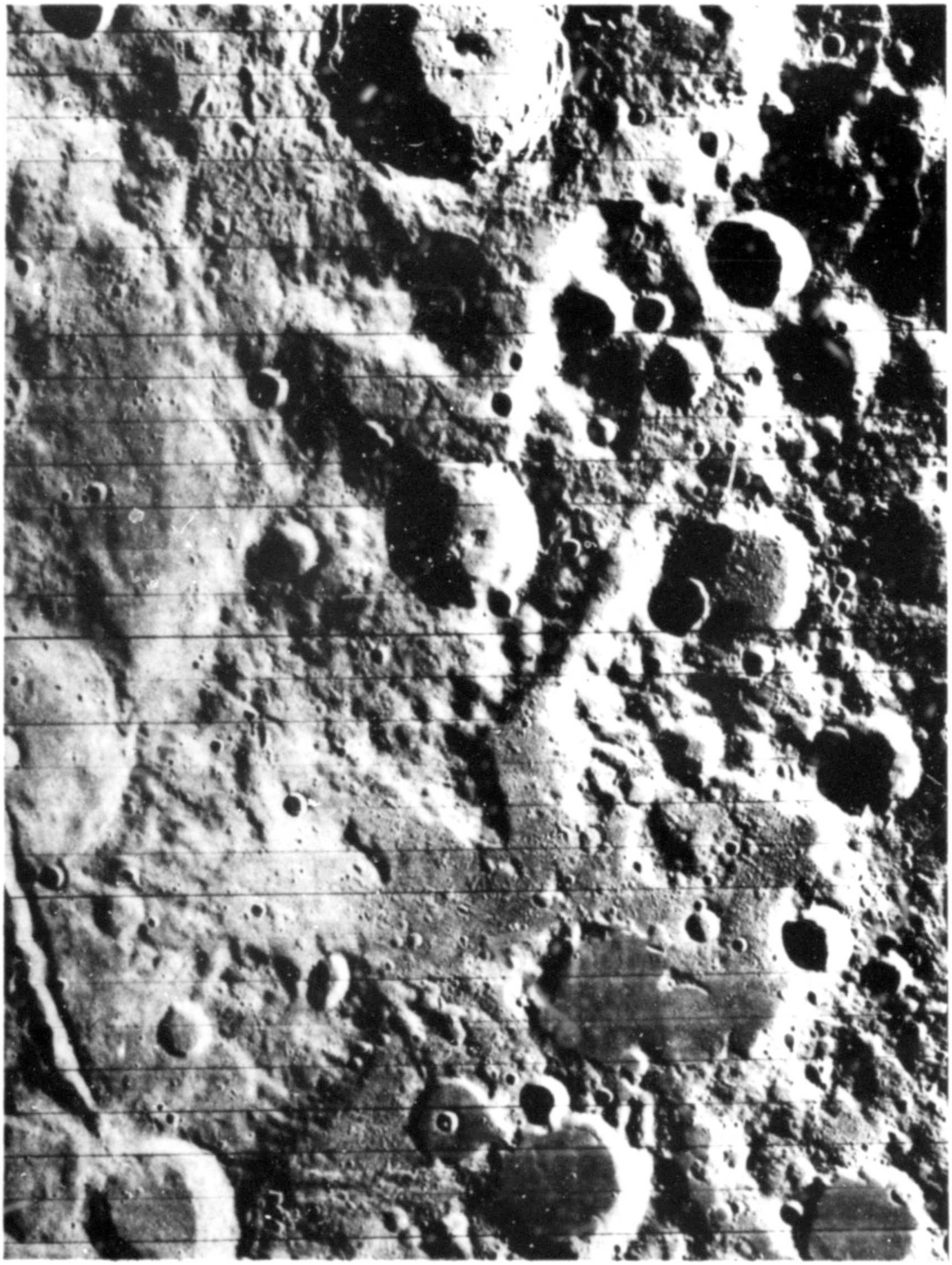


Figure 3. Lunar Orbiter Photograph of a Region Near the Moon's South Pole.

(Figure 4) This outstanding photograph of the crater of Copernicus was a target of opportunity selected during the first Orbiter mission. It was taken because of the general scientific interest in getting an oblique view of the well-known lunar crater. The small range of mountains in the center of the picture is essentially the central peak of the crater. The walls of the crater are in the background, and in the immediate foreground. Copernicus is about 50 miles in diameter.

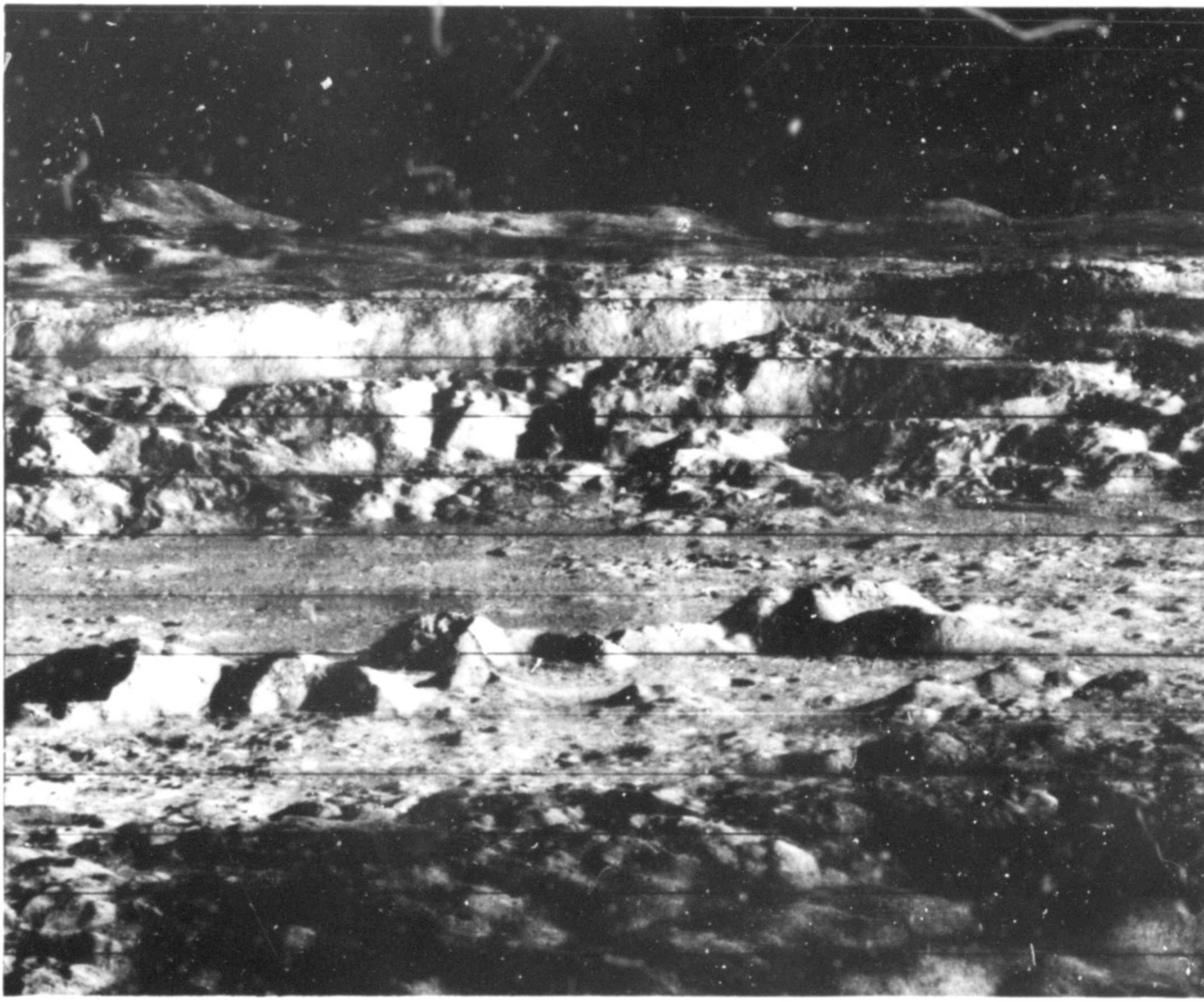


Figure 4. Crater Copernicus from Lunar Orbiter.

(Figure 5) In this remarkable photograph of the Earth, taken by Lunar Orbiter, the Moon is in the foreground.

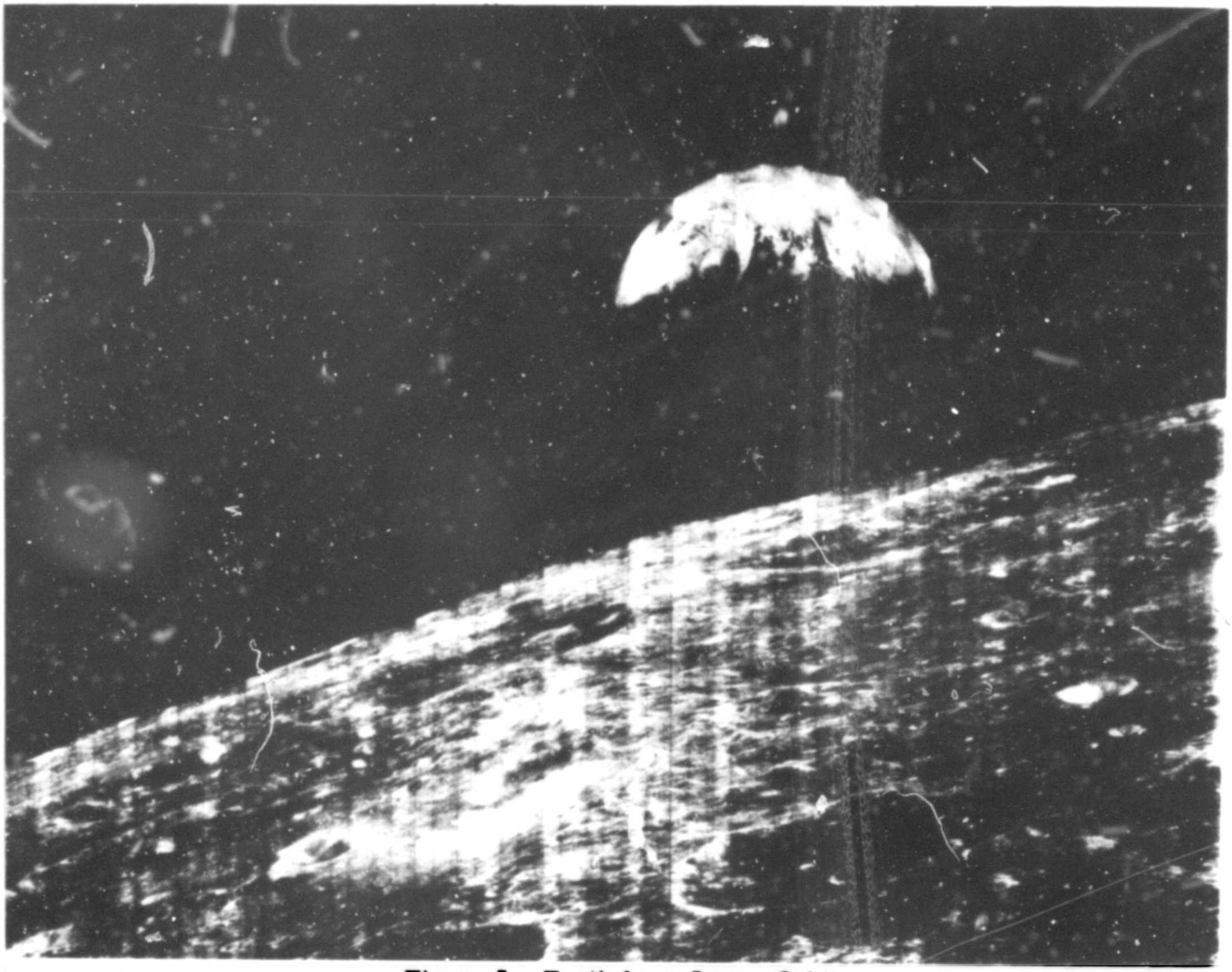


Figure 5. Earth from Lunar Orbiter.

(Figure 6) Another example of an unmanned spacecraft is the soft-landing Surveyor. This photograph shows Surveyor on the beach at Malibu, much the same as it looks on the Moon. The ability to land this device gently on the lunar surface as it arrives in the vicinity of the Moon at the speed of about 6,000 miles per hour, demonstrates the ingenuity of design of a spacecraft having a complex internal "intelligence." Surveyor carried a camera which was commanded from Earth so that photographs could be taken at will.

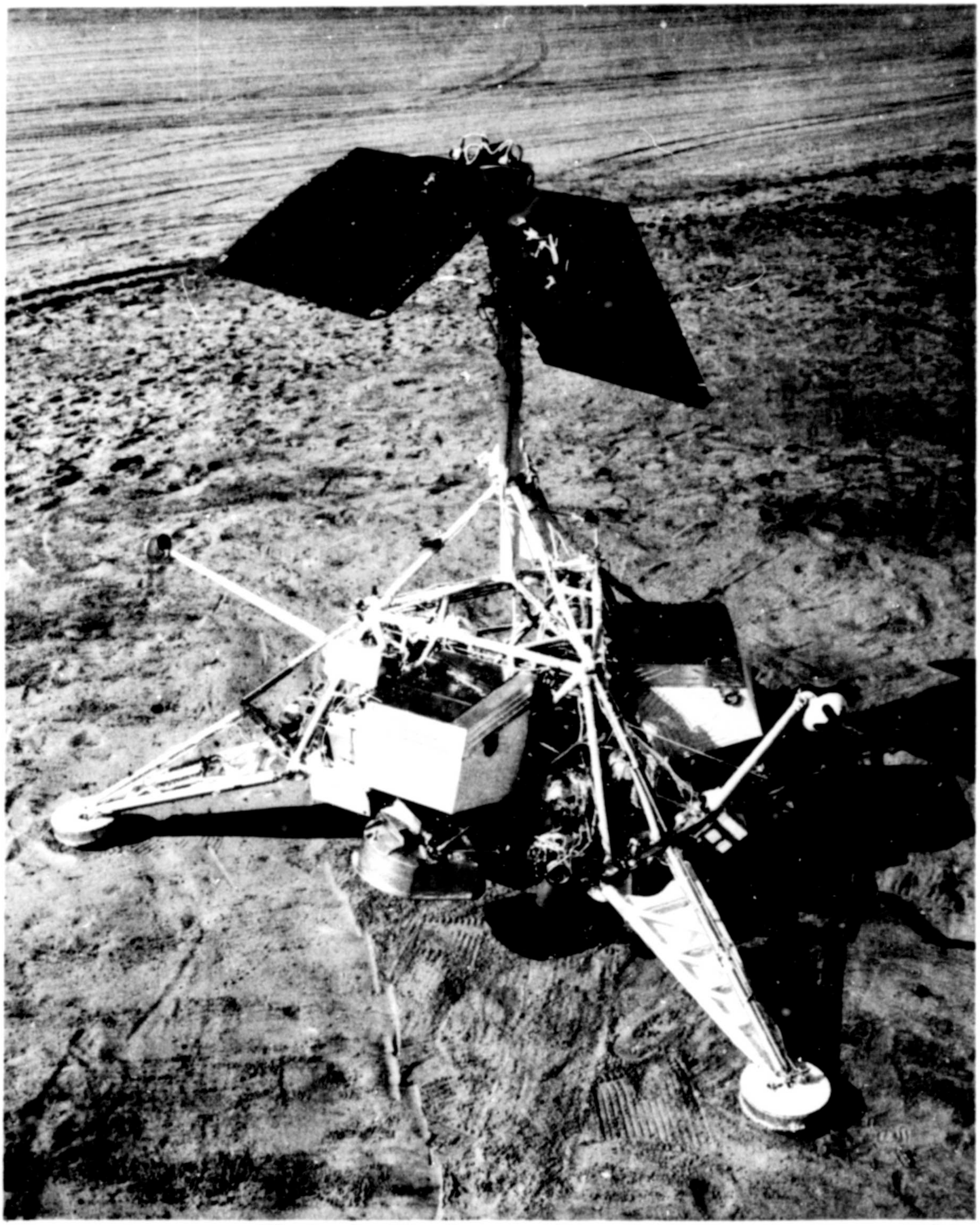


Figure 6. The Surveyor Spacecraft.

(Figure 7) Taken by Surveyor looking out towards the lunar horizon, this photograph shows a small crater, a rocket in the immediate foreground which is about a foot in dimension, and a pile of rocks in the distance, some of which are as much as five and six feet across. Because of the small radius of curvature of the Moon, the distance to the horizon is about a mile.

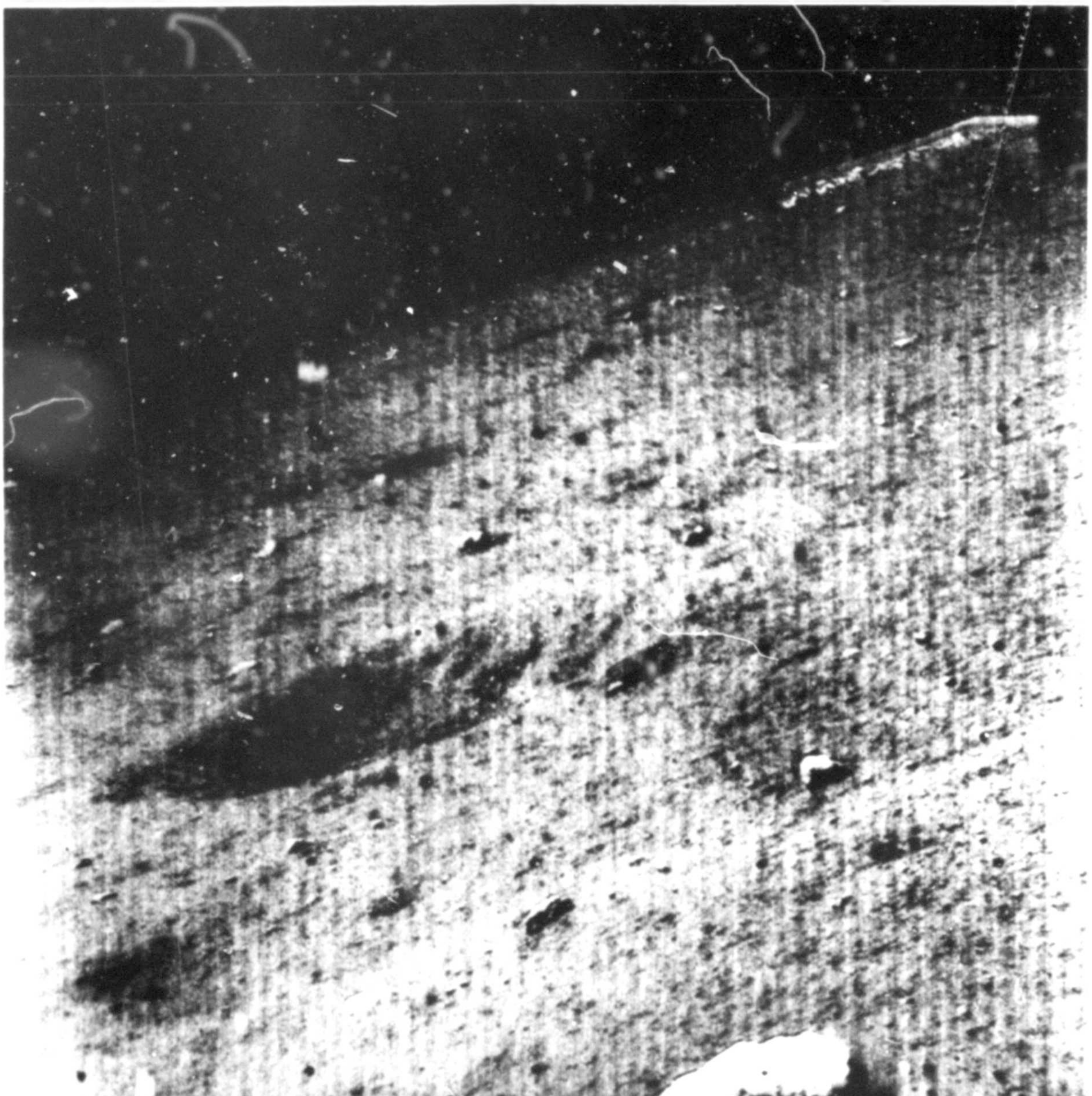


Figure 7. The Lunar Surface as seen from Surveyor I.

(Figure 8) This close-up view of the Surveyor footpad shows how it settled on the lunar surface after landing at a speed of about six miles per hour. Only a very slight depression was caused by the impact. The dimension of this footpad is about ten inches in diameter. The lunar surface in this particular area looks very much like Earth soil, freshly dug.

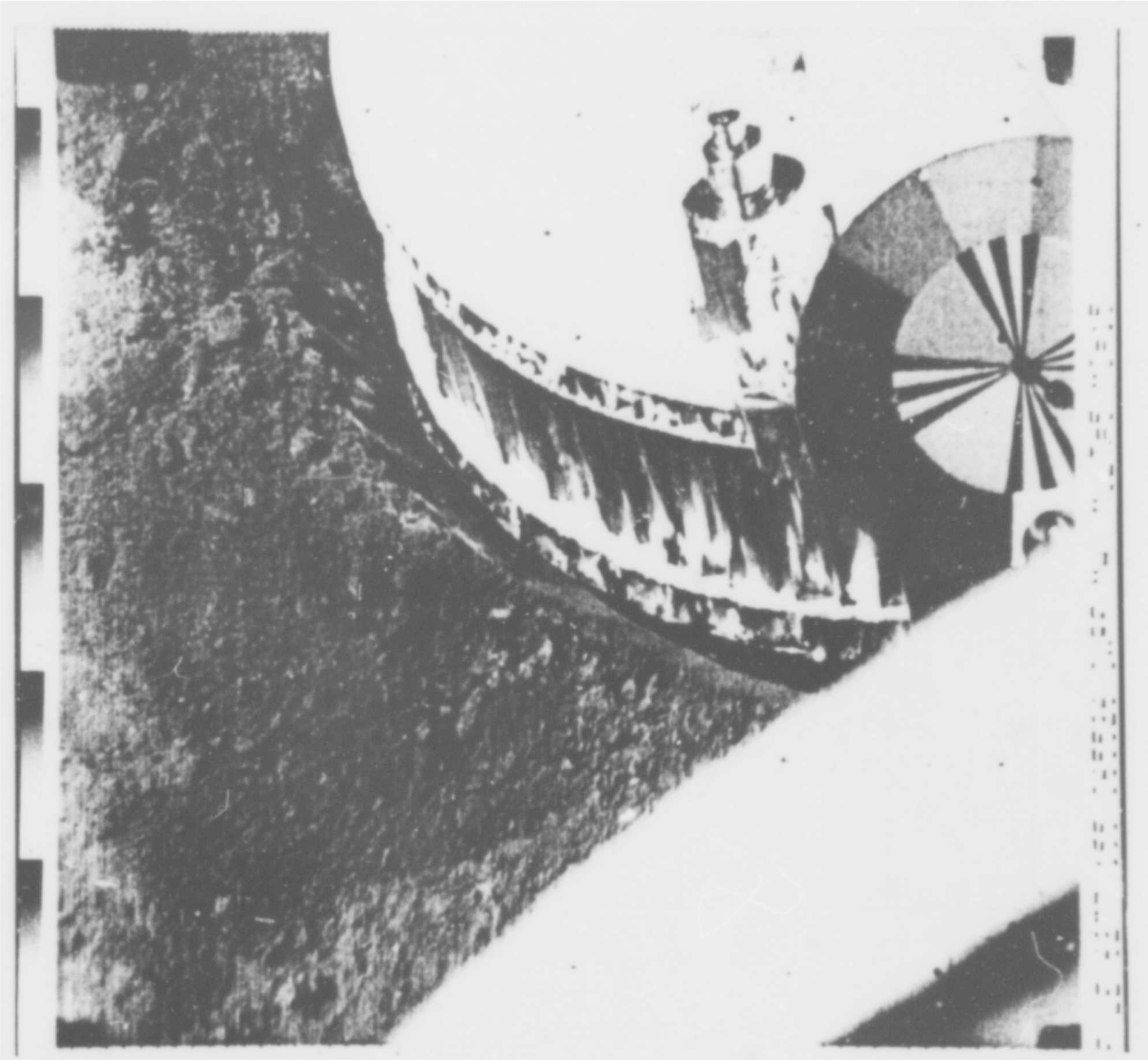


Figure 8. Surveyor I Photograph of Lunar Soil beside One of the Landing Feet.

These examples indicate what can be done today with unmanned spacecraft from the point of view of command capability: a spacecraft can be sent to a pre-selected target area, it can be instructed to turn its instruments on and off when requested, and in a prescribed manner, it can transmit a considerable amount of scientific data from great distances.

(Figure 9) From the point of view of the development of unmanned spacecraft, this picture shows the increase in complexity of a series of spacecraft over a period of time.

BASIC SPACECRAFT CONCEPTS FOR JPL FLIGHT PROJECTS

AVAILABILITY	PLANETS	MOON	MAJOR TECHNOLOGICAL ADVANCES REQUIRED
1960-1965	FLYBY	NON-SURVIVABLE PROBE	▸ THE TOTAL DEVELOPMENT OF THE ATTITUDE CONTROLLED SPACECRAFT
1966-1969		SURVIVABLE LANDER	▸ LARGER LAUNCH VEHICLES ▸ RETRO-PROPULSION AND TERMINAL CONTROL ▸ SURFACE EXTREMES ▸ MORE COMPLEXITY
1971 ⟶	ORBITER NON-SURVIVABLE PROBE		▸ STERILIZATION ▸ RELAY COMMUNICATIONS ▸ ENTRY DYNAMICS ▸ MORE COMPLEXITY
1973 ⟶	SURVIVABLE LANDER		▸ ENTRY AND LANDING BASED ON PARTICULAR ATMOSPHERIC, WIND, AND SURFACE CONDITIONS ▸ TERMINAL AND RADIO GUIDANCE ACCURACY ▸ MORE COMPLEXITY
1977 ⟶	LANDED AUTOMATED BIOLOGICAL LABORATORY		▸ BIOLOGICAL DETECTION INSTRUMENTS ▸ LONG-LIFE, NON-SOLAR POWER SYSTEMS ▸ MORE COMPLEXITY

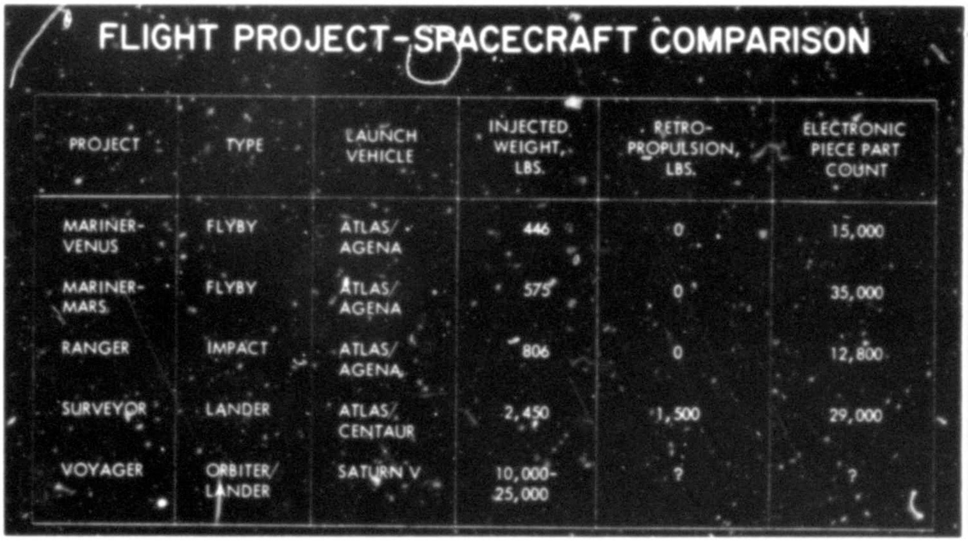
Figure 9. JPL Spacecraft Concepts.

In the 1960-65 period, the attitude controlled spacecraft was developed. If information is to be transmitted over great distances, antennas must be pointed back at the Earth, solar cells must be turned to the sun, and instruments must be aimed at the desired target. Therefore, attitude control is a first requirement.

The next order of complexity, in the 1966-69 period, is a survivable lander, where retro propulsion and terminal control become the important technological problems to be solved and this is represented by the Surveyor.

Moving on into the future, or the 1971 period, there are such possibilities as non-survivable probes landing on one of the planets. These introduce a new set of technological problems associated with sterilization. It is necessary that any spacecraft or instrument which may be landed on another planet be completely sterile if the question as to whether or not life exists on another planet is to be determined. The problem of sterilization of complex electronic devices is a vital part of this program. Relay communications are required in sending a probe to the surface of another planet since the data transmission capability of the probe is relatively small and a relay through the spacecraft in the vicinity will be necessary. In the 1973 time frame, a survivable operating lander on the surface of the planet Mars involves the problems of soft-landing on the surface, as well as an understanding of surface and atmospheric conditions. If a particular landing site is to be chosen, it becomes necessary to add terminal guidance. Finally, in the 1977 period, a landed automated biological laboratory on Mars is planned to make the search for life. A series of instruments will carry out the search and will operate on the surface over a long period of time. A radio-active power system will probably be required to operate on the surface of Mars. During this period, from the 1960's through the 1970's, there will be a continual growth in the capability of unmanned spacecraft. By the end of the 1970's another item, which is not listed here, may be included, namely, mobility on the surface of Mars, particularly if the automated biological laboratory is landed in an area which is considered to be hostile to life forms.

(Figure 10) For the sake of comparison, shown in this chart is a series



FLIGHT PROJECT-SPACECRAFT COMPARISON

PROJECT	TYPE	LAUNCH VEHICLE	INJECTED WEIGHT, LBS.	RETRO-PROPULSION, LBS.	ELECTRONIC PIECE PART COUNT
MARINER-VENUS	FLYBY	ATLAS/AGENA	446	0	15,000
MARINER-MARS	FLYBY	ATLAS/AGENA	575	0	35,000
RANGER	IMPACT	ATLAS/AGENA	806	0	12,800
SURVEYOR	LANDER	ATLAS/CENTAUR	2,450	1,500	29,000
VOYAGER	ORBITER/LANDER	SATURN V	10,000-25,000	?	?

Figure 10. JPL Spacecraft Comparisions.

of spacecraft which have successfully performed their missions -- with the exception of the future Voyager. Mariner II, flown in 1962; Mariner IV, in 1964; the Ranger and Surveyor, in 1965 and 1966; and the Voyager which will be flown in 1973. The injected weight leaving the Earth grows steadily up to the Voyager capability which uses a Saturn V launch vehicle. A measure of the complexity of the spacecraft is indicated in the electronic piece part count.

(Figure 11) The series of spacecraft developed for planetary research is illustrated in this photograph. Mariner II flew by Venus in December 1962; Mariner IV flew by in July 1965, and is still operating very nicely. Of course, it is now in orbit around the sun. About a year ago, it was approximately in line with the sun on the far side, and now is coming back toward the Earth where this summer it will be at a distance of about 30,000,000 miles. Mariner-Venus will be launched towards the planet Venus in June of this year. It is in fact regarded as being a flight spare of the Mariner IV to Mars. It was modified to travel towards the sun for Venus instead of away from the sun for Mars and some of the instrumentation was also modified. Mariner Mars in 1969 will perform a more complex mission than Mariner IV. In particular, it will observe the planet more closely as it flies by.

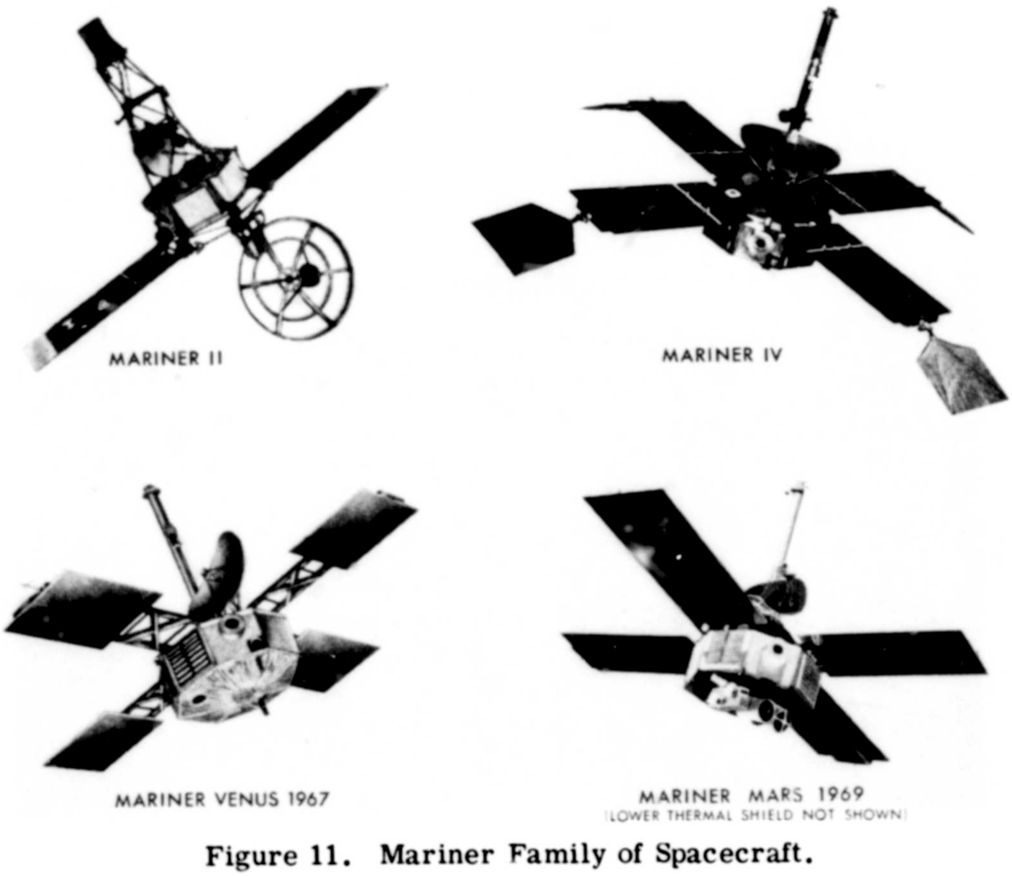


Figure 11. Mariner Family of Spacecraft.

(Figure 12) This photograph shows Mars as seen through an Earth-based telescope. It is obvious that a telescopic view of Mars gives little information of a planet comparable in size to Earth. A polar cap may be seen as well as a dark region. Astronomers have been intrigued for many years by the seasonal changes which appear on the planet, particularly since Mars has a rotation period almost the same as that of the Earth and the inclination of its axis to the plane of the ecliptic is also about the same as that of the Earth. The seasons on Mars are comparable to those on Earth, except that they are longer, since the year on Mars is about two Earth years. With the change in appearance of the polar caps and the emergence of dark areas, vegetation is suggested and possibly water vapor or carbon dioxide to form the polar cap. For many years astronomers have reported seeing canals in straight line patterns across the surface of Mars. However, canals, as such, have never been clearly photographed on Mars.

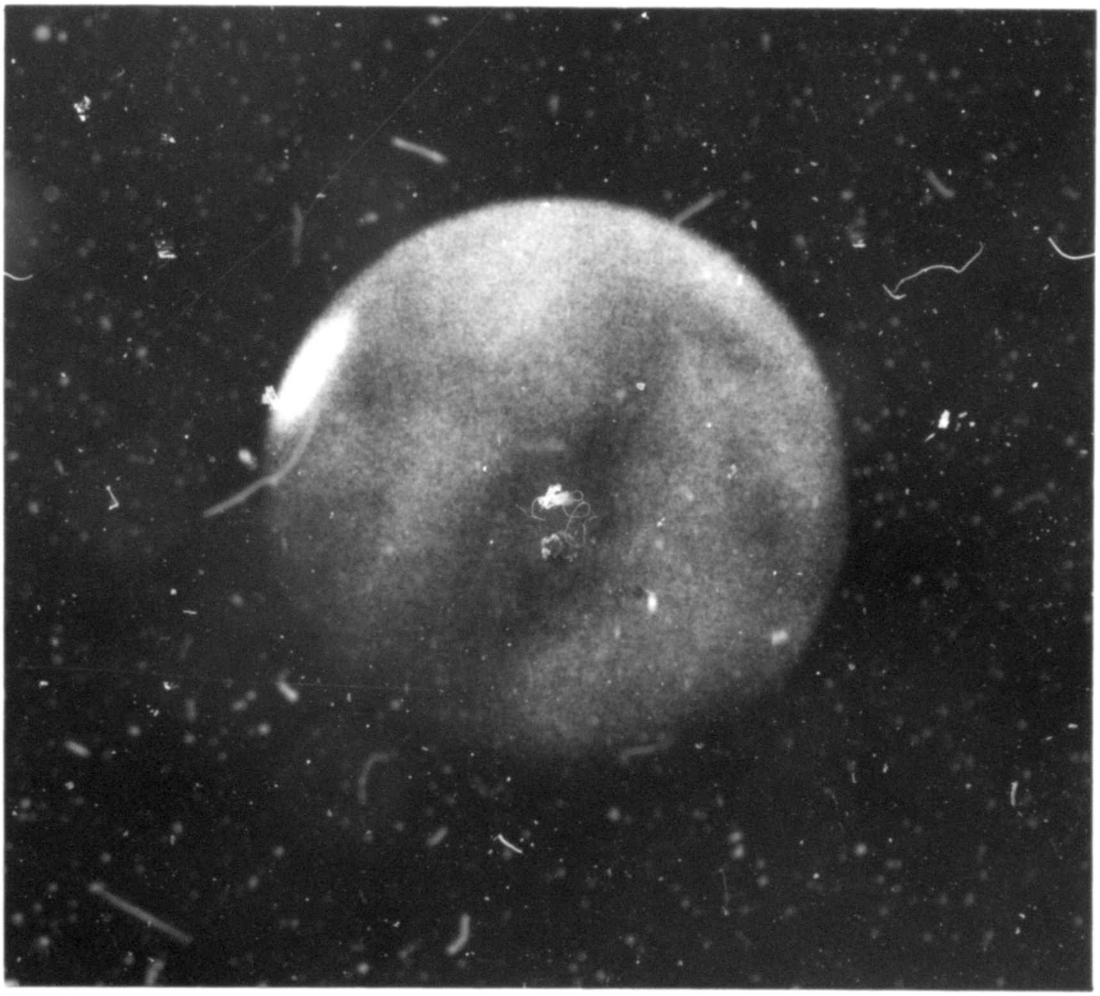


Figure 12. Mars Photo from Earth Telescope.

(Figure 13) Mariner IV returned this photograph of Mars representing an area about 150 miles on the side. The series of photographs taken by Mariner showed that the surface is pockmarked with craters resembling very much the surface of the Moon. It is clear that the surface of the planet has been bombarded by large meteorites and has not changed very much during the course of evolution. Very little erosion has taken place and very little mountain building. A lack of erosion implies a lack of water. A lack of mountain building implies a lack of earthquakes or tectonic processes. Mariner also measured the atmosphere of Mars which proved to be thin indeed. A thin atmosphere, relatively low temperatures, and no free water, does not prove encouraging for life, but from this evidence it cannot be concluded that there is no life on Mars. Life on Earth can adapt itself to an amazing variety of environmental conditions and to determine whether or not there is life on Mars will require an on-the-surface search.

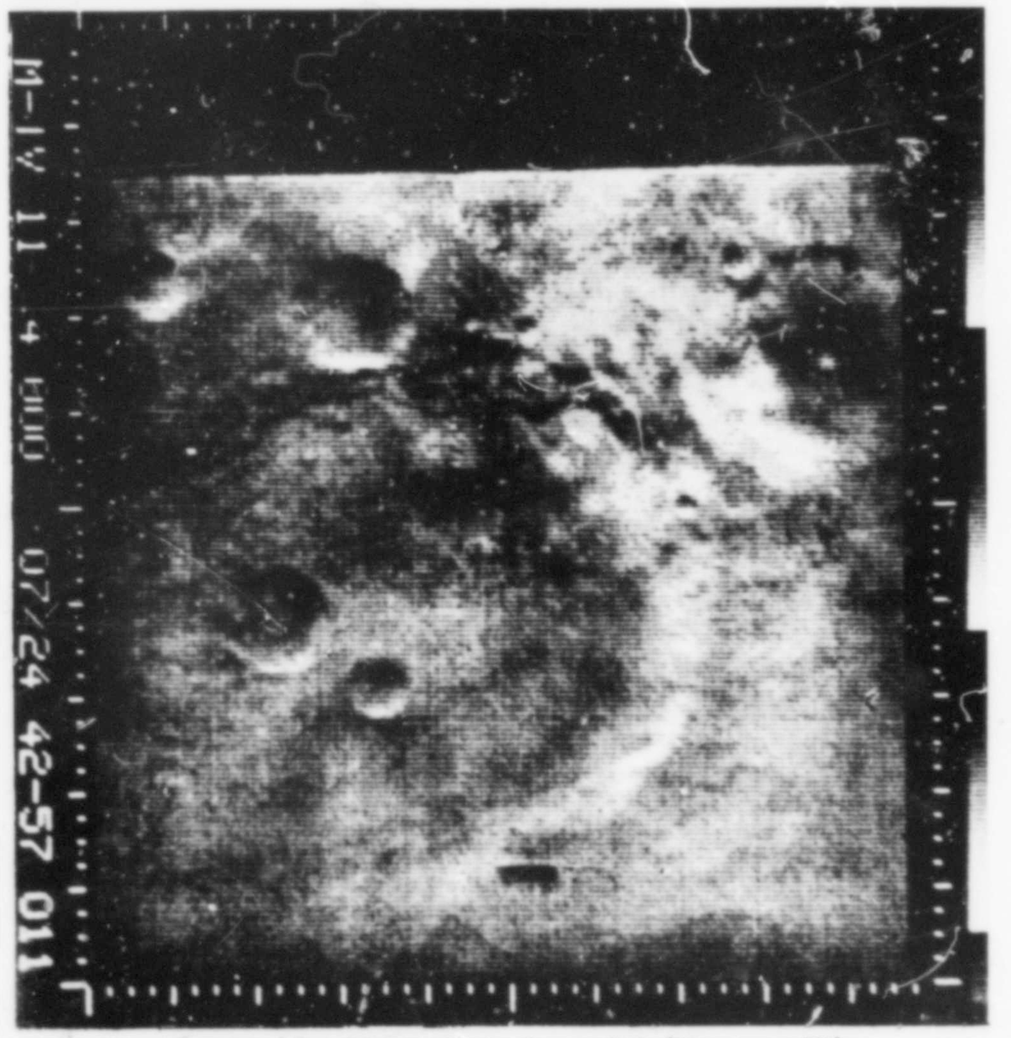
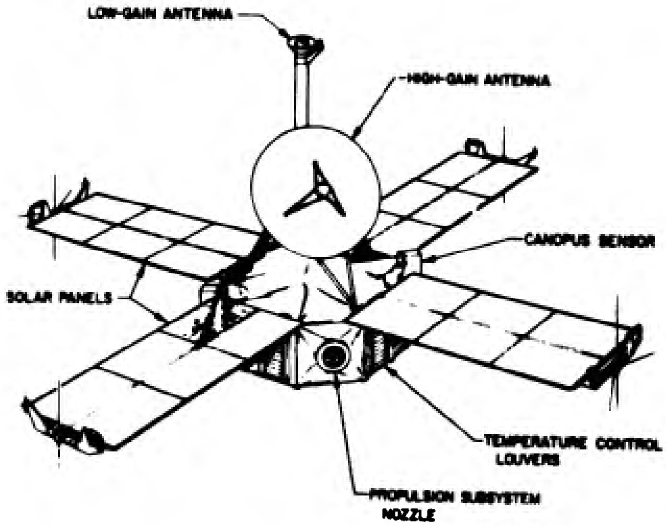


Figure 13. Mars Photo from #11 (Mariner IV).

(Figure 14) In 1969, the Mariner, which is scheduled to fly by Mars, will carry television and infra-red devices for more pictorial data and more details of the Martian surface. The spacecraft has very much the same design as the 1964 Mariner with four solar panels to collect energy en route; high gain antenna to report back to Earth; low gain antenna to operate when the spacecraft is not pointing at the Earth; and a series of instruments on a scan platform which will scan across the surface of the planet as the spacecraft flies by. While Mariner IV came within about 6,000 miles of target at a distance of about 135 million miles after seven and one-half months travel time, the accuracy of Mariner '69 should be even better.



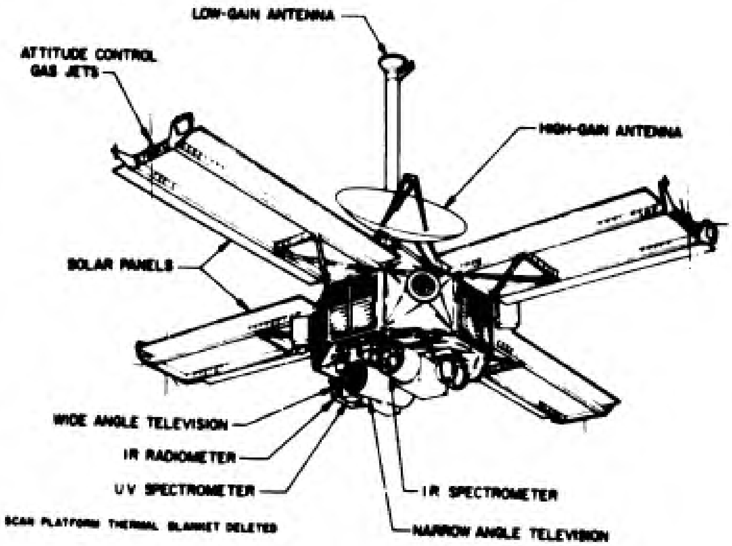


Figure 14. Mariner 69.

(Figure 15) This photograph illustrates the growth of the scan platform. On the right hand is the TV system used in Mariner IV showing the complete scan platform. On the left is a mock-up of the scan platform for the '69 mission. With the additional size of the imaging instrumentation, much better photographs of the planet should be obtained.

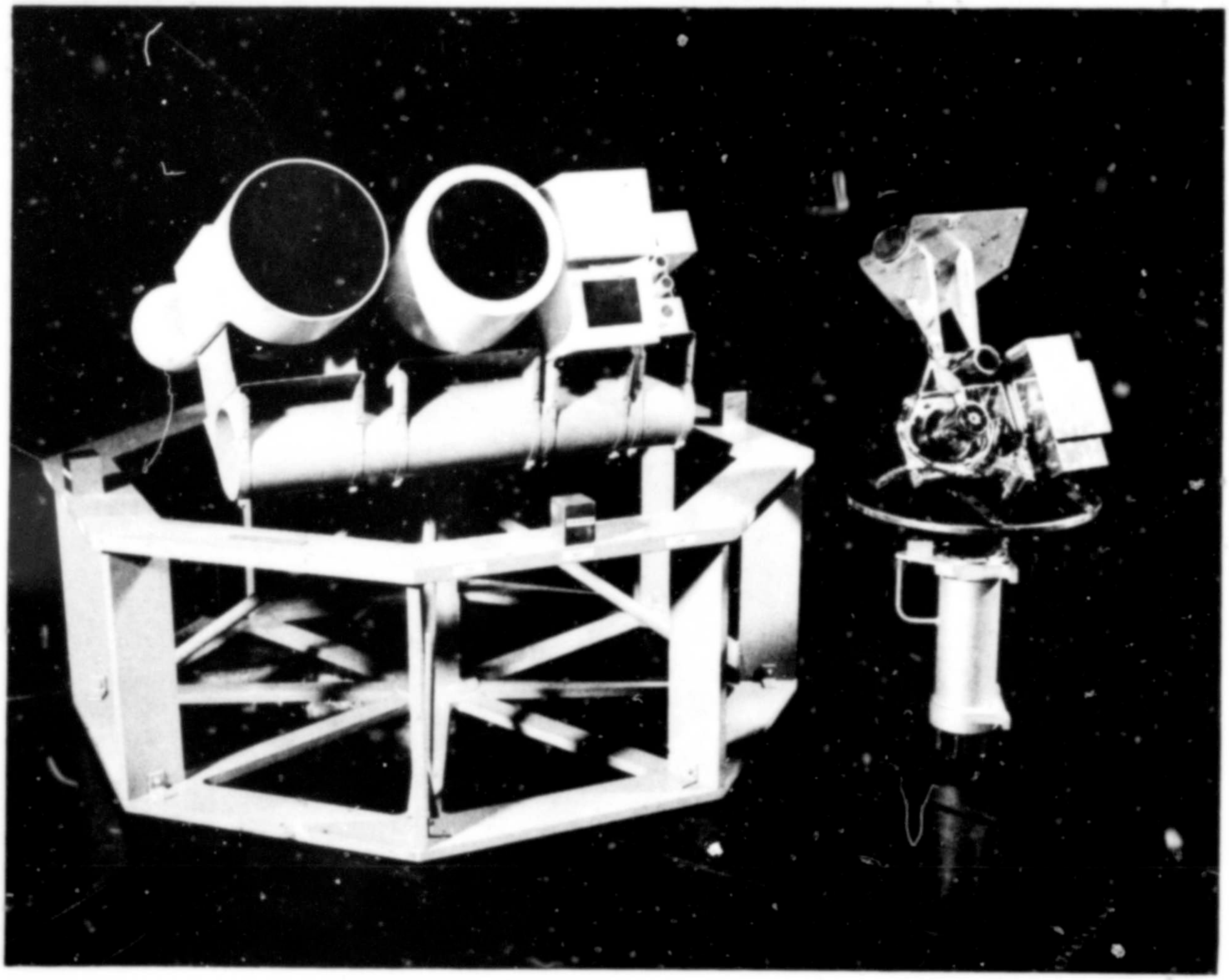


Figure 15. Mariner '69 Scan Platform (left) with Mariner '64 Scan Platform (right).

(Figure 16) This chart shows a series of scientific investigations which will be carried on the '69 flight. The S-band occultation listed is another measurement of the atmosphere on the planet. By flying behind the planet and sending radio signals through the atmosphere and observing the behavior of these radio signals, the atmospheric density at the surface of the planet may be determined.

MARINER · MARS '69

SCIENTIFIC PAYLOAD

Tentative Encounter Plan:

Closest approach: 1200 miles

Storage capacity: $\geq 10^7$ bits

Maximum A.U.: 1.54

CANDIDATE PLANETARY EXPERIMENTS

EXPERIMENT	PURPOSE
High Resolution Visual Imaging	Reconnaissance and topographic map
Visual and Infrared Imaging Photometry	Overlaid visual, water vapor and thermal map
Infrared Spectrophotometry (Grating or Filter Spectrometry or Interferometry)	Atmospheric constituents, scale height and temperature, surface albedo and temperature
Ultraviolet Spectrophotometry	High altitude constituents and scale height and atmospheric scattering
S-band Occultation	Atmospheric scale height and pressure
Dual Frequency Radio Propagation	Ionosphere and interplanetary electron density

Figure 16. Mariner '69 Science.

(Figure 17) Following the Mariner series of spacecraft will be the Voyager series. This is an artist's concept of the Voyager spacecraft indicating the manner in which Voyager may fly on the Saturn V. Actually, it is expected that two spacecraft will be mounted in tandem on the forward end of the Saturn. The spacecraft will then be separated and flown on slightly different trajectories so that they will arrive at the planet approximately a week apart. Voyager will contain an orbiting device to remain in orbit around the planet, a retro rocket to place it in orbit, and within the biological shield, a capsule which will land on the surface of the planet. The considerable increase in complexity and size over the Mariner series takes advantage of the lifting capability of Saturn V.

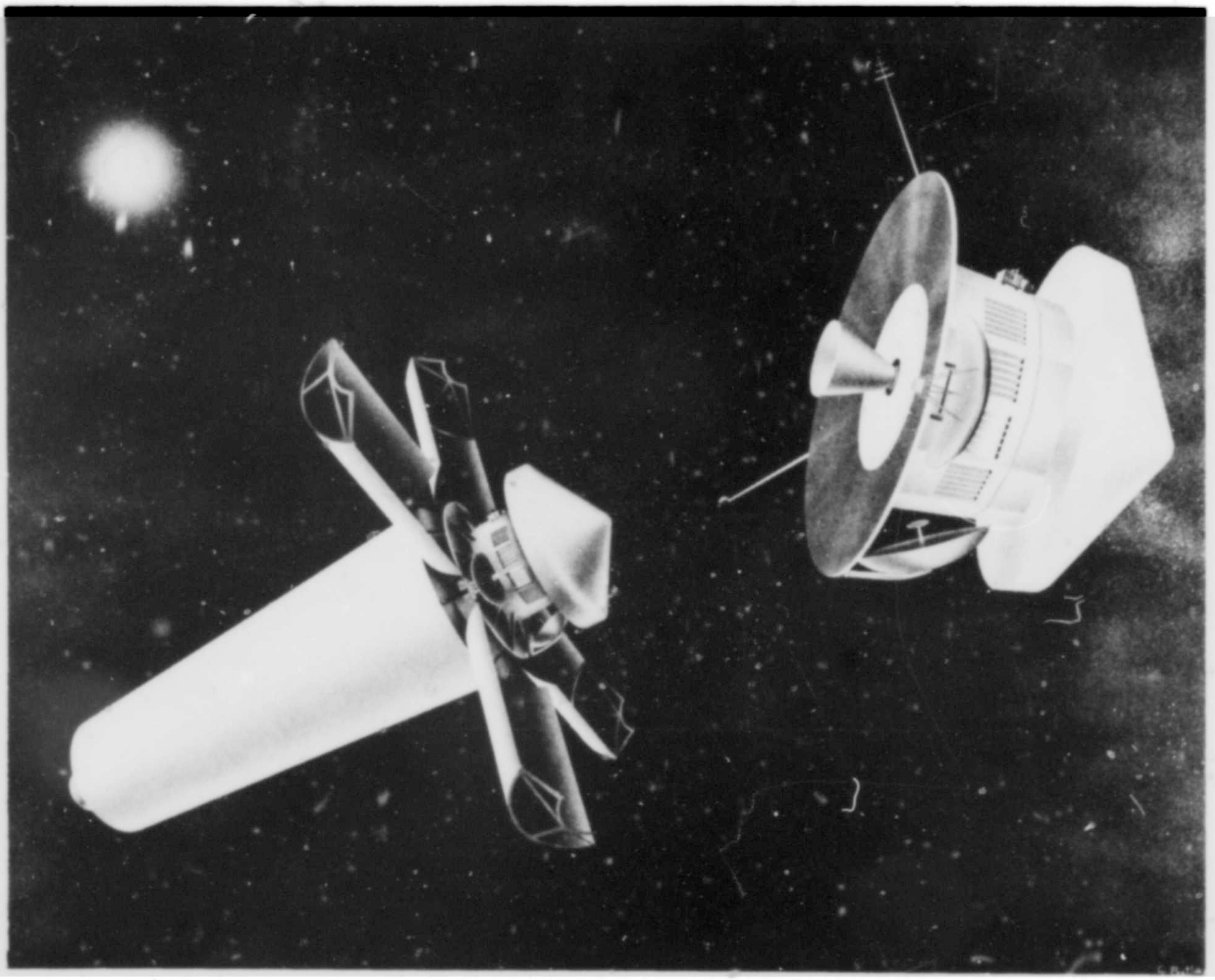


Figure 17. Voyager Concept.

(Figure 18) This chart estimates the kinds of instrumentation which might be landed on the Martian surface. In addition, there will be instruments on the orbiting device for observation and mapping of the planet, and instruments on the capsule to measure environmental conditions on descent through the atmosphere. While these suggestions are for study purposes only, the art of instrumentation is developing rapidly and instruments have been built which can survive the journey to Mars and transmit data back to Earth while still retaining their relatively small size. The GC listed is a gas chromatograph which will be allowed ten pounds of weight in 1973. The GC/MS is a gas chromatograph-mass spectrometer which will be used later.

These instruments will look for slight traces of compounds which may be evidence of life in the atmosphere or perhaps in the surface sampling. It is expected that the first Voyagers will operate on the surface for about two days, and that later, in the 1975 mission, the operation will last six months and in 1977, a year. The communications capability is also expected to increase with time. The initial communications capability will perhaps be of the order of a few hundred bits per second, which, even so, will return a significant amount of data. It is expected that by the '75 and '77 missions, both orbiters and landers will have long lives and that both an orbiter and a lander will be returning data from the planet.

VOYAGER PROJECT

VPE-14 PROJECT STUDY
Hypothetical Landed Instrumentation

	1973	1975	1977	1979
TELEVISION	15	30	30	30
ATMOS. P, T, H_2O, & WIND	5	5	5	5
UV RADIOMETER	--	--	--	--
SPECTRO RADIOMETER	5	--	--	--
ALPHA SPECTROMETER	10	10	--	--
X-RAY/ALPHA SPECTROMETER	--	--	--	--
X-RAY DIFFRACTOMETER	--	--	--	--
SPECIFIC LIFE DETECTOR	30	20	--	--
TV MICROSCOPE	--	--	25	25
SUBSURFACE PROBE	5	--	--	--
GC/MS	--	25	30	30
GC	10	--	--	--
SPECTRAL ANALYZER	--	10	30	30
pH METER	--	--	2	2
CO_2 DETECTOR	--	--	1	1
BETA DETECTOR	--	--	1	1
ALPHA DETECTOR	--	--	4	4
OPTICAL DENSITOMETER	--	--	2	2
DIALYSIS CHAMBER	--	5	5	5
WEIGHT SCALES	5	5	5	5
INSTRUMENT TOTAL	85	110	140	140
SAMPLE ACQUISITION	20	35	50	50
SAMPLE PROCESSOR	5	25	60	60
CONTROLS & DAE	20	30	50	50
SCIENCE TOTAL	130	200	300	300

Figure 18. Voyager Payload Concepts.

(Figure 19) To illustrate some of the instrumentation being developed, this is a picture of the Gulliver, which may be used in the search for life. Gulliver is a device which ejects a sticky paper which traps bacteria and small forms of life, pulls them in, puts them in a nutrient solution, marks the nutrient solution with radio-active carbon, and determines whether or not any carbon dioxide is developed by metabolic processes.

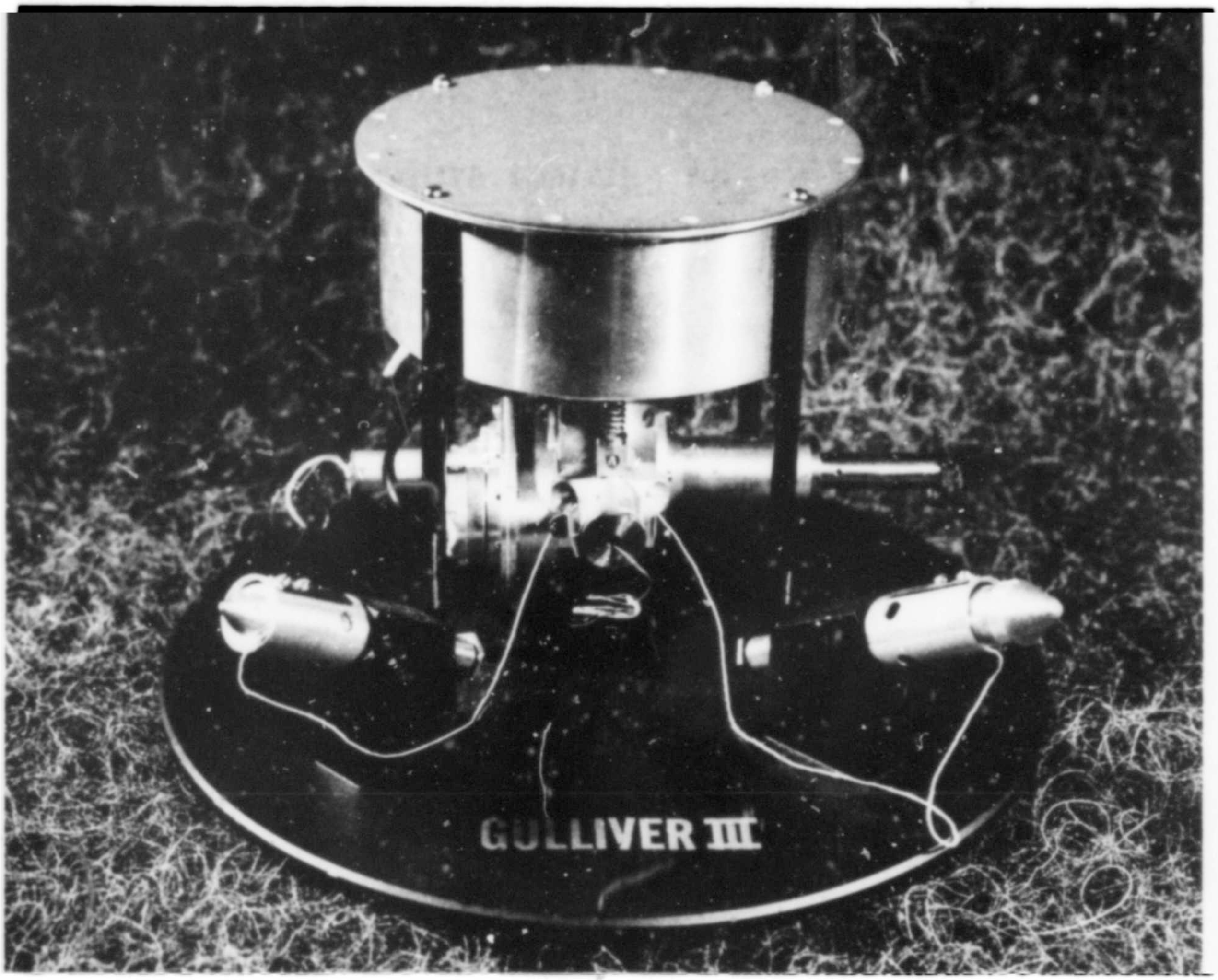


Figure 19. Gulliver Experiment.

(Figure 20) Here is Gulliver in Death Valley where it found life. Two Gullivers are under those conical hats, and the adhesive can be seen already ejected.

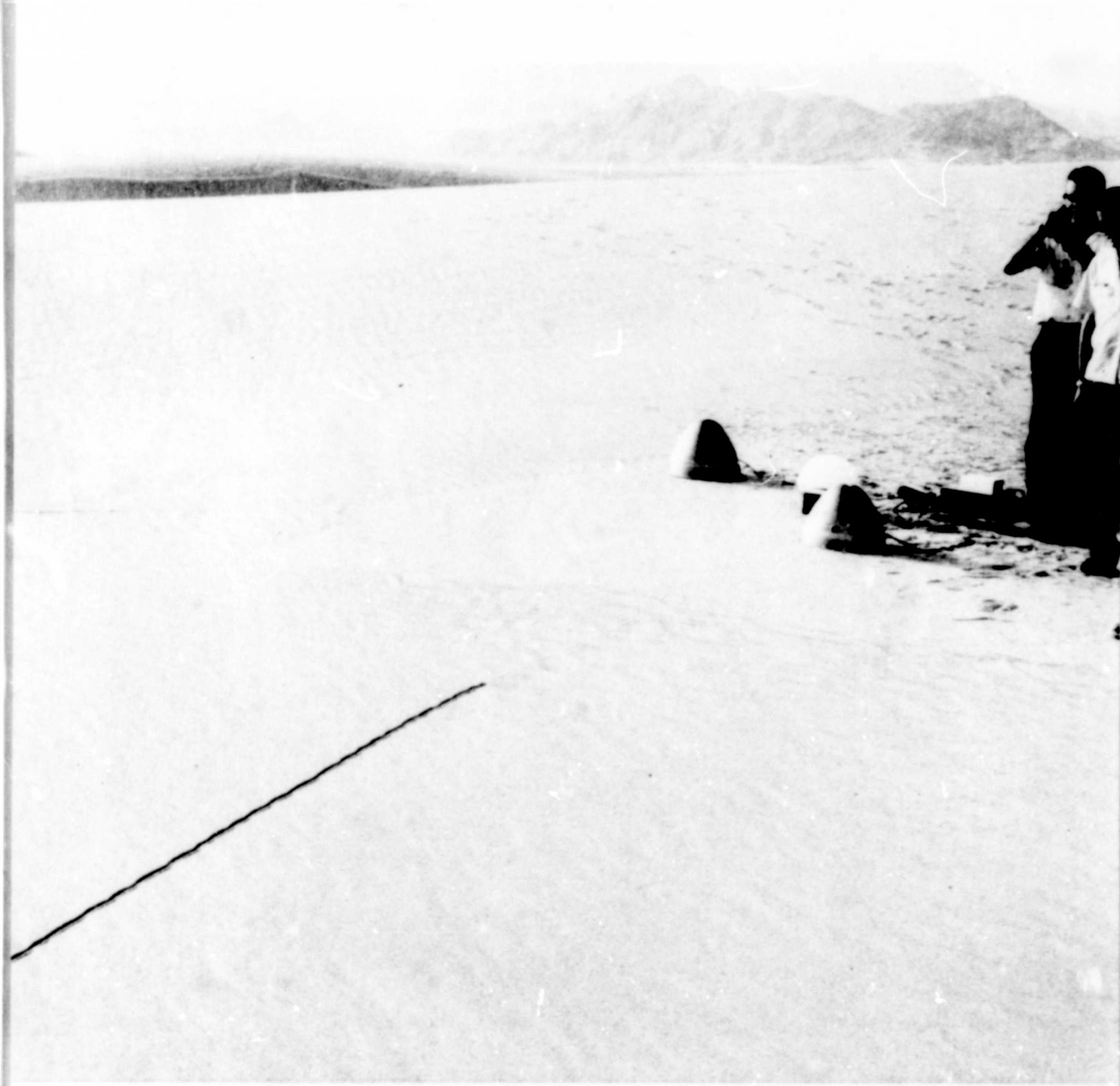


Figure 20. Gulliver in Death Valley.

(Figure 21) Gulliver also found life on White Mountain at 13, 000 feet. Incidentally, the first test of Gulliver was carried out in a parking lot in Washington, D. C. in the middle of winter and life was found in Washington.

Figure 21. Gulliver on White Mountain.

(Figure 22) Another instrument in the search for life is called "wolf trap," named after Dr. Wolf Vishniac who conceived the idea. In this experiment, the soil is innoculated into a transparent nutrient solution. A light shines through the clear solution which becomes opaque indicating that bacteria are growing.

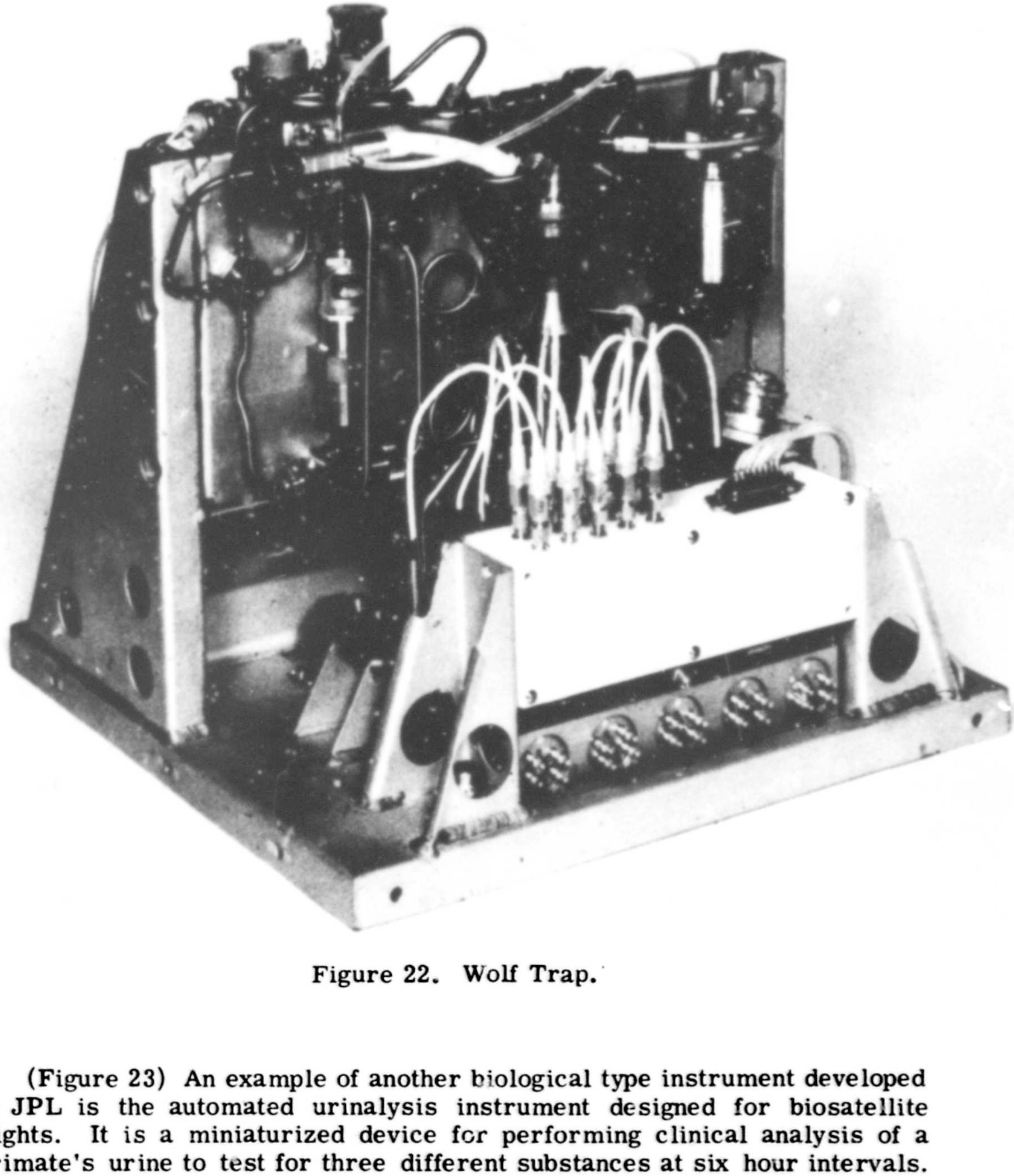


Figure 22. Wolf Trap.

(Figure 23) An example of another biological type instrument developed at JPL is the automated urinalysis instrument designed for biosatellite flights. It is a miniaturized device for performing clinical analysis of a primate's urine to test for three different substances at six hour intervals. The novel aspect of this instrument is the microanalysis, in that the test cell requires only one drop of fluid for complete analysis and is still as sensitive as the best clinical results. It is envisioned that this might have wider application in the automated hospitals of the future.

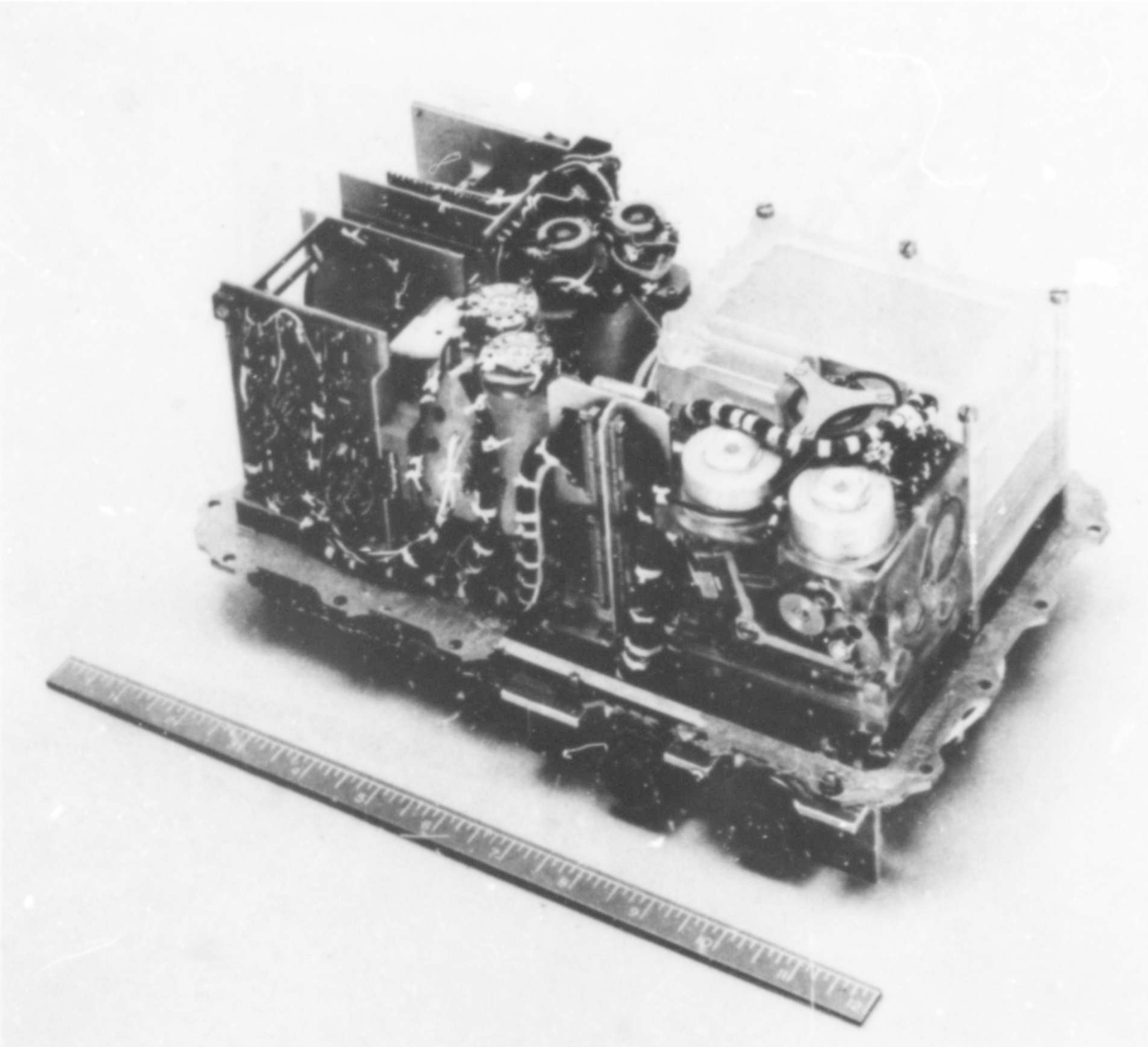


Figure 23. Urinalysis Experiment.

These examples of instrumented spacecraft illustrate some of the capabilities which exist today. It is clear that data can be sent to Earth over great distances and that data, from a variety of instruments, can be processed and sorted before transmission. In the future, on-board computers will make preliminary analyses of the data and will then select certain information for priority transmission. For example, during a solar storm, the radiation measuring instruments will be adjusted to collect data without saturation and store these data for transmission to Earth on command.

Control of unmanned spacecraft has reached a remarkable degree of sophistication. Precision guidance to the Moon and the planets has been accomplished. Mariner '69 will carry, for test purposes, a terminal guidance system capable of homing-in on a pre-selected site or location. Later flights using this system will be able to select target landing areas on the planet with precisions of perhaps a few tens of kilometers.

Attitude control of the spacecraft and of the instrument pointing angles is also well established. TV data has been transmitted from the Moon in almost real time. At lunar distances, transmission time delays are on the order of a second and a half. At planetary distances, however, transmission time delays which are due to the finite speed of the TV signals and cannot be overcome, pose a problem. For example, in the case of Mariner IV, a 12-minute one-way transmission time from the planet Mars meant that in the event of a spacecraft problem, the information would reach the Earth in 12 minutes. A command sent back to the spacecraft for possible corrective action would require another 12 minutes. Therefore, a half hour would elapse before any effective action could be brought to bear.

If we compare these unmanned flight capabilities with those of manned flights, the principal difference is the ability of man to use his own judgment, his powers of observation, and his intelligence to cope with and take advantage of the unexpected. Man can observe and record visual impressions more accurately than the TV camera, noting the unusual and interesting beyond the limited view of the camera. Man can also use his intelligence to photograph, isolate or examine objects and samples. In the search for life, his ability to make quick selective observations may be far more useful than a series of data from a blind instrument. A trained observer on a planet to supplement the instrument payload with human intelligence would make the results of a mission considerably more significant. However, before man can be sent to the planets and returned, many technical problems must be solved. In addition, a series of relatively inexpensive missions by instrumented spacecraft should be conducted. These may well result in sufficient data to conclude that a manned mission is either of little value or of great importance. In either event, the instrument data is essential as a first step.

During the next few years, manned flight capabilities will be studies with the view to making interplanetary flights possible. Long duration flights required for planetary missions will be simulated in near Earth orbits to prepare for manned flights lasting many months.

As experience with instrumented spacecraft increases, so too will manned space flight capabilities grow. By combining the two phases of space exploration, the best solution for the scientific exploration of the solar system can be obtained. While the results of the new scientific knowledge cannot now be foreseen, it is certain that they will be vital to man's future.

Pre-Gemini Medical Predictions vs. Gemini Flight Results

Dr Charles A. Berry

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PRE-GEMINI MEDICAL PREDICTIONS VERSUS GEMINI FLIGHT RESULTS

Charles A. Berry, M.D. and A. D. Catterson, M.D.

INTRODUCTION

Prior to the first exposure of man to orbital space flight, the biomedical community expressed considerable concern over man's capability not only to perform in such an environment, but even to survive in it. Since weightlessness was the one unknown factor which could not exactly be duplicated in a laboratory on the ground, numerous investigators and various committees predicted some effect on almost every body system. It is understandable that detrimental effects were the ones listed, as these could have been limiting factors in manned space flight. The many detrimental effects predicted to occur following exposure to weightlessness were anorexia, nausea, disorientation, sleepiness, sleeplessness, fatigue, restlessness, euphoria, hallucinations, decreased g-tolerance, gastrointestinal disturbance, urinary retention, diuresis, muscular incoordination, muscle atrophy, and demineralization of bones. In some respects, the medical community becomes its own worst enemy in the attempt to protect man against the hazards of new and unknown environments. Frequently the physician dwells upon the possible individual system decrements, and forgets the tremendous capability of the body to maintain a state of homeostasis in many environments. Following the first manned space flights, some of these anxieties were reduced, although most observers believed the evidence was insufficient to reject any of the dire predictions.

The successful and safely conducted Mercury and Gemini Programs have provided the first significant knowledge concerning man's capability to cope with the environment of space. In these programs, 19 men have flown 25 manned flights, for a total weightless experience of approximately 2000 man-hours. Three individuals have flown as the single crewman in Mercury and as one of the two crewmen in a Gemini spacecraft; four individuals have flown twice in the Gemini spacecraft. The flight programs are summarized in tables I and II. This flight experience only scratches the surface of detailed space exploration, but it should provide a sound basis for comparing the predictions concerning man's support and response to this environment with the reality of the findings from the actual achievement.

GENERAL ASPECTS OF THE FLIGHT PROGRAM

In evaluating the results of flight programs, it is important to realize that man is being exposed to multiple stresses and that it is impossible at the present time to evaluate the stresses singly, either inflight or postflight. Man is exposed to multiple stresses which may be summarized as: full pressure suit, confinement and restraint, 100 percent oxygen and 5-psia

TABLE I. PROJECT MERCURY MANNED FLIGHTS

Flight	Crew	Launch date	Description	Duration, hr:min
MR-3	Shepard	May 5, 1961	Suborbital	0:15
MR-4	Grissom	July 21, 1961	Suborbital	0:15
MA-6	Glenn	Feb. 20, 1962	Orbital	4:56
MA-7	Carpenter	May 24, 1962	Orbital	4:56
MA-8	Schirra	Oct. 3, 1963	Orbital	9:14
MA-9	Cooper	May 15, 1963	Orbital	34:20

TABLE II. MANNED SPACE FLIGHTS

Gemini mission	Crew	Launch date	Description	Duration, day:hr:min
III	Grissom Young	March 23, 1965	Third revolution manned test	0:04:52
IV	McDivitt White	June 3, 1965	First extended duration and extravehicular activity	4:00:56
V	Cooper Conrad	Aug. 21, 1965	First medium-duration flight	7:22:56
VII	Borman Lovell	Dec. 4, 1965	First long-duration flight	13:18:35
VI-A	Schirra Stafford	Dec. 15, 1965	First rendezvous flight	1:01:53
VIII	Armstrong Scott	March 6, 1966	First rendezvous and docking flight	0:10:41
IX-A	Stafford Cernan	June 3, 1966	Second rendezvous and docking; first extended extravehicular activity	3:01:04
X	Young Collins	July 18, 1966	Third rendezvous and docking; two extravehicular activity periods; first docked Agena-propelled high-apogee maneuver	2:22:46

atmosphere, changing cabin pressure (launch and reentry), varying cabin and suit temperature, acceleration g-force, weightlessness, vibration, dehydration, flight-plan performance, sleep need, alertness need, changing illumination, and diminished food intake. Some of the stresses can be simulated in ground-based studies but the actual flight situation has never been duplicated, and more data from additional flight programs is necessary before flight observations can be applied to the ground situation.

It is necessary to have the capability to monitor the physiologic state of man during flight activities. A great deal of consideration has been given to the definition of a set of physiologic indices which might be easily obtained in the flight situation and which could be meaningfully monitored. Routine parameters have included measurements of voice, two leads of the electrocardiogram, respiration, body temperature, and blood pressure. Other functions have been added for the experiments program, but were not monitored in real time. The sensor harness may be seen in figure 1 Monitoring of man's physiologic state inflight is necessary to provide information for real-time decision making concerning the accomplishment of additional

Figure 1. Gemini Biosensor Harness.

flight objectives. Such monitoring is also necessary to assure the safety of the flight crew, and to obtain experimental data for postflight analysis for predictions concerning the effect of extended-duration flight upon man. The sensors and equipment should interfere as little as possible with the comfort and the function of the crew. Whenever possible, the procurement of data should be virtually automatic, requiring little or no action on the part of the crewmen. A great deal has been learned about the use of minimal amounts of data obtained at intermittent intervals while a spacecraft is over a tracking station. Our extravehicular crewmen have been monitored by means of one lead each of electrocardiogram and of respiration obtained through the space-suit umbilical. Additional physiologic information, such as suit or body temperature and carbon dioxide levels, could not be obtained due to the limited number of monitoring leads available in the umbilical.

The medical objectives in the manned space-flight program are to provide medical support for man, enabling him to fly safely in order to answer the following questions:

(1) How long can man be exposed to the space-flight environment without producing significant physiologic or performance decrement?

(2) What is the cause of the changes which are observed?

(3) Are preventive measures or treatment needed, and if so, what is best?

Attainment of these objectives will involve tasks with different orientation. The most urgent task is obviously to provide medical support to assure flight safety through the development of adequate preflight preparation and examination as well as inflight monitoring. The second task is to obtain information on which to base the operational decisions for extending the flight duration in a safe manner. The third task differs from the operational orientation of the first two in that it implies an experimental approach to determine the etiology of the findings observed. Frequently, many things that would contribute to the accomplishment of the last task must be sacrificed in order to attain the overall mission objective. This requires constant interplay between the experimental and the operational medical approaches to the missions.

The medical profession requires a team effort by personnel with varied training and backgrounds in order to reach a common objective, the preservation or the restoration of health for mankind. This is no less true in a space-flight environment where a strong team effort is necessary and a strong engineering interface is imperative. If man is to be properly supported, medical requirements concerning the spacecraft environment and the equipment performance must be supplied very early in the hardware development cycle. A very long lead time is necessary to meet realistic flight schedules, and ample time must always be left for proper testing of the hardware. Flight-configured hardware should be utilized to collect the baseline physiologic data which will be compared with the inflight data.

ANTICIPATED PROBLEMS COMPARED WITH FLIGHT RESULTS

The review of a number of aerospace or space medicine texts, dating back to 1951, reveals a large number of expected problems involving man and the hardware or vehicle in the space environment. It appears logical to compare the expected problems with the actual results.

Maintenance of Cabin Pressure

Extrapolating aircraft experience to the vacuum of space led to a prediction of difficulty with the maintenance of cabin pressure. The spacecraft, to date, have maintained a cabin pressure of approximately 5 psia throughout the manned flights. The pressurization feature of the space suits served as a backup to the cabin pressure, but was not required except during the planned excursions outside the spacecraft when the cabin was intentionally depressurized. The normal suit pressures have been approximately 3.7 psia.

Cabin Atmosphere

Reduction in cabin pressure to 5 psia, equivalent to a pressure altitude of 27,000 feet, and the further reduction to 3.7 psia in the space suit created some concern about the possible development of dysbarism. Before each mission, the crew was denitrogenated by breathing 100 percent oxygen for two hours; this, coupled with the further denitrogenation accomplished in the spacecraft, has proved ample protection. There has been no evidence of dysbarism on any of the missions.

Cabin and Suit Temperature

The maintenance of an adequate temperature in the cabin and in the extravehicular pilot's suit was also a matter of concern. The temperatures were maintained generally within the comfort range around 70-degrees. During one mission, the crew reported being cold when the spacecraft was powered down and rotating. The extravehicular pilots generally have been warm while inside the spacecraft because the extravehicular suit contains additional layers of material.

Micrometeorites

Micrometeorites are a subject heading in every book relating to space flight. They are mentioned as a possible hazard to cabin integrity, to spacecraft window surfaces, and to extravehicular crewmen. No significant micrometeorite or meteorite density has been observed in the flights to date. There has been no evidence of micrometeorite hits on the extravehicular suits although a micrometeorite protective layer is provided.

Radiation

The radiation environment of space has been sampled by numerous probes and has been calculated at length. With one exception, the flights have not reached an altitude involving the inner Van Allen belt, but the flights have routinely passed through the South Atlantic Anomaly. The on-board radiation measuring system and the personal dosimeters attached to the crewmen confirmed that the radiation intensity is at the lower end of the calculated range. In a 160-nautical-mile orbit, the crew received approximately 15 millirads of radiation in each 24-hours of exposure. The total doses received on the flights to date may be seen in table III.

TABLE III. RADIATION DOSAGE ON GEMINI MISSIONS[a]

Gemini mission	Duration, day:hr:min	Mean cumulative dose, mrad	
		Command pilot	Pilot
III	0:04:52	<20	42 ± 15
IV	4:00:56	42 ± 4.5	50 ± 4.5
V	7:22:56	182 ± 18.5	170 ± 17
VI-A	1:01:53	25 ± 2	23 ± 2
VII	13:18:35	155 ± 9	170 ± 10
VIII	0:10:41	<10	10
IX-A	3:01:04	17 ± 1	22 ± 1
X	2:22:46	670 ± 6	765 ± 10
XI	2:23:17	29 ± 1	26 ± 1
XII	3:22:36	<20	<20

[a]Dosimeters located in helmet, right and left chest and thigh.

Light and Darkness

Many predictions were made concerning the effect of the changing light and darkness producing a day and a night every 90 minutes. It was generally predicted that this would totally disrupt the circadian rhythms, producing grave consequences. Certainly no overt effects of the 45 minutes of day and 45 minutes of night were observed on the short missions. As knowledge of sleep in the space-flight environment increased, it was determined best to arrange the work-rest cycles so that sleep occurred at the normal Cape Kennedy sleep time. The spacecraft was artificially darkened by covering the windows, and as far as the crew was concerned, it was night. The physiological response in heart rate and respiration to the regime used on the 14-day flight is shown in figure 2.

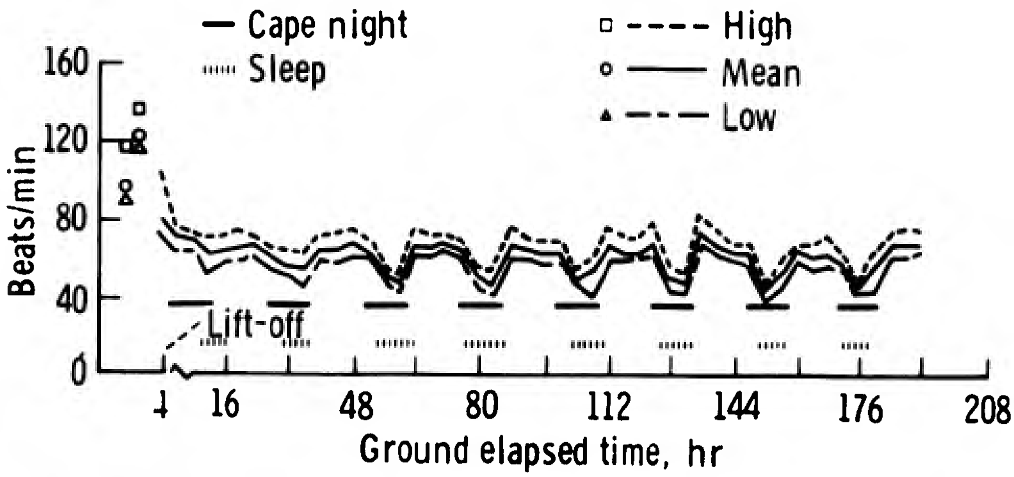

Figure 2. Gemini VII pilot heart rate.

Gravity

During space flight, the increase of gravity load during launch and reentry, and the nullification of gravity load and production of a state of weightlessness during actual flight, were expected to produce detrimental effects. Actually, during the missions, gravity loads at launch and reentry were well within man's tolerances, with two 7g peaks occurring at launch, and with g-forces varying from 4 to 8.2g at reentry. Much concern was expressed about a decreased tolerance to gravity following weightless flight. No evidence of this has been observed, and, indeed, following 4 days of weightless flight the Gemini IV crew sustained a peak of 8.2g without adverse effects.

Weightlessness has been the subject of innumerable studies and papers. Weightlessness has been produced for brief periods in parabolic flight in aircraft, and simulated by water immersion and bedrest. The Gemini Program has produced a fair amount of evidence concerning the effect of the weightless space-flight environment on various body systems.

Skin

In spite of the moisture attendant to space-suit operations, the skin of flight crew members has remained in remarkably good condition through flights up to 14 days in duration. Following the 8-day flight, there was some drying of the skin noted during the immediate postflight period, but this was easily treated with lotion. There have been no infections, and there has been minimal reaction around the sensor sites. Dandruff has been an occasional problem but has been easily controlled with preflight and postflight medication.

Central Nervous System

The best indication of central nervous system function has been the excellent performance of the crew on each of the missions. This can be graphically illustrated by such demanding performance as that during the aborted launch of Gemini VI-A; the rendezvous and the thruster problem on Gemini VIII; the extravehicular activity on Gemini IV, IX-A, X, XI, and XII; and the many accurate spacecraft landings and recoveries. Psychological tests have not been conducted as distinct entities unrelated to the inflight tasks. Instead, evaluation of total human performance has been relied on as an indication of adequate central nervous system function. There has been no evidence, either during flight or postflight, of any psychological abnormalities.

The electroencephalogram (fig. 3) was utilized to evaluate sleep during the 14-day mission. A total of 54 hours and 43 minutes of interpretable data was obtained. Variations in the depth of sleep from stage 1 to the deep sleep of stage 4 were noted in flight as in the ground-based data.

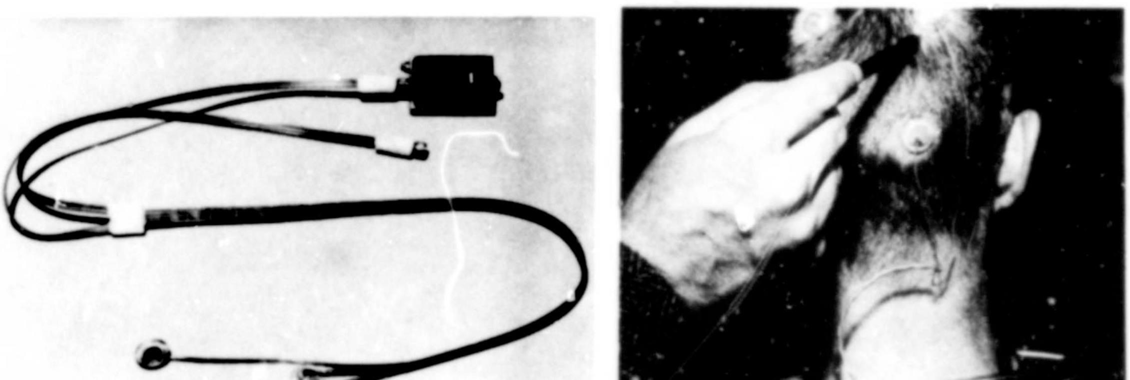

Figure 3. Electroencephalogram Equipment.

Numerous visual observations have been reported by the crews involving inflight sightings and descriptions of ground views. The actual determination of visual acuity has been made inflight as well as in preflight and postflight examinations. All of these tests support the statement that vision is not altered during weightless flight.

As previously noted, there has been much conjecture concerning vestibular changes in a weightless environment. There has been no evidence of altered vestibular function during any of the Gemini flights. Preflight and postflight caloric vestibular function studies have shown no change, and special studies of the otolith response have revealed no significant changes. There have been ample motions of the head in flight and during roll rates with the spacecraft. There has been no vertigo or disorientation noted, even during the extravehicular activity with occasional loss of all visual references. Several crewmen have reported a feeling of fullness in the head similar in character to the fullness experienced when one is turned upside down, allowing the blood to go to the head. However, there has been no sensation of being turned upside down, and the impression is that this sensation results from altered distribution of blood in the weightless state. In order to clear the record, two of the Mercury pilots developed difficulties involving the labyrinth; the difficulties were in no way related to the space flights. One developed prolonged vertigo as the result of a severe blow over the left ear in a fall, but he has completely recovered with no residual effect. The other crewman developed an inflammation of the labyrinth some 3 years after his 15-minute space flight and while he continues to have some hearing loss, there have been no further vestibular symptoms.

It is interesting to note this absolute lack of any inflight vestibular symptoms, in spite of the fact that a number of the pilots have developed motion sickness while in the spacecraft on the water.

Eye, Ear, Nose and Throat

There have been two inflight incidents of rather severe eye irritation. One was the result of exposure to lithium hydroxide in the suit circuit, and the cause of the other remains a mystery at the present time. In a few instances, some postflight conjunctival infection has been noted, but has lasted only a few hours and is believed to have been the result of the oxygen environment. During the early portions of flights, normally the first two or three days, some nasal stuffiness has been noted. This also is undoubtedly related to the 100 percent oxygen environment and is usually self-limited. On occasion, the condition has been treated locally or by oral medication.

Respiratory System

Preflight and postflight X-rays have failed to reveal any atelectasis. Pulmonary function studies before and after the 14-day mission revealed no alteration. There have been no specific difficulties or symptomatology involving the respiratory system; however, some rather high respiratory rates have been noted during heavy workloads in the extravehicular activity. Even when these rates have exceeded 40 breaths per minute, they have not been accompanied by symptomatology.

Cardiovascular System

This was the first of the major body systems to show physiologic change following flight. As a result it has been extensively investigated by a number of means (fig. 4). As previously reported, the peak heart rates have been observed at launch and at reentry (table IV); the rates normally reached higher levels during the reentry period. The midportions of all the missions have been characterized by more stable heart rates at lower levels with adequate response to physical demands.

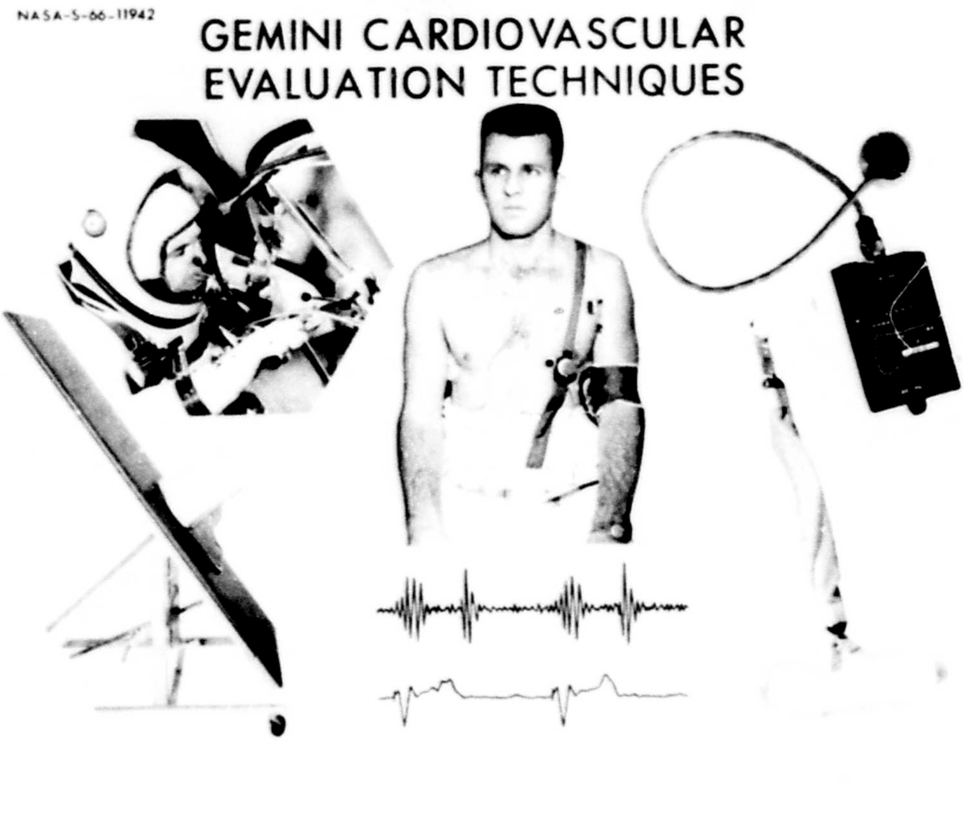

Figure 4. Gemini Cardiovascular Evaluation Technique.

TABLE IV. PEAK HEART RATES DURING LAUNCH AND REENTRY

Gemini mission	Peak rates during launch, beats/min	Peak rates during reentry, beats/min
III	152 120	165 130
IV	148 128	140 125
V	148 155	170 178
VI-A	125 150	125 140
VII	152 125	180 134
VIII	138 120	130 90
IX-A	142 120	160 126
X	120 125	110 90
XI	166 154	120 117
XII	136 110	142 137

The electrocardiogram has been studied in detail throughout the Gemini missions. The only abnormalities of note have been very rare, premature, auricular and ventricular contractions. No significant changes have been detected in the duration of specific segments of the electrocardiogram.

Blood pressure measurements obtained during the Gemini VII mission revealed that systolic and diastolic values remained within the envelope of normality and showed no significant changes throughout 14 days of space flight. As previously reported, this included the pressures taken at the time of reentry.

Some insight into the electrical and mechanical phases of the cardiac cycle was gained during the Gemini flights. The data were derived through synchronous phonocardiographic and electrocardiographic monitoring. In general, wide fluctuations in the duration of the cardiac cycle, but within physiological limits, were observed throughout the missions. Fluctuations in the duration of electromechanical systole correlated closely with changes in heart rate. Stable values were observed for electromechanical delay (onset of ventricular activity, QRS complexes, to onset of first heart sound) throughout the missions with shorter values observed during the intervals of peak heart rates recorded during lift-off, reentry, and extravehicular activity. The higher values observed for the duration of systole and for electromechanical delay in certain crewmembers suggest a preponderance of cholinergic influences (vagal tone). An increase in sympathetic tone (adrenergic reaction) was generally observed during liftoff, reentry, and in the few hours preceding reentry.

As a further measure of cardiovascular status, Experiment M003, Inflight Exerciser, determined the heart rate response to an exercise load consisting of one pull per second for 30 seconds on a bungee device (force at full extension of 12 inches equaled 70 pounds). The responses for one crewman on the Gemini V mission are shown in figure 5. The results from the 4-day Gemini IV mission, and the 14-day Gemini VII mission, did not differ. This variant of the step test revealed no physical or cardiovascular decrement after as much as 14 days exposure to a space-flight environment.

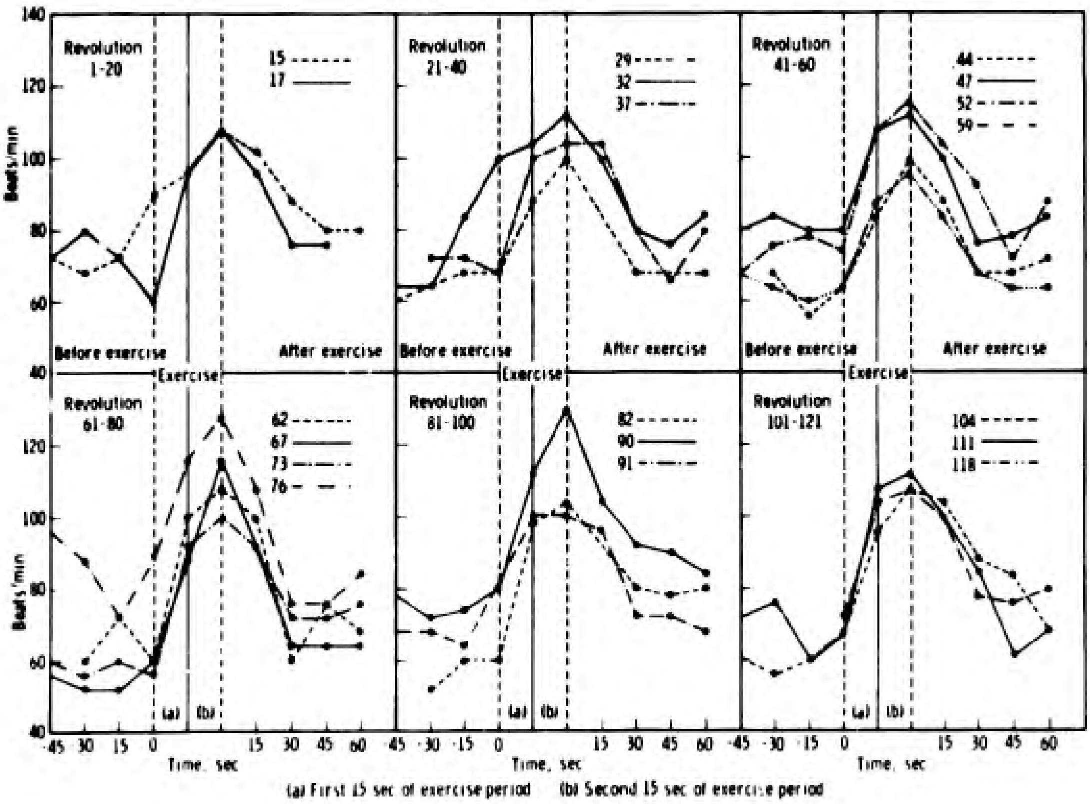

Figure 5. Heart Rate Response to Bungee Exercise, Gemini V Pilot.

In contrast to the Project Mercury results, orthostatism resulting from any Gemini mission has not been detectable, except by means of passive tilt-table provocation. Typically, the heart-rate and blood-pressure response to a 15-minute, 70-degree tilt performed postflight is compared with identical preflight testing on the same crewmen. Consistently, such testing has demonstrated a greater increase in heart rate, a greater reduction in pulse pressure, and a greater increase in leg volume, as interpreted from lower limb circumference gages during the preflight tilt (fig. 6). The

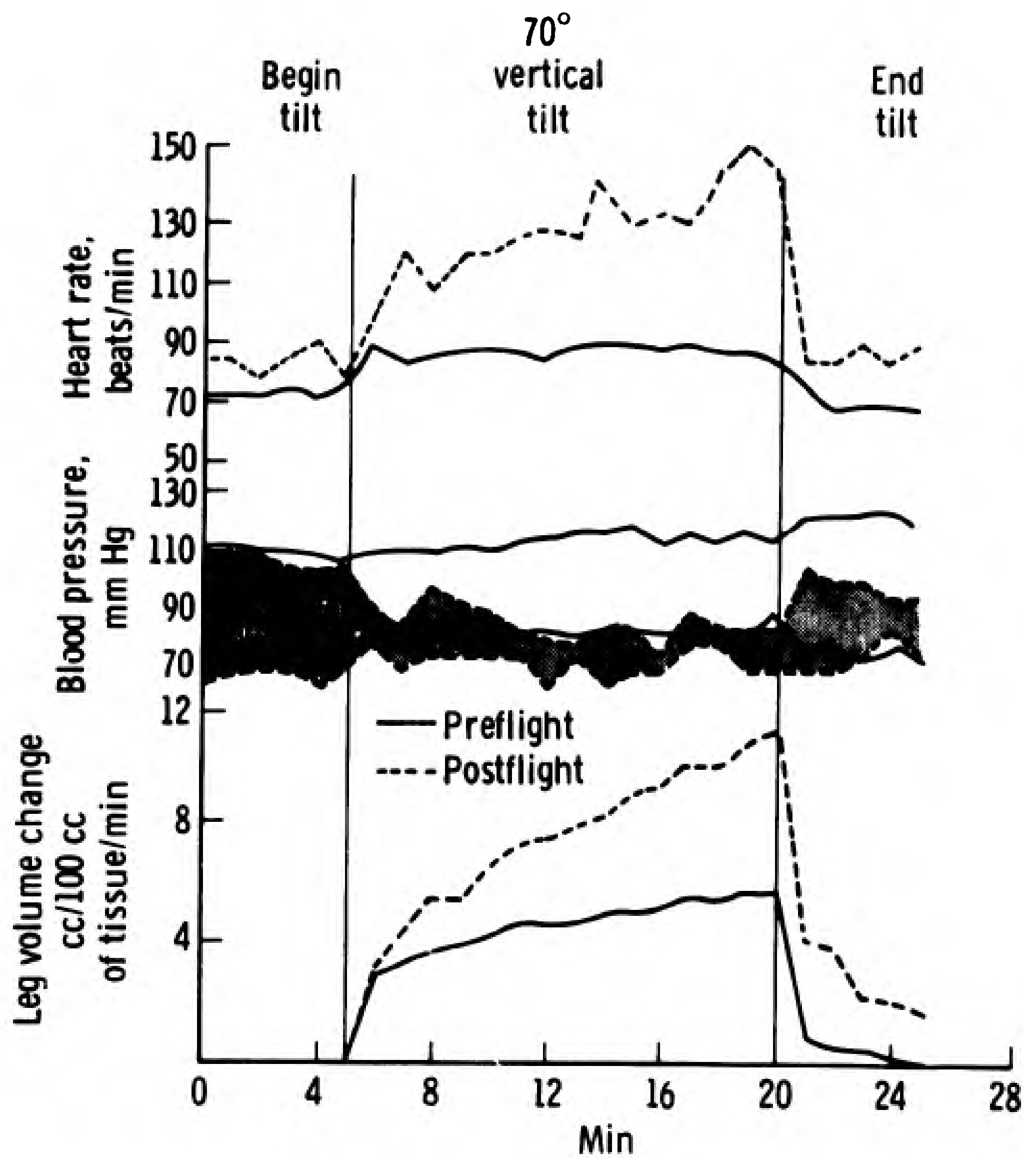

Figure 6. Typical Tilt-Table Response.

changes observed in these variables may be most significantly illustrated by examining the heart-rate changes observed during preflight and postflight tilt-table studies. When the postflight increases in heart rate during tilt are expressed as percent of the preflight tilt heart rate for each of the Gemini mission crews, the postflight increases are from 17 to 105 percent greater than those exhibited preflight. The increasing trend in these values is evident through the 8-day mission. A multiplicity of altered factors such as better diet, more exercise, desuited periods and no extravehicular activity, make the improved postflight response to the 14-day mission very difficult to interpret (fig. 7).

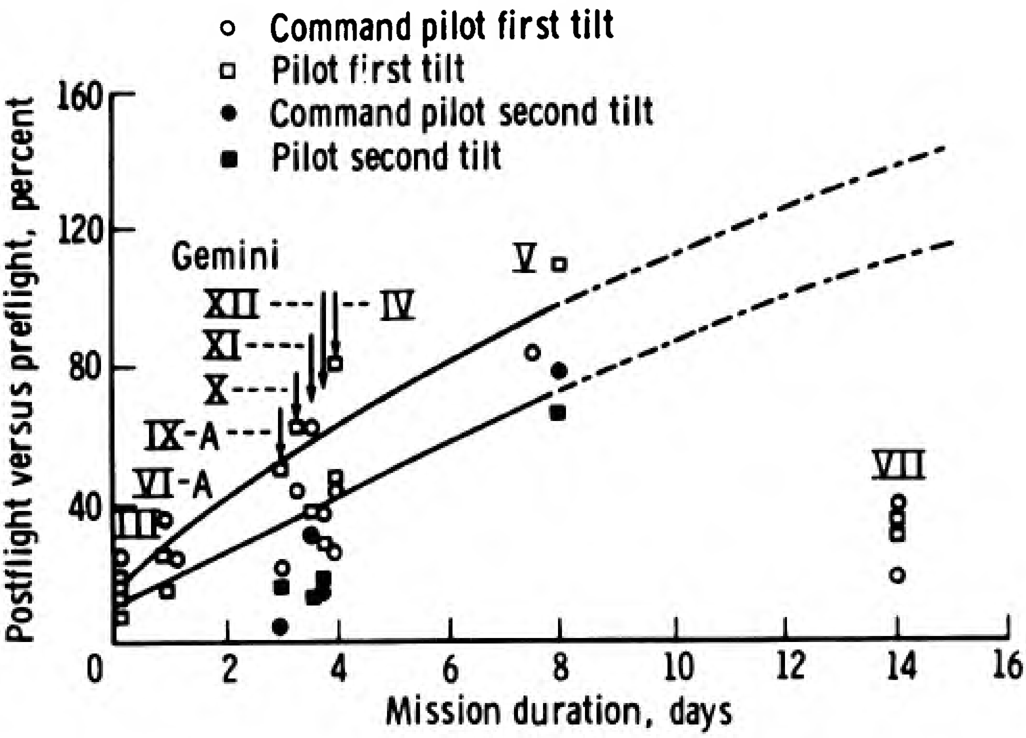

Figure 7. Heart Rate Tilt Responses Compared with Mission Duration.

For purposes of comparison, flight data and data from bedrest studies were viewed in a like manner and show a very similar trend; however, the magnitude of the changes shows marked differences, again illustrating perhaps the influence of factors other than those simulated by bed rest.

When the tilt table tests are considered, postflight leg-volume was universally greater than preflight. Postmission observations ranged from 12 to 82 percent increase in volume over premission values.

The Gemini V pilot wore intermittently occlusive lower-limb cuffs for the first 4 days of the 8-day mission. The Gemini VII pilot wore the cuffs for the entire 14-day mission; however, his heart-rate increases and pulse-pressure narrowing were greater than for the command pilot; the cuffs seemingly did not alter the variables.

Average resting heart rates range from 18 to 62 .cent higher after missions. In spite of higher resting pulse rates, the changes resulting from tilt were still greater. The exception presented by the Gemini VII crew is more apparent. The bed-rest data are not remarkable.

Blood

Significant increases have been observed in white blood cell counts manifested as an absolute neutrophilia following most flights. This condition has always returned to normal within 24 hours. Hematologic data derived from Gemini missions of 4, 8, and 14 days, demonstrated a hemolytic process originating during flight. Specific data points include red-cell mass deficits of 12, 20, and 19 percent (command pilot) following the Gemini IV, V, and VII missions, respectively (fig. 8). The 12 percent Gemini IV data

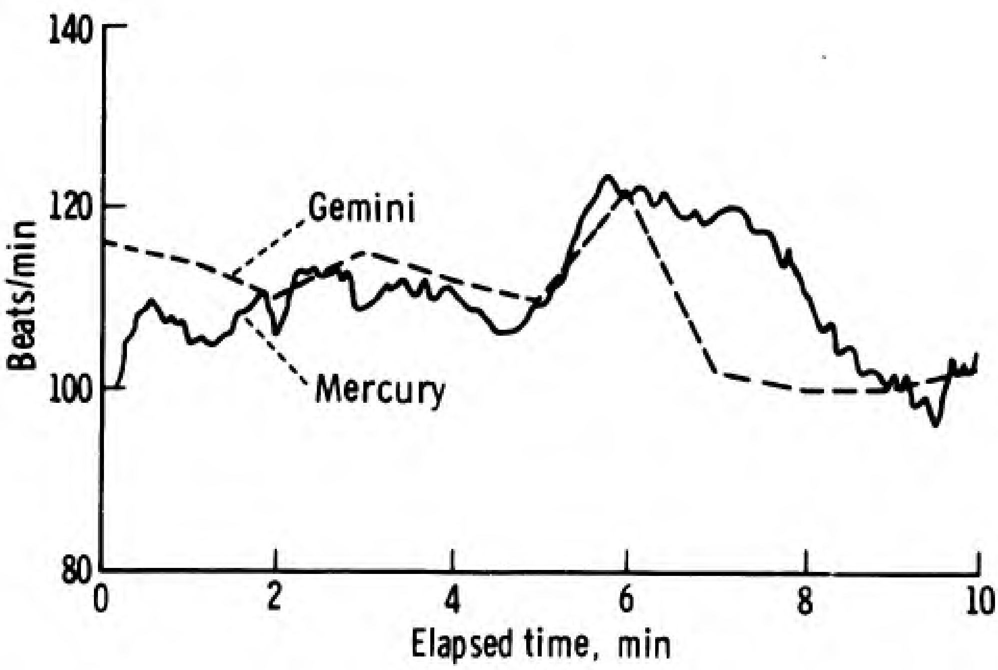

Figure 8. Command Pilot Heart Rate Comparison.

point is probably inaccurate. This 4-day point was calculated from RISA-125 plasma volume and peripheral hematocrit data, a method predicted on a constant relationship between peripheral and total body hematocrit. Subsequent direct measurements showed that alterations of the peripheral total body hematocrit ratios do occur, thereby introducing an obvious error into the calculations. Based on the direct measurements, the Gemini IV calculated red-cell mass deficits were re-examined and found to more closely approximate 5 percent. Other hematologic tests corroborated this disparity; however, to date, no satisfactory answer exists explaining the phenomenon. Complete interpretation of the red-cell mass deficit, noted in the command pilot of Gemini VII, also required special consideration. It appears that no significant progression of the hemolysis occurs after the 8th day in orbit; however, this may be more apparent than real. Analysis of the related mean corpuscular volume values shows a significant increase in this parameter during the 14-day space-flight interval. If each individual erythrocyte increased in volume, a measurement of the total red-cell volume (red-cell mass) would not accurately reflect the actual loss of erythrocytes. Correcting for the postflight corpuscular volume shift, a 29 percent circulating red-cell deficit is derived. The latter figure more accurately describes the hemolytic event. It is possible, therefore, that the true extent of the hemolytic process has not yet been determined.

Possible causative factors of the red-cell loss are hyperoxia (166 mm oxygen at the alveolar membrane), lack of inert diluent gas (nitrogen), relative immobility of the crew, dietary factors, and weightlessness. Only increased oxygen tension, immobility, and dietary factors are well known to influence the red cell. Dietary considerations may be of considerable importance; however, at this point no definite incriminations can be levied against the flight diet. A program to define certain diet levels of lipid soluble vitamins has recently been initiated. Specifically, alpha-tocopherol is an important antilipid oxidant and is essential in protecting the lipid at the red-cell plasma membrane. Immobility is effective in reducing red-cell mass by curtailing erythrocyte production; however, all flight observations support hemolysis as the significant event. Although not demonstrated by any previous studies, it is possible that weightlessness is a contributing factor in the hemolysis observed. Altered hemodynamics, resulting in hemostasis, could result in the premature demise of the cell. The role of a diluent gas (nitrogen) is not well understood; however, some investigators have shown significant reduction in hematologic and neurologic toxicity in animals exposed to high oxygen pressure when an inert gas is present. Therefore, the absence of an inert atmospheric diluent could be significant at the hyperoxic levels encountered within the Gemini spacecraft.

Of all the mechanisms previously stated, oxygen has the greatest proven potential as a hemolytic agent. Basically, two modes of oxygen toxicity are described. It has been demonstrated that red-cell plasma membrane lipids undergo peroxidation when exposed to conditions of hyperoxia.

It has also been demonstrated that the lipid peroxides thus formed are detrimental to the cell. Specifically, lipid peroxides are known to affect enzyme systems essential for normal red-cell function. It is also possible that peroxidation of the erythrocyte plasma membrane lipids changes this tissue to curtail erythrocyte survival. The second mode of oxygen toxicity expression may be more direct, for inferential evidence is available showing a direct inhibitory effect on some glycolytic enzymes. Oxygen has several documented deleterious effects on red-cell plasma membranes and metabolic functions, any combinations of which could be operative within a Gemini spacecraft.

Biochemical

The analysis of urine and plasma has been used as an indication of crew physiological status preflight, inflight, and postflight. Analyses of the results obtained on all three phases were performed on the 14-day Gemini VII flight; while essentially complete analyses were performed on the preflight and postflight phases of the 3-day Gemini IX-A mission.

The first attempt at accumulation of inflight data was essentially a shakedown and provided an n of two, which for biological data, is insignificant. Some of the data are presented, but interpretation is dependent upon more refined techniques and upon accumulation of a sufficient number of observations to establish variabilities and trends. The high degree of individual variation should be noted. The Gemini VII pilot and command pilot did not always respond qualitatively or quantitatively in the same way.

The biochemical determinations are grouped into several profiles, each of which provides information concerning the effect of space-flight on one or more of the physiological systems. The first profile, water and electrolyte balance, is related to an examination of the weight loss which occurs during flight and the mechanisms involved in this loss. To this end, the levels of sodium, potassium, and chloride in the plasma were measured preflight and postflight, and the rates of excretion of these electrolytes in the urine were observed in all three phases of the study. Total plasma protein concentration measured both preflight and postflight was used as an indication of possible dehydration. Water intake and urine output were measured to determine whether the primary loss of weight was due to sweat and insensible losses or to changes in renal function. The vasopressin (antidiuretic hormone) and aldosterone hormones were measured in the urine in an attempt to establish the functional contribution of baroreceptors in a zero-gravity condition.

As may be expected, since one of the prime functions of the homeostatic mechanisms of the body is to maintain the composition of blood and extracellular fluid as nearly constant as possible; significant changes in plasma were not observed. As seen in figure 9, 48-hour pooled samples of flight

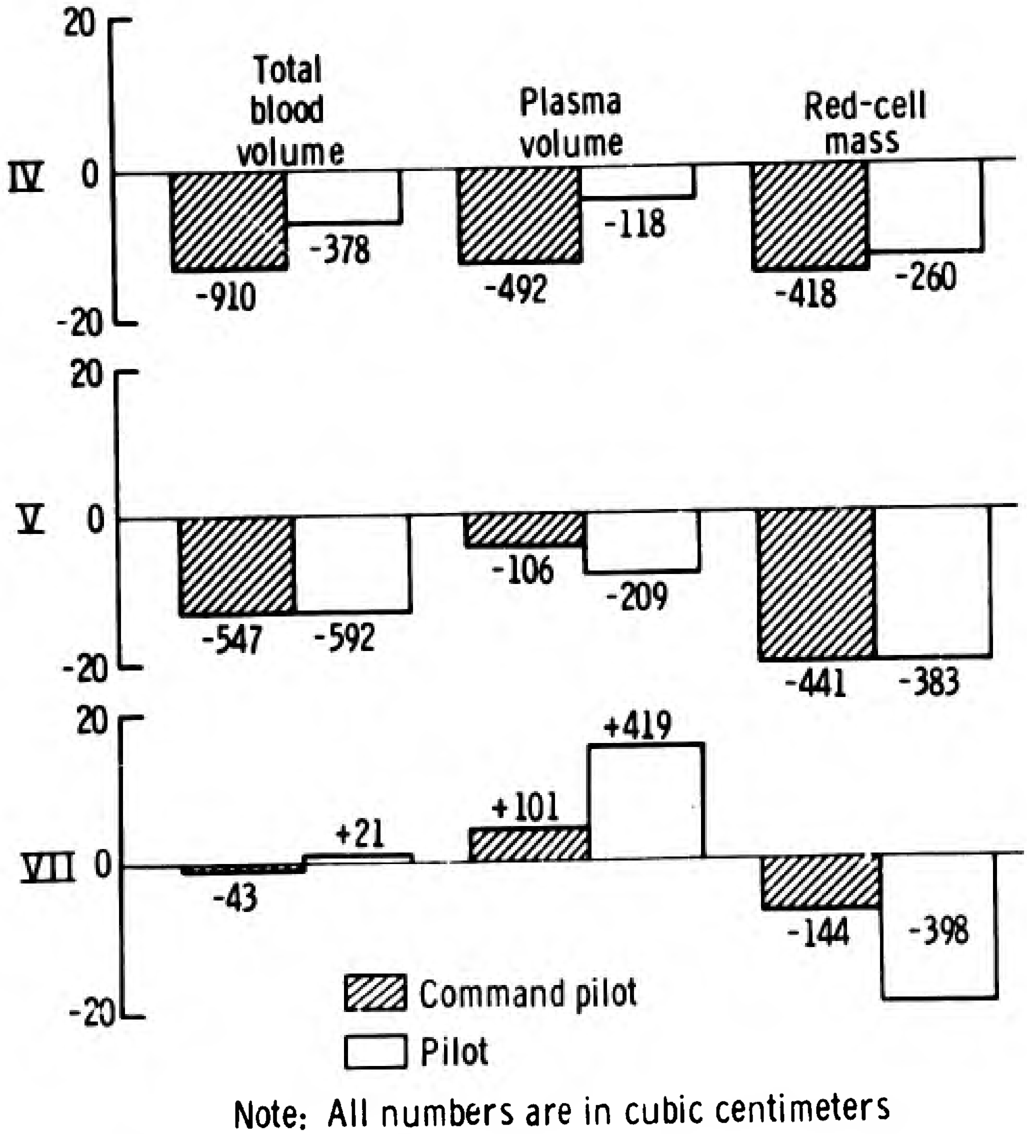

Figure 9. Blood Volume Studies for Gemini IV, V, and VII.

urine indicate a slight reduction in the output of sodium during flight. This is associated, as seen in the hashed bars, with some increase in aldosterone excretion. Postflight; there is a marked retention of sodium. As expected, chloride excretion parallels the sodium excretion. Potassium excretion during flight (fig. 10) appears depressed, and in all but the command pilot of Gemini VII, it was depressed immediately postflight. This depression could be observed in total 24-hour output and in minute output. The antidiuretic hormone appeared elevated in only the first postflight sample of the Gemini VII pilot. The crudities of this biological assay may account for the inability to observe any gross changes. The retention of electrolytes is very closely associated with the retention of water postflight.

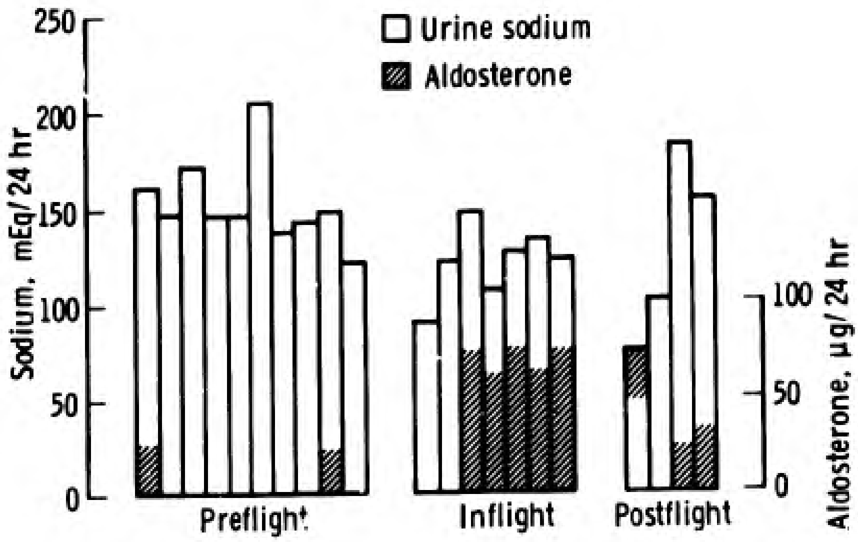

Figure 10. Urine Sodium and Aldosterone, Gemini VII Command Pilot.

The second profile involves the estimation of the physiological cost of maintaining a given level of performance during space flight. This could be considered a measure of the effects of stress during space flight. Two groups of hormones were assayed; the first, 17-hydroxycorticosteroids, provides a measure of long-term stress responses. The second, catecholamines, provides a measure of short-term, or emergency, responses. The results obtained with the catecholamine determinations are anomalous and changes observed could be considered well within the error of the methodology. As seen in figure 11, the 17-hydroxycorticosteroid levels are depressed during the flight. An elevation immediately postflight may be related to the stress of reentry and recovery. Although there may be considerable speculation regarding the low inflight steroids, it must be reemphasized that these results are from a single flight, and much more data will be essential before a valid evaluation is possible.

The third profile constitutes a continuing evaluation of the effects of space flight on bone demineralization. Calcium, magnesium, phosphate, and hydroxyproline are measured in plasma and in urine obtained preflight, inflight, and postflight. This is an attempt to determine whether the status, or the changes in the status of bone mineral, are accompanied by alterations in plasma calcium and hydroxyproline, and by alterations in urinary excretion of calcium, phosphate, magnesium, and hydroxyproline. The amino acid, hydroxyproline, is unique to collagen, and it was presumed that an increased excretion of hydroxyproline might accompany demineralization accompanied by dissolution of a bone matrix (fig. 12). The first postflight plasma samples following the 14-day flight show a marked increase in the bound hydroxyproline, while larger quantities of calcium were excreted later in the flight than during the early phases of the flight. This is consistent with a change in bone structure.

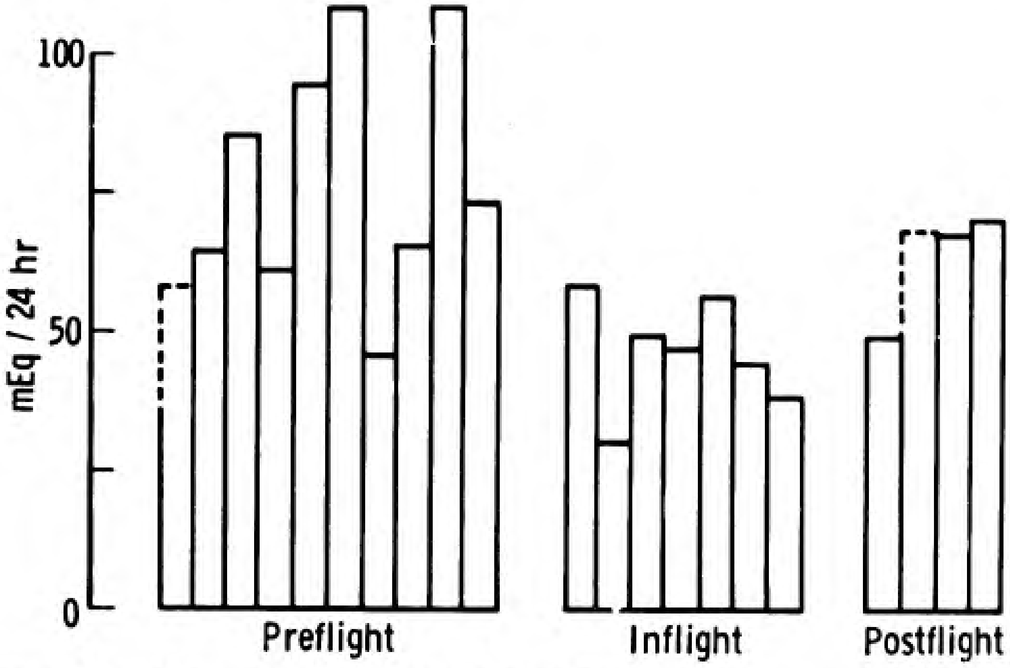

Figure 11. Urine Potassium, Gemini VII Pilot.

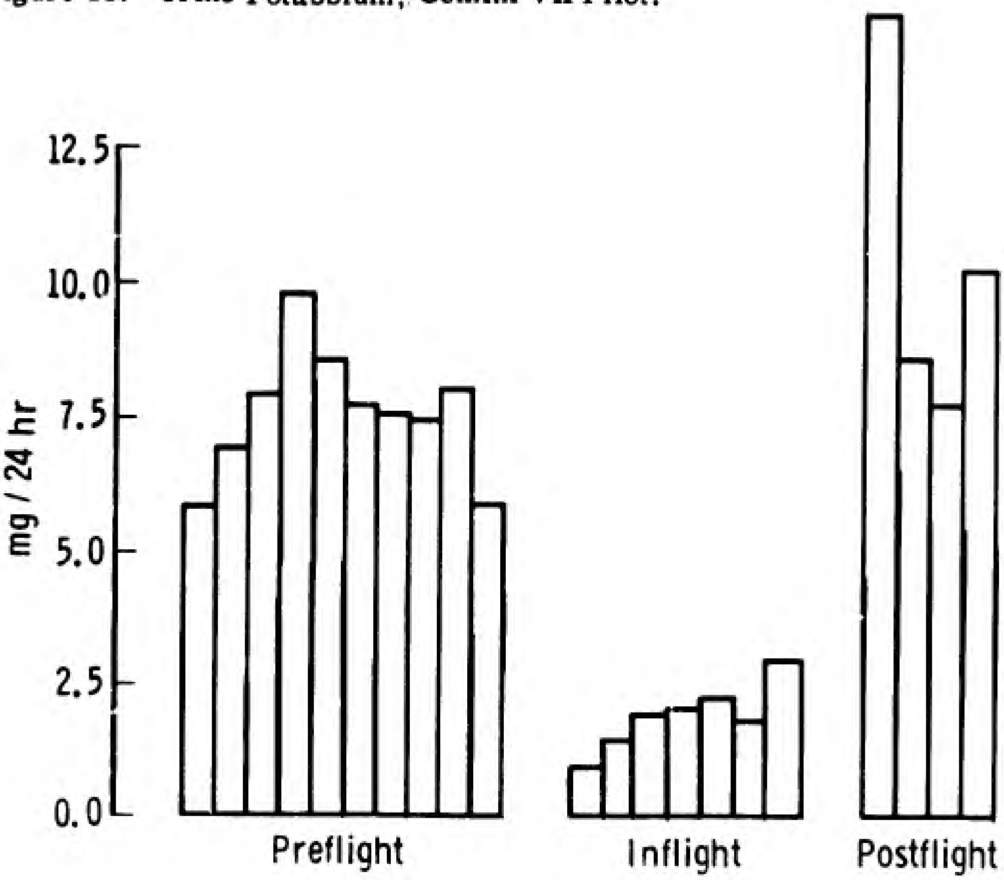

Figure 12. Urine 17-Hydroxycorticosteroids, Gemini VII Command Pilot.

The fourth group may be related to protein metabolism and tissue status. When total nitrogen was related to intake during flight, a negative balance was noted.

Gastrointestinal System

The design and fabrication of foods for consumption during space flights have imposed unique technological considerations. The volume of space food per man-day has varied in the Gemini missions from 130 to 162 cubic inches (2131 to 2656 cc). Current menus are made up of approximately 50 to 60 percent rehydratables (foods requiring the addition of water prior to ingestion); therefore, food packaging is required that permits a method for rehydration and for dispensing food in zero gravity. The remaining foods are bite-size; that is, food items which are ingested in one bite and rehydrated in the mouth. About 50 percent of the rehydratable and the bite-size foods are freeze-dried products, the remaining are other types of dried or low-moisture foods, some of which are compressed. A typical menu (table V) has an approximate calorie distribution of 17 percent protein, 32 percent

TABLE V. TYPICAL GEMINI MENU
[Days 2, 6, 10, and 14]

	Calories
Meal A:	
Grapefruit drink	83
Chicken and gravy	92
Beef sandwiches	268
Applesauce	165
Peanut cubes	297
	905
Meal B:	
Orange-grapefruit drink	83
Beef pot roast	119
Bacon and egg bites	206
Chocolate pudding	307
Strawberry cereal cubes	114
	829
Meal C:	
Potato soup	220
Shrimp cocktail	119
Date fruitcake	262
Orange drink	83
	684
Total calories	2418

fat, and 51 percent carbohydrate. Total calories provided and eaten per day varied from flight to flight. Food consumption during Gemini IV, V, and VII is summarized in figures 13, 14, and 15. Food consumption during Gemini IV and VII was very good, but weight loss on Gemini IV for a shorter duration mission was definitely substantial. The anorexia of the Gemini V crew is unexplained although many hypotheses could be presented. Although weight loss has occurred on all missions, it has not increased with mission duration (table VI). Obviously, more calories and water must be consumed to maintain body weight inflight at preflight levels.

Gastrointestinal tract function on all missions has been normal, and no evidence exists for excess nutrient losses due to poor food digestibility during flight. Before the missions, the crews ate a low-residue diet, and, on all flights beginning with the Gemini V mission, an oral and usually a suppository laxative have been used within two days before launch. On the shorter extravehicular missions, this preflight preparation has generally allowed the crew to avoid defecation inflight.

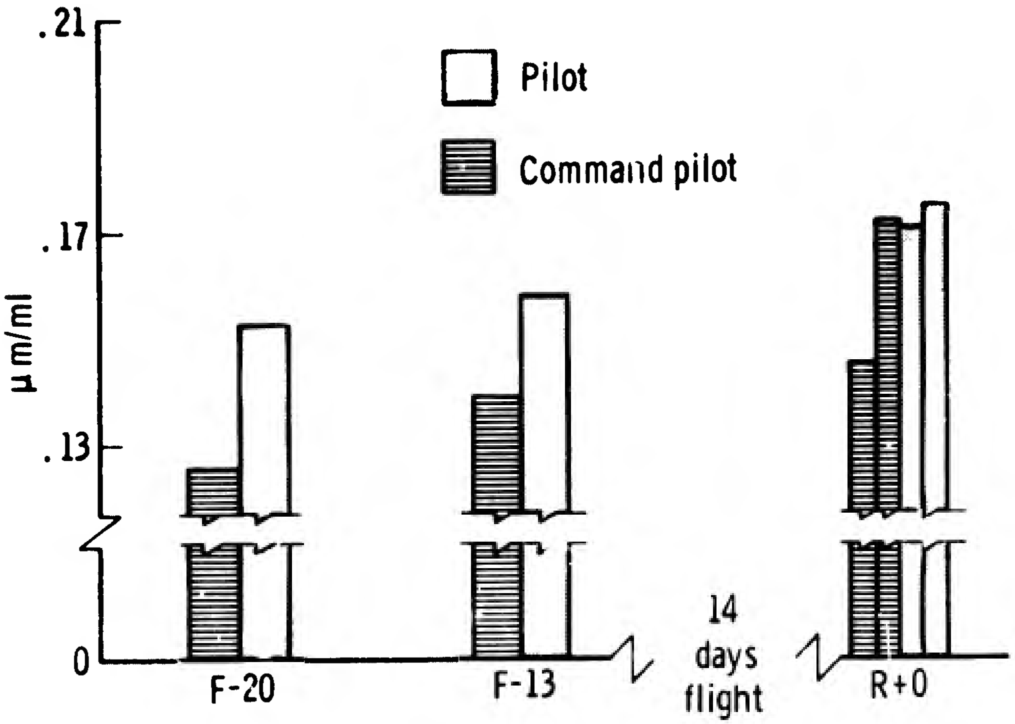

Figure 13. Bound Plasma Hydroxyproline, Gemini VII.

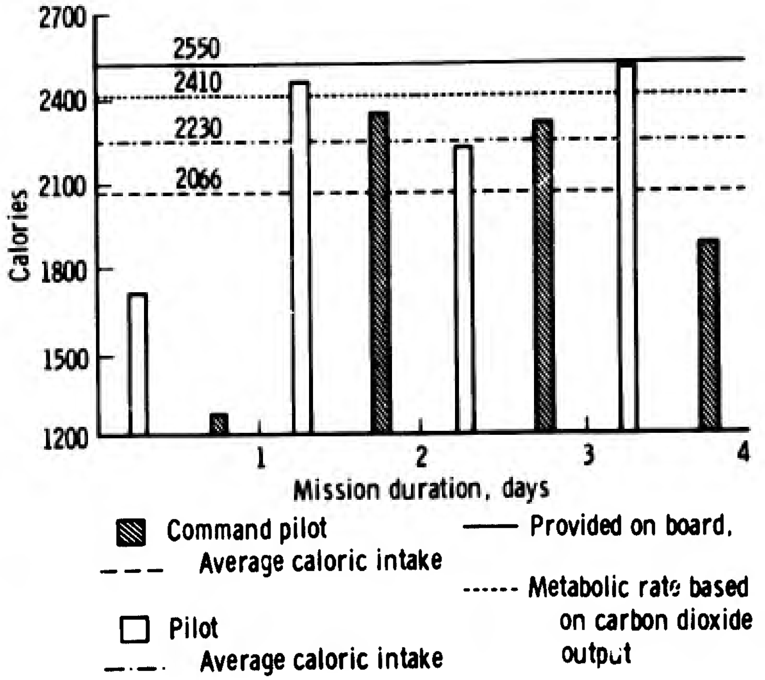

Figure 14. Caloric Intake on Gemini IV.

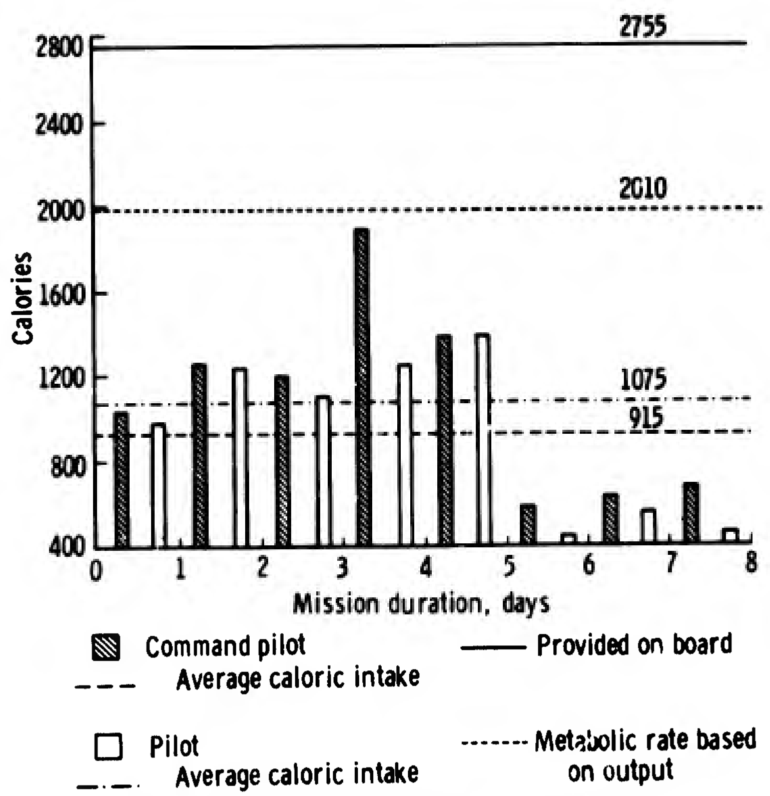

Figure 15. Caloric Intake on Gemini V.

TABLE VI. FLIGHT CREW WEIGHT LOSS

Gemini mission	Command pilot weight loss, lb	Pilot weight loss, lb
III	3	3.5
IV	4.5	8.5
V	7.5	8.5
VI-A	2.5	8
VII	10	6
VIII	Not available	Not available
IX-A	5.2	13.6
X	3.0	3.0
XI	2.7	<0.1
XII	6.5	7.25

Genitourinary System

There have been no difficulties involving the genital system. Urination has occurred normally both inflight and postflight, and there has been no evidence of renal calculi.

Musculoskeletal System

Here again, interpretation of the information gathered to date on bone and muscle metabolism as affected by space flight must be cautious due to the very few subjects observed under varying dietary intakes and exposed to multiple flight stresses.

The bone demineralization (percent change in density) which occurs in the os calcis (heel) and phalanx 5-2 (little finger) during space flight and under equivalent periods of bed rest and analogous intakes of calcium is compared in figures 16 and 17. The changes, as compared with bed rest, were definitely less in the 14-day flight where calcium intake approached 1000 mg per day and the crew routinely exercised. The phalanx changes are remarkable because significant differences in density have not been observed during 30 days of complete bed rest when calcium intake has been adequate; that

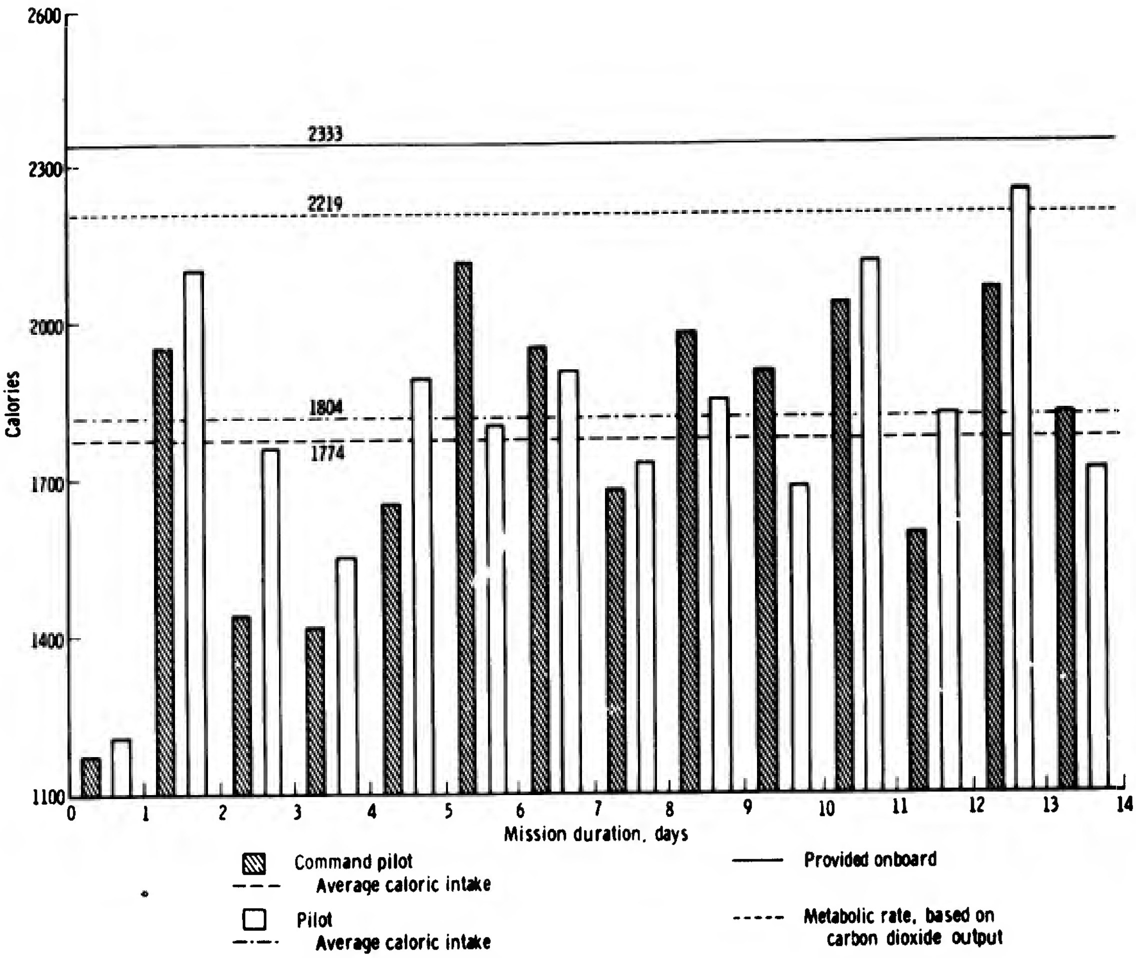

Figure 16. Caloric Intake on Gemini VII.

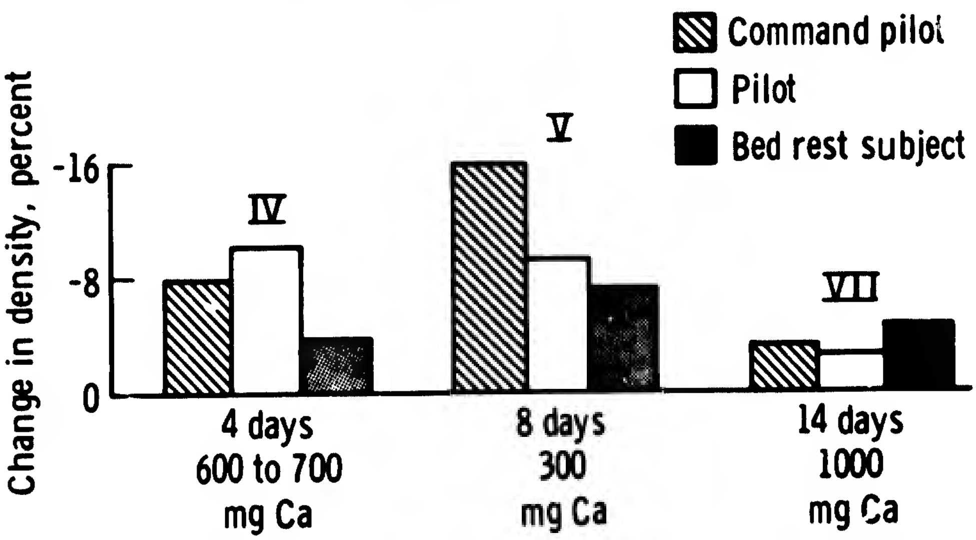

Figure 17. Loss of Ascalcis Densityon Gemini IV, V, and VII Missions.

is, over 500 mg per day. In all instances the data for the bones examined indicate a negative change, and the calcium balance data collected on Gemini VII verify a negative balance trend. None of the changes are pathological but indicate that further research is needed, and that ameliorative methods for use during longer duration flights need to be examined.

The detailed 14-day inflight balance study revealed some loss in protein nitrogen.

Exercise Capacity Tests

Previous investigations have shown that a limitation of optimal cardiovascular and respiratory function exists when a heart rate of 180 beats per minute is reached during a gradually increased workload. With this in mind, an exercise capacity test was incorporated into the Gemini operational preflight and postflight procedures in order to determine whether changes occur in crew physiologic reaction to work.

The tests have been performed by the crewmembers of the Gemini VII mission and by the pilots of the Gemini IX-A, X, XI, and XII missions. All but one of the crewmen tested exhibited a decrease in exercise capacity as monitored by heart rate, and a concomitant reduction in oxygen consumption to a quantitated workload. These findings are graphically demonstrated in figure 18.

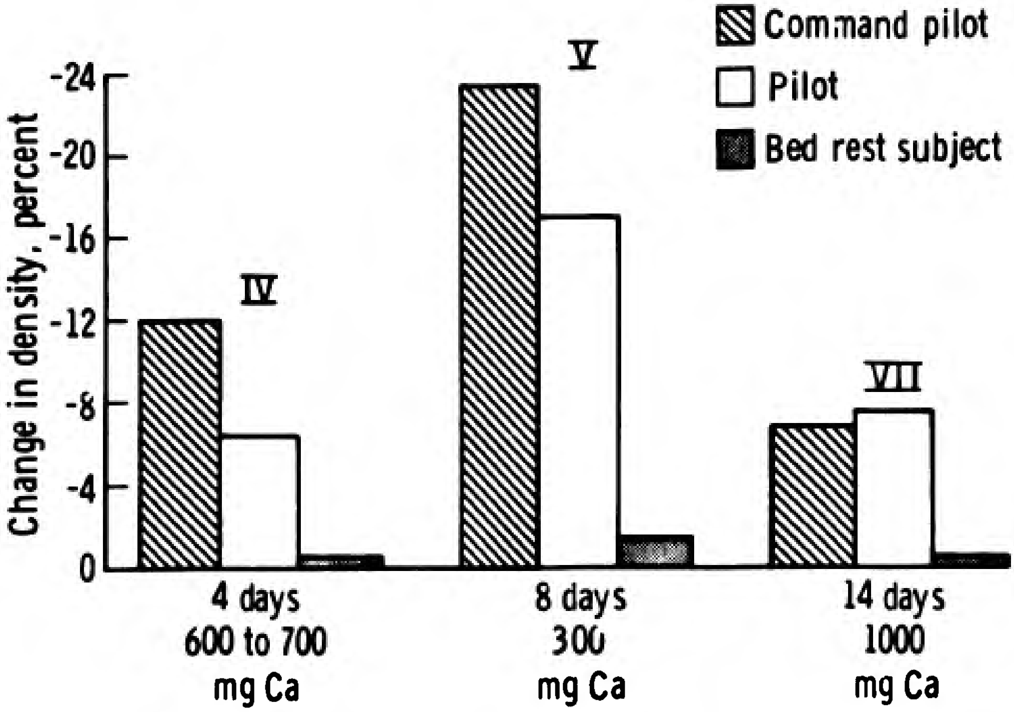

Figure 18. Change in Density of Hand Phalanx on Gemini IV, V, and VII Missions.

Additionally, the heart rate/workload information collected preflight has been of value as a very rough index of the metabolic rate of crewmen during extravehicular activity. It is realized that many other stresses above and beyond the simple imposition of workload can and do affect heart rate. The heart rate as measured during extravehicular activity is not considered an exact index of the workload being performed, but rather as a reflection of total physiological and psychological strain.

Inflight Metabolic Data

Metabolic measurement during United States space flights has been limited to the determinations of the total carbon dioxide production by the chemical analysis of the spent lithium hydroxide canister. This method is of value only in establishing the average heat-production rate for crewmen during space flight. Figure 19 shows close agreement between the U.S.S.R. and the U.S.A. metabolic data. The higher metabolic data observed during the Mercury flights are explained by the fact that these were short-duration flights in which the crewmen did not sleep.

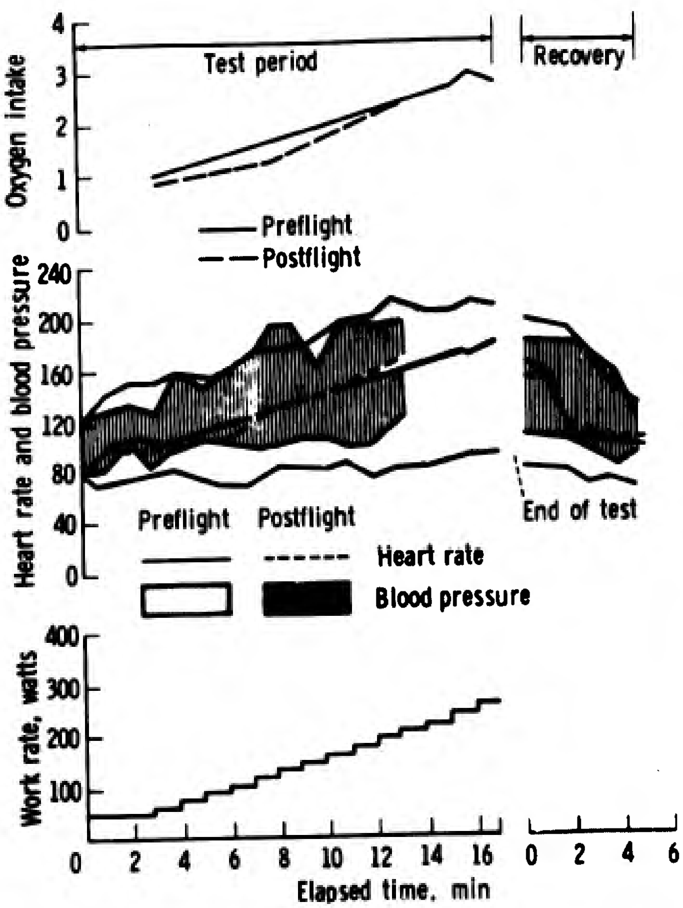

Figure 19. Preflight and Postflight Exercise Capacity Test Results, Gemini IX-A.

Other Observations Concerning Weightless Flights

The crews have never slept well on the first night in space, and many factors other than weightlessness may be active in limiting the sleep obtained, regardless of flight duration. All crewmembers have reported a tendency to sleep with the arms folded at chest height and the fingers interlocked. The legs also tend to assume a slightly elevated position. On return to the one-g environment, the crews are aware of the readaption period because they are aware for a short time that the arms and legs have weight and require effort to move. There has been some postflight muscle stiffness following the prolonged missions that may be more associated with the confinement of the spacecraft than with weightlessness.

Exercise has varied in degree even on the long-duration flights. On the 14-day mission, there were three 10-minute exercise periods programmed and completed per day. On the short-duration flights with great demands upon the crew for rendezvous and extravehicular activity, no specific conditioning exercises have been conducted. There appears to be a need for a definite exercise regime on long-duration flights.

Crew Performance

Strange reactions to the isolation and the monotony of space flight were originally predicted. Hallucinations and a feeling separation from the world described as the breakoff phenomenon had also been predicted along with space euphoria. The experience to date has shown no evidence of the presence of any of these responses. There have been no abnormal psychological reactions of any sort, and the flights have been far from monotonous. In the single-man flights of the Mercury series, there was always ample ground contact and certainly no feeling of isolation or monotony. In the two-man Gemini flights, the same was true and of course there has always been a companion crewman, thus avoiding isolation. The crews have exhibited remarkable psychomotor performance capabilities, and have demonstrated a high level of central nervous system function by the performance of a number of demanding tasks under very stressful circumstances.

Drugs

A number of predictions were made that man would require the assistance of drugs to cope with the space-flight environment. In particular, sedation prior to launch and stimulation prior to reentry have been mentioned. In the early planning for space flight, a drug kit was made available for inflight prescription. The crews have been pretested to each of the drugs carried; thus, the individual reaction to the particular drug is known. Aspirin and APC's have been used in flight for occasional mild headache and for relief of muscular discomfort prior to sleep. Dextroamphetamine sulfate has been taken on several occasions by fatigued crewmen prior to reentry. A decongestant has been used to relieve nasal congestion and alleviate the necessity for frequent clearing of the ears prior to reentry. The antimotion sickness medication has been taken in one instance prior to reentry to reduce motion sickness resulting from motion of the spacecraft in the water postlanding. An inhibitor of gastrointestinal propulsion has been prescribed to assist in avoiding inflight defecation when necessary. No difficulty has been experienced in the use of these medications which have produced the desired and expected effects. None of the injectors have been used inflight.

Inflight Disease

Preventive medicine enthusiasts have predicted the possible development of infectious disease inflight as a result of preflight exposure and the lack of symptoms or signs which can be detected in a preflight examination.

Quarantine of the crews for a period of time preflight has been discussed, and has been rejected as being an impractical method in the missions to date. The immediate preflight period is very demanding of crew participation, and our efforts have been directed at screening the contacts in so far as possible in attempting to reduce crew exposure to possible viral and bacterial infections, particularly the upper respiratory type. A number of short-lived flu-like syndromes have developed in the immediate preflight period as well as one exposure to mumps and one incident of betahemolytic streptococcal pharyngitis. In every incident, the situation has been handled without affecting the scheduled launch and, in retrospect, the policy of modified quarantine has worked well. Stricter measures may have to be adopted as longer flights are contemplated.

Fatigue

It was predicted that markedly fatigued flight crews would result from the discomfort of flight in a suited condition, a confined spacecraft, and inadequate rest. In reviewing the flight program to date, it appears that the crews obtain less sleep than in similar circumstances on the ground, but this has not resulted in undue fatigue. Intermittent periods of fatigue have been observed resulting from demanding mission requirements and from the fascination of the crew with the unique opportunity to view the universe. This has been cyclic in nature and on the long-duration flights has always been followed by periods of more restful sleep. No interference with performance has been noted due to inflight fatigue.

Medical Support

In preparing for the medical support of manned space flights, the possibility of injury at the time of launch and recovery was carefully evaluated. A detailed plan of support involving medical and surgical specialists in the launch and recovery areas was evolved and modified as the program progresses. In retrospect, it might appear that the support of surgeons, anesthesiologists, and supporting teams in these areas has been overdone in view of the results. This is always a difficult area to evaluate, however, because none of the support is needed unless a disaster occurs. The best that can be said at the moment is that this support will be critically reviewed in the light of the experience to date and rendered more realistic in the demands placed on highly trained medical personnel.

When originally established, the preflight and postflight examinations were aimed at identifying gross changes in man resulting from exposure to the space-flight environment. The examinations have been tailored along standard clinical lines, and although these techniques have been satisfactory, little in the way of change has been noted. The procedures have been modified to include more dynamic tests such as bicycle ergometry, and to reduce the emphasis on those static tests which showed little or no change. Increased use of dynamic testing should continue in the support of future manned space-flight programs.

Concluding Remarks

There has been increased scientific interest in the effect of the space-flight environment on man. The scientific requirements for additional information on man's function must be evaluated in regard to operational and mission requirements and the effect upon future manned space flight. The input of the crews and the operations planners must be weighed along with the basic medical and scientific requirements, and a realistic plan must be established which will provide needed medical answers at the proper time and allow projections of man's further exposure. This has been one of the most difficult tasks in the medical support area. The entire manned space-flight program has required the strictest cooperation and understanding between physician and engineer, and it is believed that this has been accomplished. The medical management of the diverse personnel necessary to properly provide medical support for manned space missions has provided experiences of great value to future progress.

In reviewing the flights accomplished, the plan of orderly doubling man's flight duration, and observing the results in order to plan for the next step, has been successful and effective. There is no reason to alter this plan in determining the next increments in manned space flight.

While it is difficult to define physiological adaptation, it might be stated as any alteration or response which favors the survival of an organism in a changed environment. This definition implies a useful alteration. In the space-flight situation, man is adapting to a weightless environment into which he has been thrust in a matter of minutes and stays a variable time; then a second adaptation is required after return to the one-g environment of earth. The latter adaptation can be measured under direct observation. Some of the physiological changes return to normal over an extended time; for instance, the tilt responses have all returned to normal within a 50-hour period, regardless of the duration of exposure to the space-flight environment.

To date, the observations on the effect of space flight on man's systems have shown significant changes involving only the cardiovascular, hematopoietic, and musculoskeletal systems. Even these changes appear adaptive in nature and are measured principally during the readaptive phase to the one-g environment. It appears that adequate information has been obtained to permit anticipation of a nominal lunar mission without being surprised by unforeseen physiologic changes. Medical results from the United States spaceflights appear to differ from the results reported by Russia. The Russians seem to have a unique problem in the area of vestibular response. In the cardiovascular area, the United States has not confirmed the Russian reports on electromechanical delay in cardiac response, and Russia has not confirmed the United States findings of decreased red-cell mass.

The Gemini flights have also provided some excellent examples of human variability and emphasize the necessity for care in arriving at conclusions. In making projections based on very limited results in small numbers of people, the current trend is to bank heavily upon comparisons in a given individual; that is, differences between baseline data and responses observed during and after a flight. The crewmen who have flown twice have shown variability between flights in the same manner as have different men on the same flight. Figure 20 shows the heart rates for one crewman during the

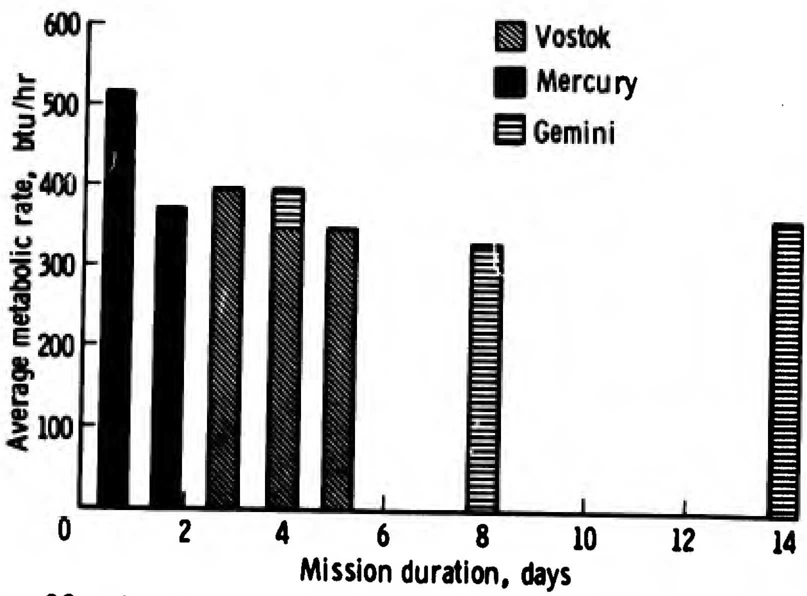

Figure 20. Average Metabolic Rates During Actual Space Flight.

launch phase of his Mercury and also of his Gemini missions. The two curves show little correlation and could as easily have come from different individuals. Obviously, confidence in the results and the definition of variability will be improved as more information is gained on future flights. Also, these are gross system findings, and much must still be accomplished in the laboratory and inflight if the mechanisms of the findings are to be understood.

In general, the space environment has been much better than predicted. In addition, man has been far more capable in this environment than predicted, and weightlessness and the accompanying stresses have had less effect than predicted. While all these items are extremely encouraging and are the medical legacy of the Gemini Program, it is important to concentrate on some of the possible problems of future, very long duration flights, and application of the Gemini knowledge. Consideration must be given to (1) obtaining additional information on normal baseline reactions to stress in order to predict crew response, (2) determining psychological implications of long-duration confinement and crew interrelations, (3) solving the difficult logistics of food and water and supply of waste management, and (4) providing easy, noninterfering physiologic monitoring.

The first steps into space have provided a rich background on which to build for the future. In addition to the information provided for planning future space activities, benefits to general medicine must accrue as smaller and better bioinstrumentation with wider applicability to ground-based medicine is developed; as normal values are defined for various physiologic responses in man; and as ground-based research is conducted, such as bed-rest studies. These results should yield a large amount of information applicable to hospitalized patients. It has been observed how the human body can adapt to a new and hostile situation and then readapt in a surprisingly effective manner to the normal one-g earth environment. Continued observation of these changes will help determine whether the space environment may be utilized for any form of therapy in the future. The space-flight environment will certainly prove to be a vital laboratory, allowing study of the basic physiology of body systems, such as the vestibular system. Even incidental findings such as the red-cell membrane changes which are markedly applicably to hyperbaric applications in medicine, may be of benefit to general scientific and medical research.

SUMMARY

The Mercury and Gemini space flights provided approximately 2000 man-hours of weightless exposure for evaluating predicted effects of space flight versus actual findings. In general, the environmental hazards and the effects on man appear to be of less magnitude than originally anticipated. The principal physiologic changes noted were orthostatism for some 50 hours postflight as measured with a tilt table, reduced red cell mass (5 to

20 percent), and reduced X-ray density (calcium) in the os calcis and the small finger. No abnormal psychological reactions have been observed, and no vestibular disturbances have occurred that were related to flight. Drugs have been prescribed for inflight use. The role of the physician in supporting normal space flight is complex, requiring the practice of clinical medicine, research, and diplomacy. Although much remains to be learned, it appears that if man is properly supported, his limitations will not be a barrier to the exploration of the universe.

Advanced Aspects of Pressure Suit Developments

Major Jefferson C. Davis

Major Davis received his M. D. degree from the University of Missouri School of Medicine and completed his internship at Bellevue Hospital in New York. His M. P. H. degree was earned at the University of California, Berkeley. He entered the U. S. Air Force in 1958. He has served as Chief of Aerospace Medicine at Ellsworth AFB, South Dakota, and instructor in flight medicine at the USAF School of Aerospace Medicine, Brooks AFB, Texas. Major Davis is presently assigned to the Aeromedical Indoctrination Branch, USAF School of Aerospace Medicine. He is the medical officer for the USAF Compression Training Program. In this capacity he is responsible for training flight surgeons and others in the recognition and compression therapy of altitude decompression sickness. He is certified by the American Board of Preventive Medicine in Aerospace Medicine.

ADVANCED ASPECTS OF PRESSURE SUIT DEVELOPMENTS

Major Jefferson C. Davis, USAF, MC

The use of pressure suits to provide physiological protection at reduced barometric pressures is a relatively new endeavor. The first high-altitude pressure suit was constructed only 34 years ago. The purpose of this presentation is to discuss physiological requirements for pressure suits and to examine the relative merits of various methods of providing necessary protection. Specific pressure suits will not be discussed as such but only as they exemplify current and proposed concepts basic to pressure suit design. The vast strides in pressure suit development in recent years have yielded excellent reliability and protection even in the hostile extravehicular environment of space flight. Crewmember objections to current pressure suits are often based on encumbrance, impaired vision and loss of mobility even in the unpressurized mode during the prolonged periods when they are worn as back-up or emergency equipment, needed only in the event of loss of cabin pressurization. I wish to impart the notion that pressure suits should be developed for specific purposes - designed to provide the physiological support necessary for a particular aircraft or spacecraft and for a particular type mission profile.

Physiological Parameters - For prolonged function without impairment, arterial oxygen saturation (PaO_2) must be maintained at or above 87%. According to the oxyhemoglobin dissociation curve, this can be attained, at a blood pH of 7.40, if the alveolar partial pressure of oxygen (P_{AO_2}) is maintained at or above 60 mmHg. Thus, we find that simply breathing 100% oxygen at ambient pressure is sufficient to prevent significant hypoxia at altitudes up to 40,000 feet (P_B = 140.7 mmHg).

$$P_{AO_2} = F_{IO_2} (P_B - P_{AH_2O}) - P_{ACO_2}$$

(assuming R = 1.0)

Breathing 100% oxygen at 40,000 feet:

$$P_{AO_2} = 1.0 (140.7 - 47) - 35$$

$$P_{AO_2} = 58.7 \text{ mm Hg}$$

However, ascent to altitudes above this requires that 100% oxygen under increased pressure be supplied if hypoxic arterial saturations are to be avoided. Within narrow limits this can be accomplished by positive pressure breathing, with the amount of pressure required calculated according to the formula:

$$P_{AO_2} = F_{IO_2} \ (P_B - P_{AH_2O}) - P_{ACO_2} + P$$
$$P = P_{AO_2} - \left[F_{IO_2} \ (P_B - P_{AH_2O}) - P_{ACO_2}\right]$$

Where P = the required positive pressure to maintain P_{AO_2} in the range of 60 mmHg.

Thus at 43,000 feet (P_B = 122 mmHg), the amount of positive pressure which must be added to the inspired oxygen is:

$$P = 60 - \left[1.0 \ (122 - 47) - 35\right]$$
$$P = 20 \text{ mmHg}$$

Using a mask only, positive pressure breathing of even 20 mmHg causes eye and ear discomfort. The untrained subject soon suffers fatigue of the respiratory muscles as they work to counter the increased intrapulmonic pressure. Pressures above 30 mmHg are considered dangerous except for the highly trained individual. Using these pressures and accepting a moderate degree of hypoxia, pressure breathing alone can suffice for brief periods of emergency from 43,000-50,000 feet.

In addition to the pulmonary hazards of pressure breathing we need only mention the problem of venous pooling. Parry showed a reduction of about 50% in cardiac output during pressure breathing at 30 mmHg. The increase in intrapleural pressure impedes venous return to the right atrium and consequent peripheral venous pooling and finally tissue edema. Thus, if flight must be sustained for more than a few minutes even between 43,000 and 50,000 feet, additional equipment is required to prevent hypoxia and venous pooling.

Aside from the basic requirements to maintain arterial oxygen saturation above hypoxic levels, prolonged flights at high altitude may impose other stresses. In the event of failure of cabin pressurization, the occupant may be exposed to extremes of temperature or windblast as in the case of high speed ejection from disabled aircraft or loss of an aircraft canopy. Within wide limits, experience has shown that short term exposure to temperature extremes can be tolerated for a few minutes without severe damage even without protection but prolonged exposure requires that a habitable microclimate be supplied by protective garments.

Hence, in all these problem areas we must consider several factors in providing protective garments:

a. In the event of loss of cabin pressure, how long must the pilot remain at altitudes above 40,000 feet equivalent pressure?

b. If emergency escape is required, will he eject from the vehicle in an open ejection seat or a capsule ejection system? i.e., does he require windblast protection?

c. What other capabilities should the garment possess? e.g. flotation, cold water immersion protection, dry cold protection, temperature control during ground and normal in-flight profiles.

The pressurized aircraft or sealed spacecraft environments provide habitable pressure and temperature control so that with the exception of extravehicular activity in space flight and planned aircraft depressurizations, pressure suits are worn as back-up or emergency garments.

Pressure Suits - The first recorded suggestion for the use of pressure suits was by J. S. Haldane (1). "If it were required to go much above 40, 000 feet, and to a barometric pressure below 130 mmHg, it would be necessary to inclose the airman in an air-tight dress, somewhat similar to a diving dress, but capable of resisting an internal pressure of say 130 mm of mercury. This dress would be so arranged that even in a complete vacuum the contained oxygen would still have a pressure of 130 mm. There would then be no physiological limit to the height attainable."

Haldane's suggestion was put to use in 1933 when modification of a diving dress in England allowed American balloonist Mark Ridge to make altitude chamber flights to an ambient pressure of 17 mmHg equivalent to 84,000 feet. The suit was pressurized to 150 mmHg. Concurrently Wiley Post in the United States worked with the Goodrich Company to develop a pressure suit for his high altitude aircraft flights (fig. 1).

Pneumatic Pressure Suits - These were the first in a series of refinements in pressure garments utilizing pneumatic pressure to provide the flyer a pressurized microenvironment, leading to today's highly sophisticated full pressure suits (fig. 2). Depending on design, the entire suit may be pressurized with oxygen or the suit may be pressurized with air or another gas and the breathing zone pressurized with oxygen, with separation maintained by a face barrier or an oxygen mask. The pressure used for the suit represents a compromise between physiological protection and mobility. To minimize the incidence of decompression sickness, it would be desirable to maintain suit pressure at or above 280 mmHg (25, 000 feet) but increasing pressure means reduction of mobility. Suit pressures of 180 mmHg (35, 000 feet) to 260 mmHg (27, 000 feet) are commonly used in pneumatic pressure suits.

The great technological advances in materials and techniques used in construction of full pressure suits have resulted in greatly improved mobility, comfort and reliability. New concepts in full pressure suit joint

Figure 1

Figure 2

design such as the use of bellows, mechanical joints and the so-called stovepipe joints offer the promise of further enhancement of mobility in the pressurized state. The full pressure suit truly supplies the flyer or astronaut with a microenvironment which can be controlled for temperature and pressure to maintain conditions with normal physiological range for extended periods of time.

On the other hand a penalty must be paid for this protection because when the full pressure suit is worn as an emergency back-up garment, it is worn uninflated during the vast majority of the time. Even in this mode, current full pressure suits are heavy, cumbersome and restrictive to vision and a full range of mobility. Over prolonged hours of wear they add greatly to fatigue. These objections are less noticeable in an experimental aircraft or spaceflight situation because of the high motivation of the selected crewmembers. However, in routine operational situations they become quite marked.

Mechanical Pressure Suits (Partial Pressure Suits) - Attempts to find answers to some of these objections were begun during the 1940's by the R. A. F. and the U. S. Air Force. The basic idea was to provide a compromise garment which would provide adequate physiological protection to allow descent or corrective action in the event of an emergency or if possible to permit the completion of the prescribed mission at high altitude but to cause a minimum of inconvenience during routine operations.

The search for comfortable yet adequate combinations led to a spectrum of garments ranging from a pressure breathing mask or pressure helmet with torso counterpressurization only (Royal Air Force jerkin) to suits providing mechanical counterpressure to the torso, upper extremities and lower extremities except the feet.

Pressure breathing with torso counterpressurization only is unsatisfactory because of syncope, due to venous pooling, in most subjects after as little as 30 seconds even at 55,000 feet. However, when pressure breathing is performed with a pressure helmet and balanced torso and extremity counterpressure, durations of up to 4 hours at 65,000 feet altitude, with the suit and helmet pressurized to 100 mmHg above ambient, have been attained with no ill effects. Peak altitudes of over 198,000 feet have been reached in the altitude chamber wearing mechanical pressure suits so configured.

Mechanical pressure has been applied to the skin in two techniques. In the capstan or pneumatic lever principle developed in 1945 by Dr. James Henry of the University of Southern California (2), fabric is drawn tightly over the skin to apply mechanical pressure (fig. 3) while in bladder suits, pressure is applied by pneumatic bladders covering the entire body except the head and neck, hands and feet (fig. 4). Pressures applied to the helmet, breathing bladders, capstans and pneumatic bladders are controlled by

Figure 3

Figure 4

regulators preset to maintain desired levels of pressurization, usually resulting in a total pressure (ambient + suit) of 140 - 150 mmHg (38,000 - 40,000 feet).

The advantages of the partial pressure suit concept have been stated as an attempt to provide emergency pressure protection with as near "shirt-sleeve comfort" as possible in the normal unpressurized state. With the current state-of-the-art partial pressure suits disadvantages are the lack of environmental control possible, the need for tight fitting of capstan suits even when unpressurized and the large bulk of bladder suits when pressurized.

Passive Pressurization Mechanical Pressure Suits - Efforts to improve uninflated comfort led to attempts to utilize the expansion of trapped gases at altitude, according to Boyle's Law. This was first tried in the form of closed cell sponge material, which it was proposed to use to make suits which would inflate automatically at altitude providing mechanical pressure to the skin (3 and 4). Inherent difficulties with this material are the thickness required even uninflated, rigidity of the material at altitude and difficulty finding a material which would produce predictable rates of expansion on repeated exposures to low altitude.

Using this principle, we turned to other forms of flexible sealed gas containers and have successfully completed feasibility studies on the basic principle of passive pressurization in the form of sealed rubber tubes.

I wish to briefly present the methods and results of our work to date, outline our plans for the future and to speculate on possible refinements of the concept. The basic suit construction is quite simple. The outer layer is an inelastic, lightweight porous fabric; the inner layer is quite loose, light and elastic and the two layers are sewn together so that multiple channels or pockets are formed between them, extending longitudinally along the extremities and torso. Into these pockets are inserted scaled expandable tubes containing a small specified volume of room air. By keeping the volume of air in the tubes constant at ground level, the only variable affecting the amount of pressure applied to the skin during ascent is the tightness of fit of the suit. Lacings in the suit allow alterations for each subject and in an operational situation, fitting would be performed by use of a thick special fitting garment over which the suit would be laced tightly, then to assume the standard loose fit when worn without that garment. Lower extremity tubes extend from the ankles to the shoulders, continuously in order to provide decreased resistance to breathing when inflated at altitude (fig. 5). Extra short tubes from the shoulders to the groin level provide necessary extrathoracic counterpressure; i.e. there is a 3:1 ratio of number of tubes, torso: extremities.

A helmet is utilized which pressurizes the entire head and neck with a

Figure 5

Figure 6

standard partial pressure suit rubber dam neck seal. Breathing pressure is supplied to the helmet, equal to that provided the skin by expansion of the tubes, by a helmet mounted mini-regulator, pre-set to follow the measured suit pressure curve as its bellows expands also according to Boyle's Law. The helmet may be either a soft, inflatable configuration (fig. 6) or a standard partial pressure suit hardhat for buffeting protection (fig. 7).

Figure 7

Wearing this suit with both types of helmets, altitude chamber flights have been made to altitudes of 75, 000 feet, with 7 minutes at 70, 000 feet, 20 minutes above 50, 000 feet with no adverse effects. Electrocardiogram, respiratory rate, skin temperatures, helmet CO_2 levels, and skin pressures were monitored during the flights. The only changes of note were pulse rate elevations to 100-130 per minute, considered to be due primarily to anxiety. Hand protection is by tightfitting standard leather flying gloves or uninflated standard partial pressure suit gloves. The feet are protected only by standard flying boots. There has been no evidence of aeroemphysema or edema. Skin pressure measurements were made at several locations using a waterfilled system consisting of a rubber bladder next to the skin connected to a manometer. Fitting the suit quite loosely at ground level, with slight increases in the initial air volumes (120 ml per long tube, 60 ml per short arm and torso tube), skin pressures at altitudes up to 20, 000 feet are negligible but with adequate counterpressure at altitudes above 40, 000 feet, peaking at 150 mm Hg at 75, 000 feet.

Mobility in the unpressurized state, at altitudes below 20, 000 feet, is as good as with a conventional flying coverall.

Even in our feasibility models, mobility at altitude with 150 mmHg skin pressure is considerably better than with previous partial pressure suits. At the present stage of development, the garment described is considered to be a so-called get-me-down pressure suit, supplying adequate physiological protection for at least 20 minutes at any altitudes above 50, 000 feet. If mission requirements are such that this protection will suffice, then the suit as configured now is adequate. The advantages of this system include:

1. Lightweight, loosely fitting garment offering a minimum of encumbrance at normal cabin altitudes below 20, 000 feet.

2. Adequate passive ventilation through the fabric between the tubes in the uninflated state to preclude the need for accessory ventilating systems.

3. Protection against the cold of rapid decompression at high altitude due to the dead air space created in the expanded tubes, which then become confluent in their body coverage.

4. Independence of each tube so that damage to one does not affect counterpressure afforded by the rest of the suit.

5. In water tests with the suit at ground level it has been found that there is adequate gas volume in the tubes to provide flotation for a man. With the largest volume in the torso region, flotation is naturally upright.

6. In situations where buffeting protection is not critical, the soft helmet can be worn folded back around the neck, to be closed manually or possibly automatically with further refinement.

Disadvantages of the current garment are:

1. Measurable skin pressure of some 20 mmHg at cabin altitudes above 25,000 feet. It would be preferable to have no added skin pressure until 40,000 feet is reached.

2. Temperature control is passive only so that in the unpressurized state the occupant is at the mercy of the ambient cockpit temperature as he would be in standard clothing. At altitude for prolonged periods, there is no method for elimination of body heat

3. Extrathoracic counterpressure by direct application of pressure by tube expansion results in increased work of breathing during inhalation. The torso breathing bladder of the standard partial pressure suit offsets this problem by providing a common breathing zone - extrathoracic system with the bladder volume decreasing with each inhalation, reducing the work of breathing. It was eliminated in this suit to provide passive cooling of the torso between tubes.

Applications - With further development, the concept described should be considered for sustained flights above 50,000 feet where normally "shirtsleeve" cabin conditions prevail, with cabin altitude below 20,000 feet, temperature normally controlled by the cabin system and where the aircraft could immediately descent in the evert of sudden loss of cabin pressure. One possible application might be for use by pilots of the proposed supersonic transport. Here, the possibility of unexpected loss of cabin pressure will be so slight, cabin conditions so ideal with cabin altitudes below 10,000 feet and excellent temperature control that pilots will justifiably reject any protective garment that does not provide shirtsleeve comfort. The soft helmet could be worn folded back in normal flight. The time of useful consciousness at altitudes above 50,000 feet is only a few seconds but several studies have shown that animals decompressed even to a near vacuum will survive if recompressed within 90 seconds or even longer so that while passengers would be rendered unconscious, they could be saved if at least one pilot were protected and able to make a rapid descent.

Proposed Refinements - To offset the disadvantages outlined above for mission profiles which require features not included in the present configuration we are planning to explore certain additions. Inasmuch as all tubes in the suit have one end in the yoke region, one flexible tube with T extensions into each tube may be provided to supply active pressurization of the tubes either from a gas source in the cabin or a portable high pressure cylinder on the suit. A pop-off valve on each tube would prevent overpressurization. This would obviate the need for any gas volume in the suit below 40,000 feet and eliminate the problem of even moderate skin pressure between 20,000 and 40,000 feet.

Possible refinements in torso breathing bladder construction techniques will be studied. Possibly the torso tubes can be interconnected and controlled from the helmet regulator to provide full torso coverage with balanced, reciprocal pressures during the breathing cycle but provide passive ventilation between tubes when uninflated. Perhaps the inner layer of the suit can be converted to electrically heated underwear similar to the experimental R. A. F. garment with heating elements sewn throughout. The same underwear could also be fitted with tiny tubes for circulation of cooling fluid, so that the suit could automatically or manually be adjusted for comfort and physiological protection. If such a garment can be made light and comfortable enough to obtain pilot acceptance it could possibly provide the comfort at reduced cabin pressures between 20-40,000 feet as well as the prolonged emergency protection to make it useful as a constant wear intravehicular suit for extended space flight or for high altitude military aircraft flights.

Discussion - The final chapter in pressure suit design will not be complete until every possible avenue has been thoroughly explored. We must diligently seek new approaches and not overlook any feasible new ideas.

Perhaps the ultimate goal would be a very thin garment with thousands of tiny, flexible tubes, arranged in the body's "lines of non-extension", actively pressurized when required, with heating and cooling elements incorporated into the garment. It could fit very close to the skin, fitting and functioning as an additional, protective skin. Gloves and socks could be made of the same material. We would then need only a comfortable torso breathing bladder and helmet to complete the ensemble. Perhaps the helmet would be of clear, tough plastic, stowed telescoped into the rear of a neck ring, to be closed only in the event of an emergency. The head would then be free to move about in the clear bubble for excellent visibility. The rubber neck seal could be in fact a 2-layered sealed bag about the neck, quite loose during normal operations but inflating automatically upon decompression to provide a seal to hold helmet pressure.

Our studies with the passively pressurizing pressure suit concept were presented primarily to demonstrate that there may indeed be radical new methods possible for supplying protection against the stresses of high altitude and space flight. To conclude that this particular concept is an end in itself would be totally unrealistic. As man explores new and hostile environments, we in the field of aerospace medicine must seek better methods to protect him without so encumbering him that his ability to do useful work is impaired.

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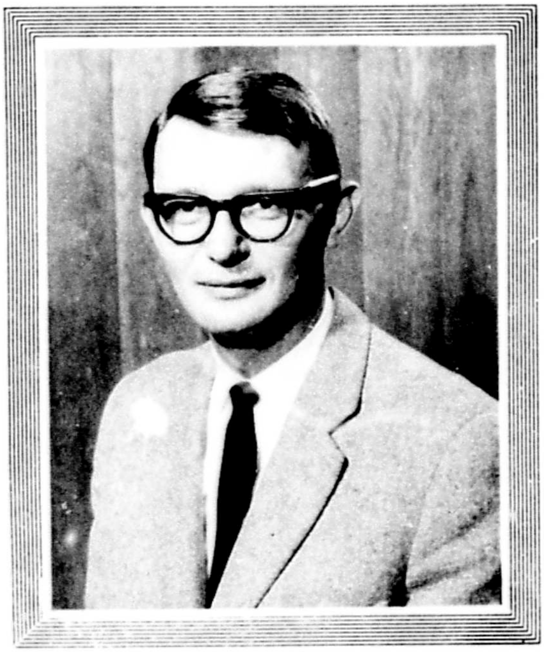
A Study of High Altitude Decompression*

Mr Alfred G. Koestler



Mr. Koestler received his B. A. degree from Baylor University, Waco, Texas, in 1960. As a National Defense and Education Act Fellow he continued graduate study in experimental and physiological psychology under Dr. W. D. Thompson at Baylor University. He has completed all requirements towards a Ph. D. and is presently working on his dissertation. He joined the staff of the 6571 Aeromedical Research Laboratory at Holloman AFB, New Mexico, in 1964, where he is now heading the Altered Atmospheric Pressures Laboratory in the Comparative Psychology Division. He has devoted a major part of his research efforts towards the study of behavioral responses of chimpanzees to unusual environments, particularly near vacuum or hyperbaric environments. He is the author or co-author of seven articles dealing with primate behavioral research.

* This research was accomplished by a joint effort of the Medical Directorate, NASA Manned Spacecraft Center, Houston, Texas, and the 6571st Aeromedical Research Laboratory, Holloman AFB, New Mexico under NASA projects 7210 and 9909.

Complete results of this research may be found in NASA CR-329, November 1965, and Aeromedical Research Laboratory technical report (ARL-TR) 67-2 of January 1967.

A STUDY OF HIGH ALTITUDE DECOMPRESSION

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Captain Martin L. Reite, USAF, MC
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INTRODUCTION

Since manned orbital flights have paved the way for long term space exploration the occurrence of decompression accidents to vacuum such as cabin punctures by cosmic particles or suit ruptures during an extra-vehicular exploration has become a distinct possibility. The probability of such occurrences have necessitated research on the effects of decompression to vacuum on unprotected and performing organisms. In past official statements, personnel of the NASA Manned Spacecraft Center at Houston have posed the following questions: First, what are the chances for survival for varying times of exposure to a vacuum? 2. What emergency repressurization schedules should be planned ? 3. How soon will the crew member recover consciousness after varying periods of exposure to vacuum? 4. How soon and how well will the crew member be able to carry out his duties after varying periods of exposure to vacuum? 5. Will irrational behavior or illness present any hazards to the completion of the mission?

Answers to these questions were partially provided by a research effort of the 6571st Aeromedical Research Laboratory at Holloman AFB which in two series of nine decompression experiments rapidly decompressed 17 chimpanzees to a near vacuum (less than 2 mm. Hg) varying the exposure times at altitude from five seconds to 3-1/2 minutes.

Emphasis will be placed upon the behavioral and physiological results of longer duration exposures, i. e., 90 seconds to 210 seconds, since the interest in the shorter exposure times has become mainly academic.

METHODOLOGY

1. Subjects: Seventeen chimpanzees, 11 males and 6 females, were selected from the colonies at the 6571st Aeromedical Research Laboratory. Their ages ranged from 53 to 81 months and their weights ranged from 15 kg. to 28 kg.

2. Apparatus: During experimentation, subjects were maintained in a decompression chamber, 76 x 122 x 122 cm., containing approximately a volume of 1 cubic meter.

Atmospheric conditions (pressure, gas composition, temperature, and relative humidity) inside the chamber were monitored and controlled by a coupled life support system.

The decompression chamber was connected via a 46 cm. diameter decompression valve to a 117. 5 cubic meter vacuum system. With the chamber at 179 mm. Hg (35, 000 ft) and the accumulator system at approximately 140 microns Hg, the resultant initial pressure equillibrium after decompression (approximately 1 second) was less than 2 mm. Hg.

A schematic of the chamber, valve, and vacuum tanks is presented in figure 1. Also evident in the schematic is a liquid nitrogen coil shroud covering the entrance to the first vacuum tank. This super cooled coil condensed moisture as it left the decompression chamber and assisted in maintaining a near vacuum during the decompression period.

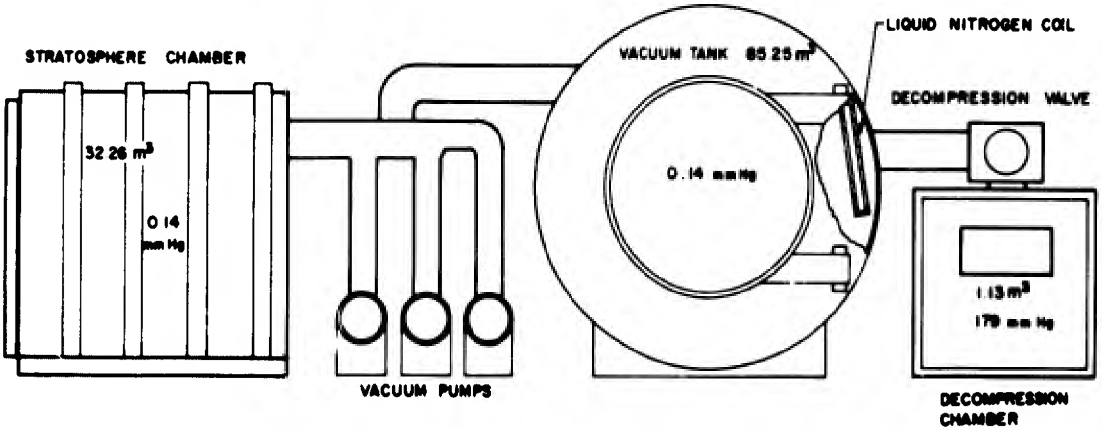

Figure 1. Schematic of Vacuum System and Parasitic Chamber.

PERFORMANCE PANEL AND RESTRAINT COUCH

Since the emphasis for this research endeavor was to determine the effects of exposure to a vacuum on a working or performing subject, all chimpanzees were trained on a complex behavioral schedule. The performance panel consisted of 10 visual and auditory stimulus displays and corresponding response manipulanda which were located within easy reach of the subject. The performance unit also contained automatic food pellet dispensers and a water reservoir. The panel was removable from a form fitted fiberglass couch which kept the subject's thighs perpendicular to its back as is shown in figure 2. The subjects were restrained in the couch with straps from a loosely fitting net restraint suit which also protected physiological sensors.

During those experiments which provided for neurophysiological recordings, a well ventilated plexiglas shield was mounted over the subject's head. This shield permitted excellent visibility and an opportunity for feeding, yet it prevented the subject from tampering with the EEG electrodes and EEG cables.

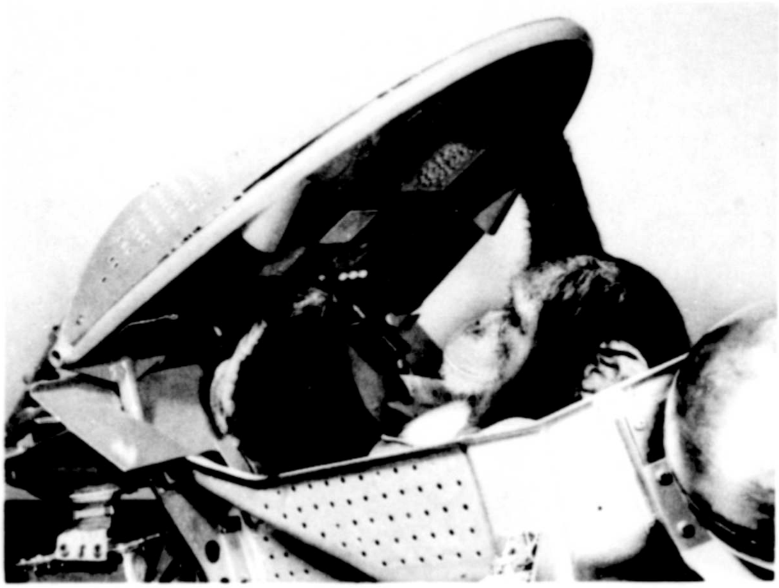

Figure 2. Decompression Subject Restrained in Performance Couch.

PERFORMANCE SCHEDULE

A standard 22 minute performance module was used on all decompression experiments.

The first twelve minutes of the performance module constituted the avoidance phase, i. e., the subject performed tasks in order to avoid delivery of a mild electric shock. This phase consisted of a continuous motor task and superimposed reaction time tasks. The continuous avoidance task (CA) covered the entire period and required the subject to depress a lever at least once every 5 seconds in order to avoid shock. The following dependent variables were considered: average lever presses per minute and an efficiency measure based on the ratio of the number of shocks avoided vs. the total possible number of shocks (144) the subject could receive.

Concurrent with the continuous avoidance task the subject was conditioned to respond to three reaction time tasks: auditory monitoring (AM), visual monitoring (VM), and discrete avoidance (DA). Auditory monitoring required the subject to press a push button within one second of the onset of a 60 db, 1,000 hertz tone. Reaction time tasks to visual cues required the subject to either depress a lever as in DA or push a response plate (VM) within one second of the onset of the respective visual stimuli. These discrete events occurred either alone or in conjunction with another discrete stimulus. For instance, while a VM stimulus occurred paired with an AM or a DA cue, the subject was also attending to the continuous avoidance task. The measured parameters of all discrete events, 77 in all, consisted of response latencies determined in tenths of seconds and of an efficiency percentage measure derived from the ratio of number of correct responses vs. the total number of presentations.

The last ten minutes of the performance module was an "oddity" task which was designed to evaluate discrimination efficiency and choice response latency. This program required the subject to select the "odd" symbol of three presented geometric symbols by pressing the corresponding response plate. The procedure was corrective (wrong choices were repeated). Successful choices were reinforced (rewarded) by the avoidance of electric shock and an opportunity to select either food or water. Following the oddity task a rest period of 13 minutes was provided before a new performance module was cycled.

PROCEDURE

Each decompression subject underwent intensive training on all tasks of the performance schedule. Training was initiated in a restraint chair (fig. 3) and was continued in a restraint couch to acquaint each subject with a reclining body position, a restraint suit, and the new location of the performance panel (fig. 2).

Figure 3. Decompression Subject Undergoing Behavioral Training.

Each decompression subject was monitored for ECG, skin temperature, respiration, heart rate, and some subjects were monitored for EEG. ECG was recorded between the sternum and the 5th lumbar vertebra, and skin temperature from the inner mid-thigh region. Respiratory excursions were measured from a copper sulfate respiration sensor. Several methods were used to record EEG, however, only one is described. Subject No. 218 used in experiment No. 17 with a 180 second exposure was implanted with chronic subcortical electrodes and skull screws several months prior to the decompression. Electrodes were bi-polar pairs of 29 gage stainless steel tubing, epoxy varnished, bared 0.5 mm at the tip, with an inter-electrode distance of approximately 1 mm. Sub-cortical locations included the amygdala, uncus, hippocampi, mesencephalic reticular formation, and nucleus centrum medianum. Stainless steel screws were placed in the skull overlying the frontal, central, parietal and occipital cortex. Following the implantation, the subjects were trained on the performance program previously described and baseline EEG recordings were obtained during wakefulness and sleep. Seven channels of electroencephalographic data were also recorded on magnetic tape for computer analysis.

Average evoked responses to stimulation of the right nucleus centrum medianum were recorded from the right central occipital cortex and the right amygdala. However, results from stimulation as well as computer analysis of the EEG are not included in this paper.

BASELINE PROCEDURE

Two days prior to an actual decompression experiment, baseline or control data were collected. Baseline procedures were duplicates of the experimental procedures, excepting, of course, the actual decompression. A thorough physical examination was performed four days prior to the baseline day.

EXPERIMENTAL PROCEDURES

Following a brief physical examination, physiological sensors were attached and the subject was secured in the performance couch. The subject was placed in the decompression chamber and the chamber door was sealed. Purging with dry, bottled oxygen began with the sealing of the chamber door and the attainment of a 95% oxygen concentration in the chamber marked the beginning of the denitrogenation period which continued for 180 minutes with a maximum attainable oxygen concentration approximating 100%. Ambient pressure (660 mm. Hg) was maintained in the chamber during this time.

A profile of the experimental procedure is presented in fig. 4. Thirty minutes and again at two hours after the onset of the denitrogenation period a complete performance module was presented to the subject.

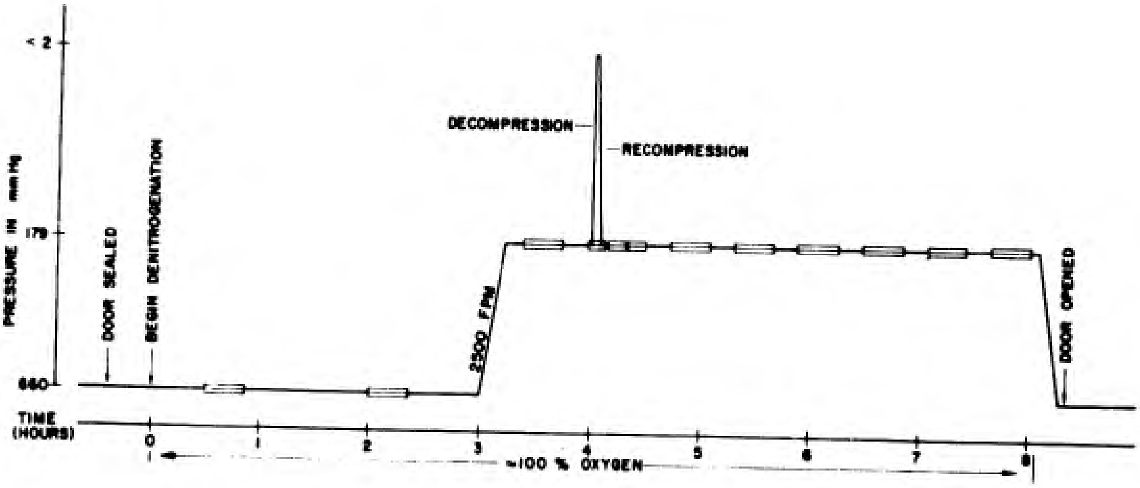

Figure 4. Schematic of Experimental Profile.

Ascent to 179 mm. Hg with 100% oxygen began at the termination of the denitrogenation period. This reduction in pressure was accomplished in an average of 13 minutes. A complete performance module was presented 10 minutes after the attainment of 179 mm. Hg and was followed by a 13 minute rest period. The exact point of the decompression was determined by a performance module and occurred at the onset of the third minute of the performance schedule. Decompression from 179 mm. Hg (100% oxygen) to less than 2 mm. Hg was accomplished on the average in 0.8 seconds while recompression from the near vacuum to 179 mm. Hg (100% oxygen) was always accomplished in 30 seconds. Exposure times to the near vacuum were predetermined and were measured from the onset of decompression to the onset of recompression.

The negative reinforcement device (shock) was switched off 30 seconds after the subject made the last appropriate response to a meaningful stimulus and was reactivated when the attending physiologist indicated beginning physiological and neurophysiological recovery.

STATISTICAL APPROACH FOR BEHAVIORAL DATA

Definitions: Time of Useful Consciousness (TUC) encompassed the time elapsed between the onset of decompression and the last appropriate response to a meaningful stimulus immediately following decompression.

Time of Total Impairment (TTI): Described the time elapsed between the end of TUC and the first appropriate response to a meaningful stimulus following the TUC. Total Behavioral Recovery (TBR) represented the time elapsed between the onset of decompression and the point in time when the last behavioral measure had returned to or crossed the respective lower baseline limit.

For each decompression experiment tests of significance of difference (Students t) between baseline and experimental means for reaction times and efficiencies on all tasks were performed. A performance module by module comparison was made between baseline and experimental reaction time means to illustrate impairment and recovery of these measures for different exposure times. Product moment correlation co-efficients and correlation ratios were computed bewteen TTI and exposure time as well as TBR and exposure time to vacuum.

BEHAVIORAL RESULTS

A total of 18 decompressions were conducted with exposure to vacuum ranging from 5 seconds to 3-1/2 minutes (one exposure at 5, 30 and 60 seconds, five exposures at 90 seconds, four exposures at 120, and 150 seconds, and one exposure at 3 minutes and 3-1/2 minutes). Seventeen subjects survived the experiments in excellent health and were able to perform on a complex behavioral schedule at pre-exposure level within a maximum time of 4 hours. One subject expired during a 90 second exposure to near vacuum.

A summary of the effects of rapid decompression to a near vacuum on learned behavior is presented in figs. 5 and 6. Representative recordings of

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

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

Figure 5. Summary of Decompression Effects.

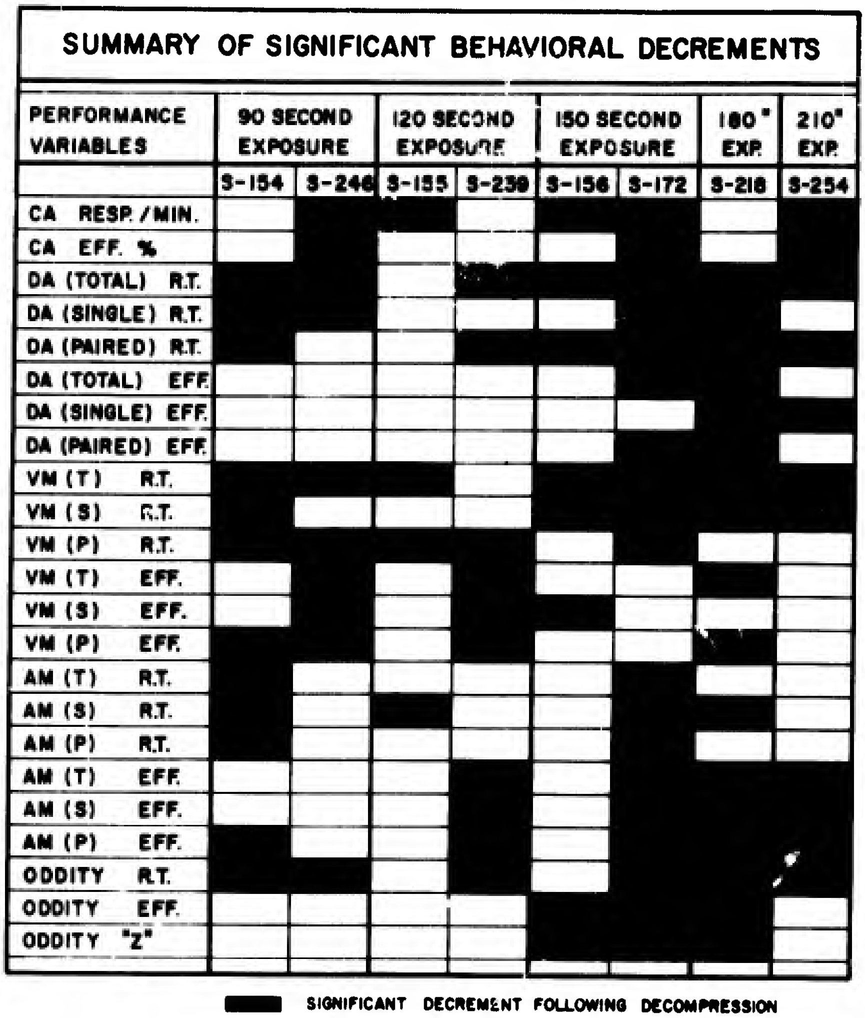

Figure 6. Representative Summary of Significant Behavioral Decrements.

the continuous motor response rates at exposures of 90, 120, 150, 180, and 210 seconds, showing impairment and recovery during and following decompression are presented in figs. 7 and 7a.

Detailed statistical comparisons of baseline and experimental performance on each subject were performed but are not contained in this report.

After removal from the chamber, the subjects appeared to be fatigued but displayed little change in their responses to handlers and the routines of post-decompression examinations. All subjects were quite dehydrated, drank large amounts of water and generally showed good appetites. Most subjects lost some weight, with the maximum weight loss ranging to 800 grams.

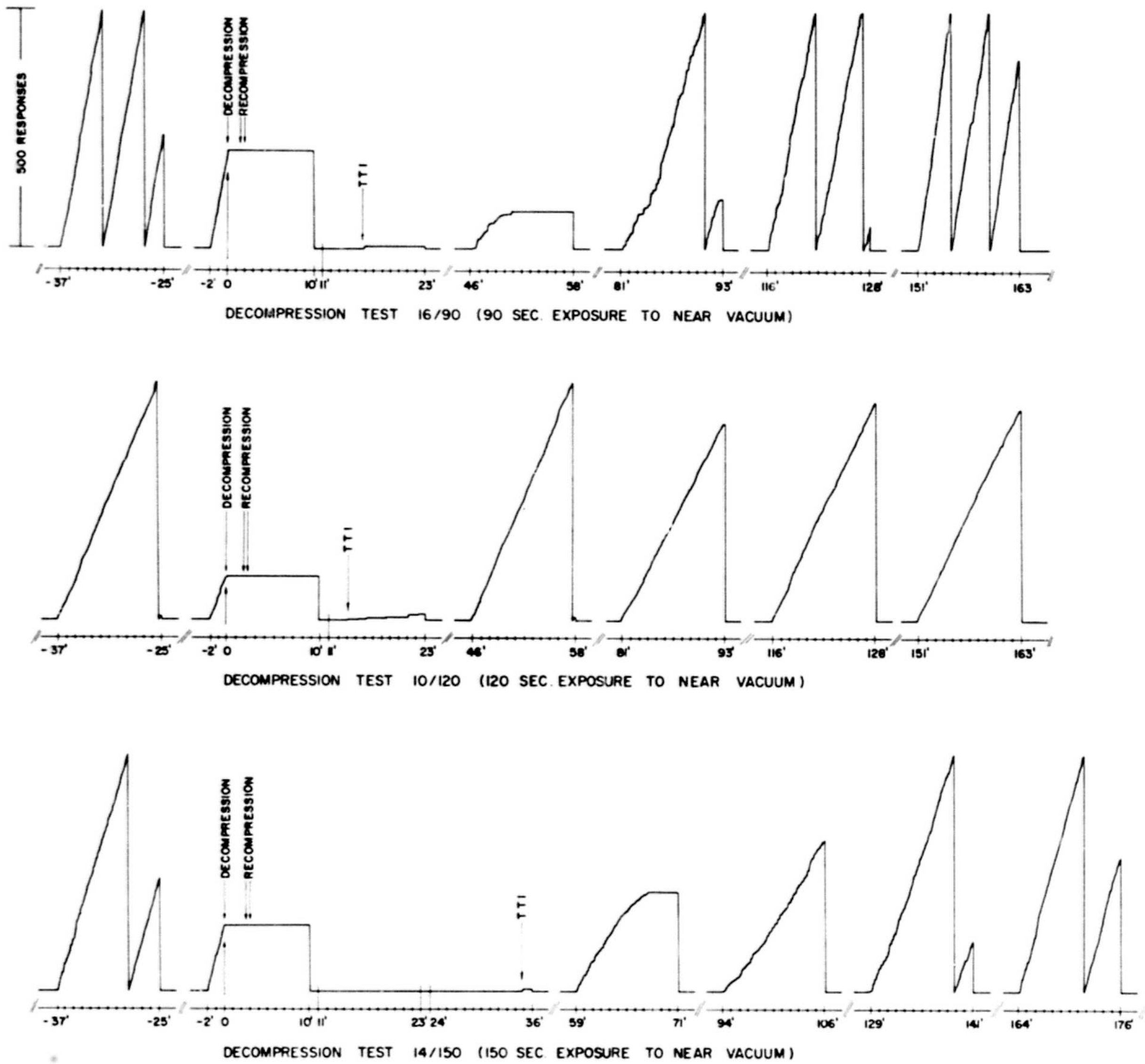

Figure 7. Effects of Rapid Decompression to Near Vacuum on Continuous Motor Behavior.

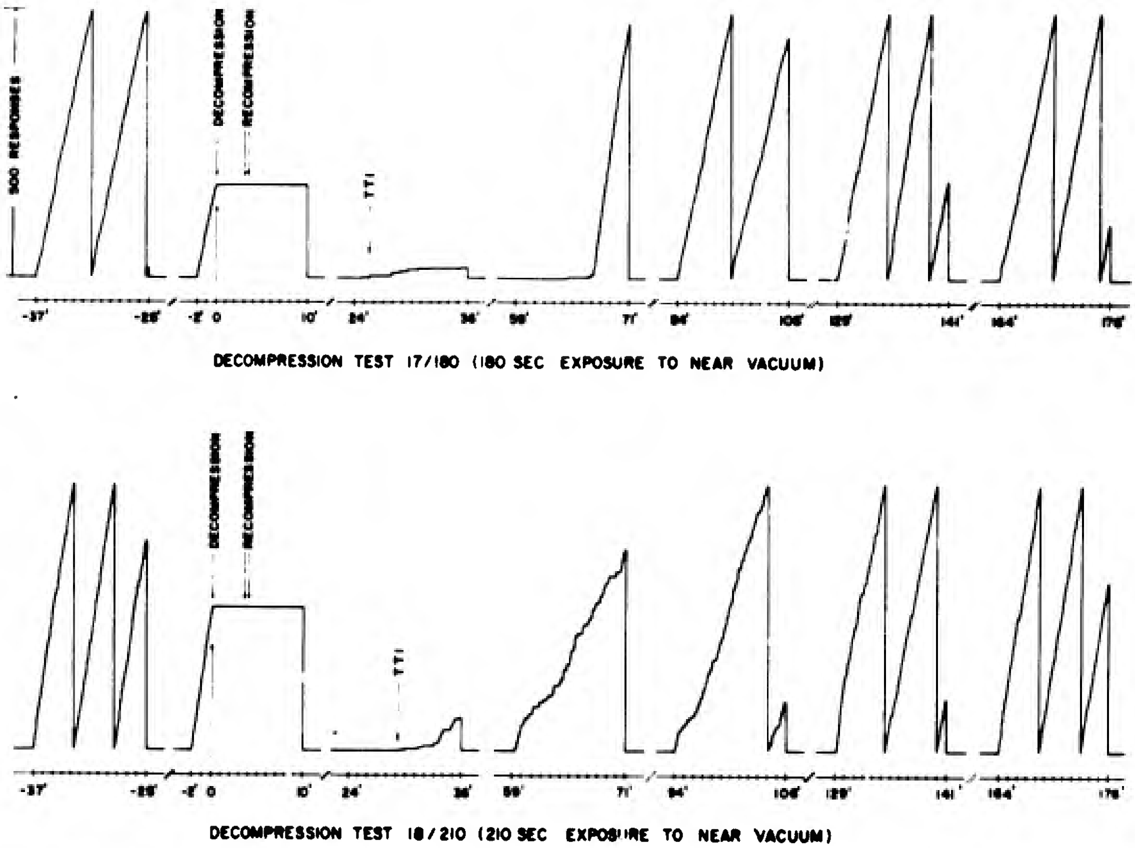

Figure 7a. Effects of Rapid Decompression to Near Vacuum on Continuous Motor Behavior.

DISCUSSION OF BEHAVIORAL RESULTS

After exposure to a near vacuum, experimental subjects showed a statistically significant impairment on 1 to 9 (the range) of 23 behavioral measures. It is important, however, to note that each subject had recovered sufficiently within 4 hours of decompression to respond on all behavioral measures within its respective baseline limits. Responses immediately following decompression were impaired to a point far below the respective baseline average and reduced the experimental performance means, thus bringing about the statistical differences -- but responses towards the end of the 4-hour period were well within the subject's normal pre-exposure limits, demonstrating behavioral recovery.

The performance variables most consistently affected by the exposure to a near vacuum were pushbutton and lever press reaction times to visual cues. Response latencies to auditory cues were least affected by the experimental conditions.

At longer exposure times (150 to 210 seconds) it became evident that a "trade-off" was taking place in almost all subjects. For tasks involving visual cues subjects were successful in attending to and reacting to stimulus presentations at the expense of quick reaction times, while auditory response reaction time was maintained, but fewer successful responses were made. In essence, it may be said that following decompression to a near vacuum, the chimpanzee can respond to most visual signals but does more slowly than before decompression. On the other hand, he fails to respond to as many auditory signals, but when he does respond to a sound stimulus he responds as fast as he did before he was decompressed.

One subject which was exposed to a near vacuum for three minutes showed a general decrement of behavior during a follow-up study which was not evident during follow-up studies performed with subjects exposed to shorter durations at near vacuum. Reaction times to auditory cues and some visual cues as well as all efficiency measures on discrete events showed statistically significant decrements. However, reaction times to the oddity problems were significantly improved with discrimination efficiency unchanged from the pre-exposure value. Even though response rate on the continuous motor task was lowered it did not impair the efficiency on this task which could mean that the subject was able to adjust its behavior and still be successful at a lowered work output. These data may be indicative of some residual behavioral impairment following a 3-minute exposure to a near vacuum.

A product moment correlation between exposure times to a near vacuum and the times of total behavioral impairment produced a Pearson r of .78 (fig. 8). Curvilinear correlation analysis ($\eta = 0.96$) supported a marked and

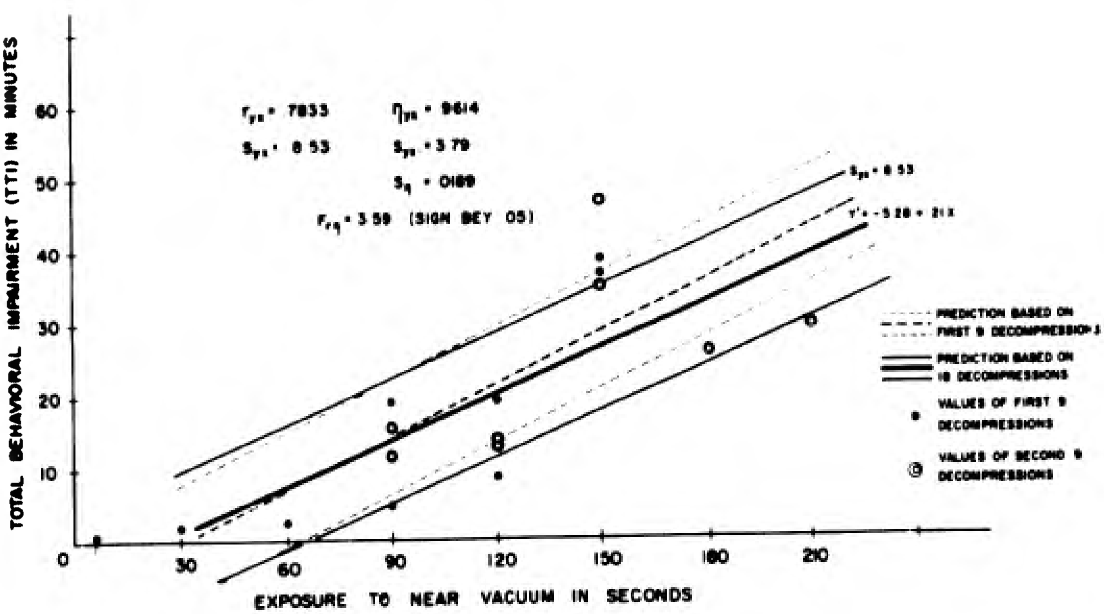

Figure 8. Predictions Based upon Relationship Between Exposure to Near Vacuum and Total Behavioral Impairment.

consistent deviation from linearity at the 150-second exposure time. Product-moment correlation between exposure time and the time of total behavioral recovery produced a Pearson 4 of 0.70. The data from the current series of nine decompressions did not vary markedly from the prediction based on the first series of nine decompressions, suggesting the reliability of the total findings (fig. 8a).

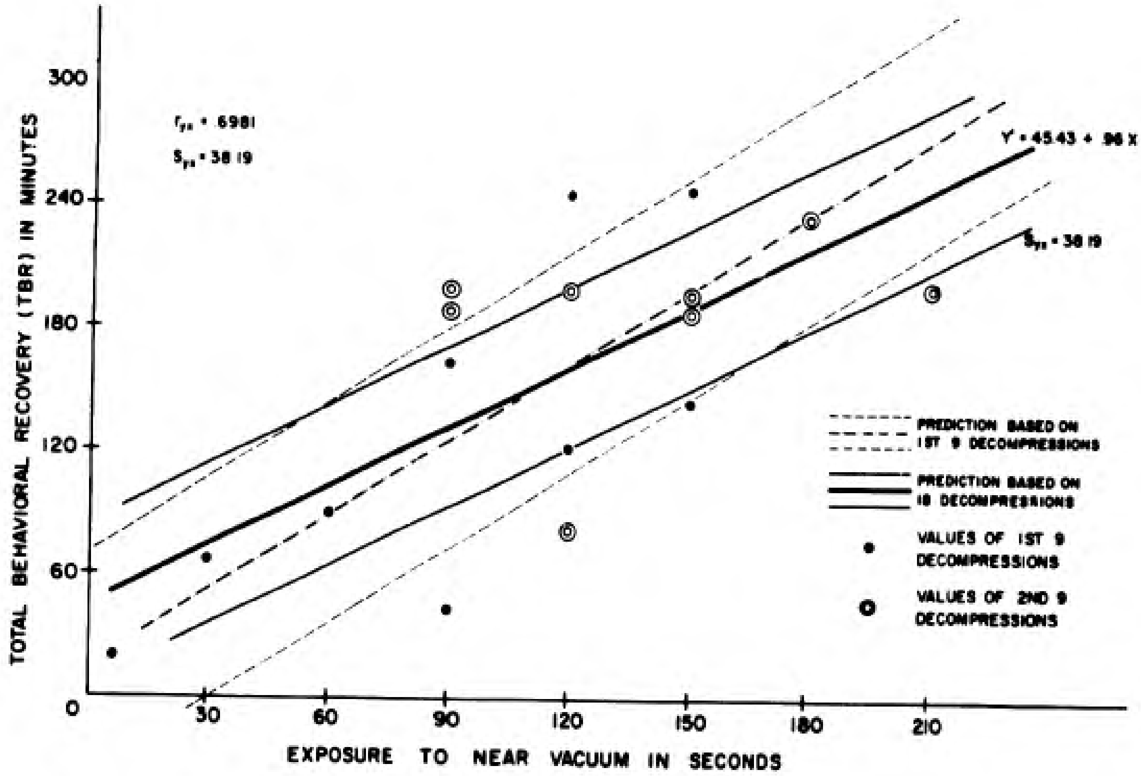

Figure 8a. Predictions Based upon Relationship Between Exposure to Near Vacuum and Total Behavioral Impairment.

PHYSIOLOGICAL AND NEUROPHYSIOLOGICAL RESULTS

All subjects demonstrated a tachycardia immediately following decompression which was regularly followed by a rather sudden bradycardia with a maximum slowing 40 to 60 seconds post decompression (fig. 9). A gradual increase in rate was seen until recompression, and in longer exposures the rate had returned to normal baseline limits by the time of recompression.

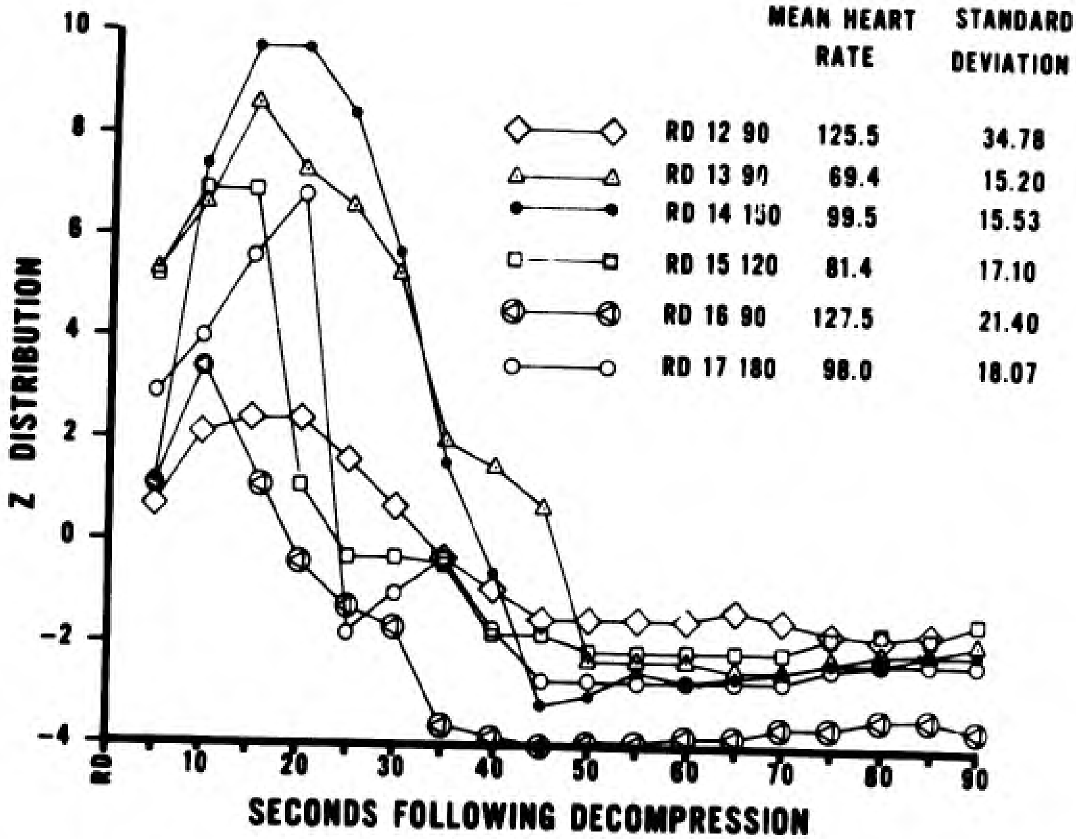

Figure 9. Standardized Heart Rates During and Following Decompression to Near Vacuum.

One subject, exposed for 1-1/2 minutes, had the normal post decompression tachycardia followed by bradycardia until 85 seconds post rapid decompression (RD) at which time irregular ectopic beats were noted which progressed to ventricular tachycardia in 63 seconds and ventricular fibrillation 7 seconds later. Fibrillation persisted and no attempt was made to resuscitate the animal. Another subject also with 90 seconds of exposure to near vacuum developed a bigeminal rhythm which progressed to ventricular tachycardia reaching a rate of 300 before spontaneously converting to a normal sinus rhythm.

After an initial drop in skin temperature the decrease continued at a slower rate for as long as 110 seconds post decompression, resulting in a total average decrease of 1.7 to 2.0° C.

The normal EEG of the alert animal is illustrated in fig. 10. Cortical slowing can be seen at RD plus 12 seconds proceeding to electrical silence within 45 seconds. The TUC (11.1 seconds in this case) corresponds well to the loss of cortical fast activity (fig. 11). The subcortical record continues

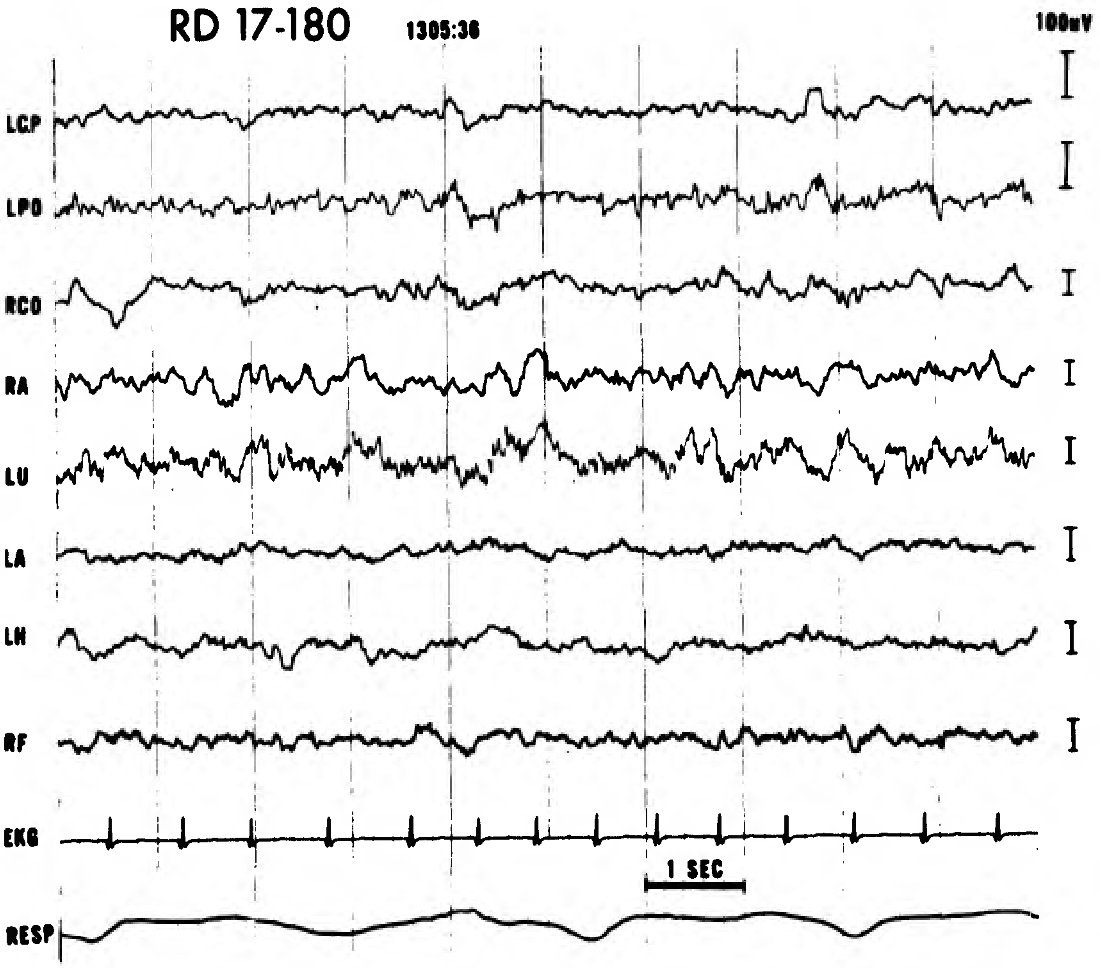

Figure 10. Normal EEG of Alert Chimpanzee.

Abbreviations: LCP = Left Central Pariatal
LPO = Left Parietal Occocipital
RCO = Right Central Occipital
RA = Right Amygdala
LU = Left Uncus
LA = Left Amygdala
LH = Left Hypothalamus
RF = Reticular Formation

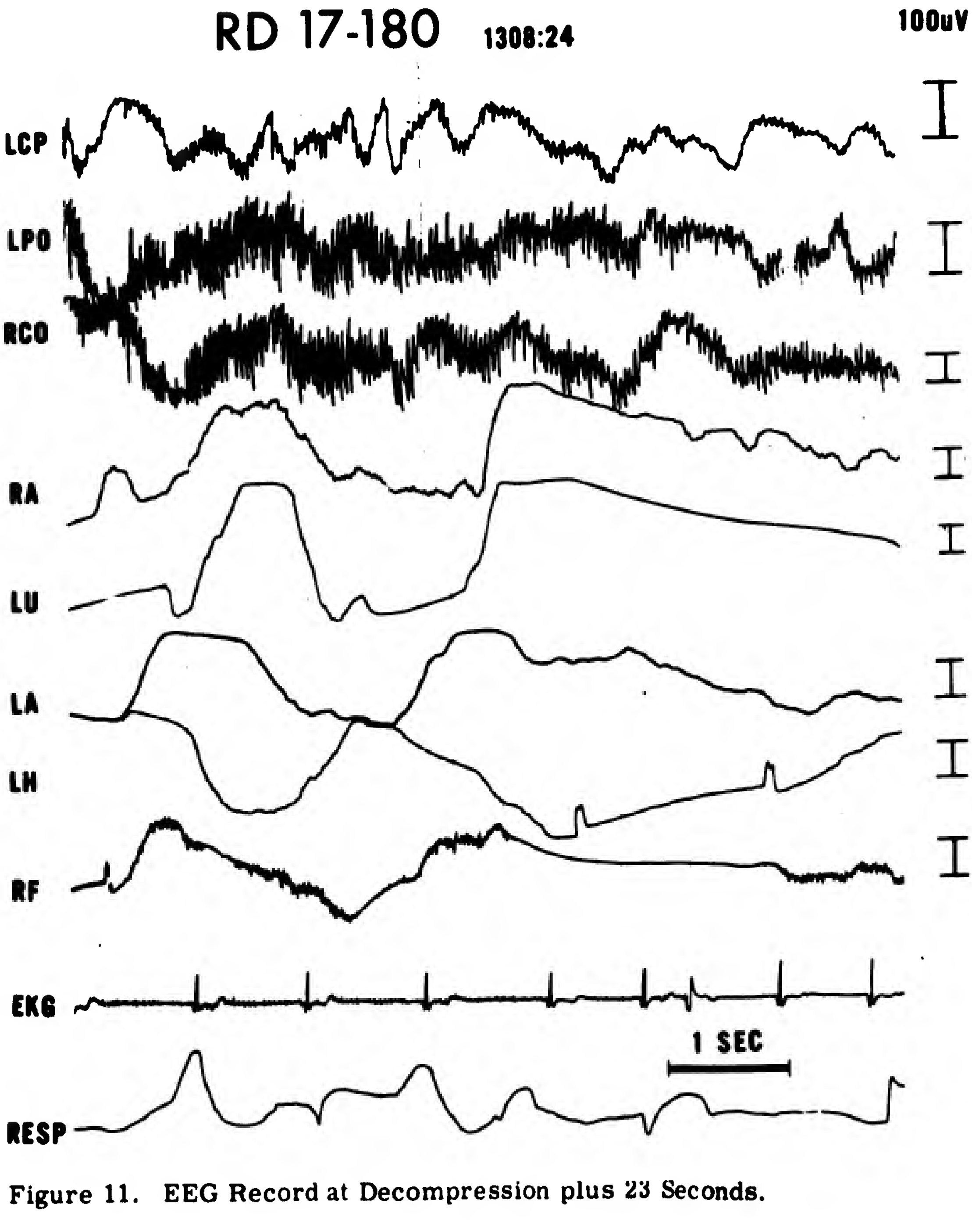

Figure 11. EEG Record at Decompression plus 23 Seconds.

to show very slow and low amplitude activity following cortical electrical silence although it also proceeds to electrical silence within 75 seconds of decompression. The reticular formation continues to display rhythmical slow wave activity throughout the period of decompression that is time locked to the ECG (fig. 12).

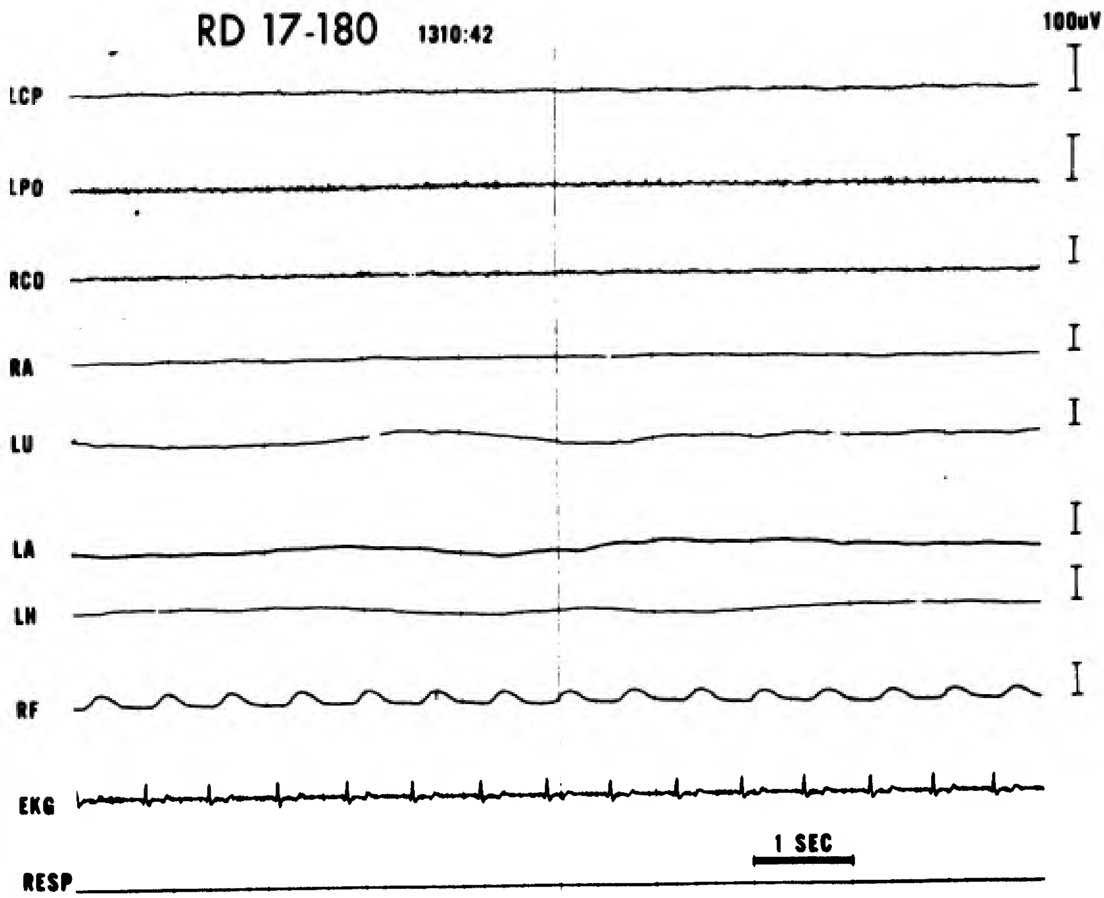

Figure 12. EEG Record at Decompression plus 2 Minutes and 41 Seconds.

The first prominent EEG activity occurs at about 5 minutes post decompression and consists of paroxysmal bursts in the limbic structures (fig. 13). Fast activity returns first to the uncus and hippocampus, then to the amygdala, and considerably later to the reticular formation. The cortex remains essentially silent during the first several minutes of subcortical recovery (fig. 14). Slow cortical activity begins at about decompression plus 7 minutes. At the time when the subject is first able to respond to the behavioral schedule (approximately 27 minutes after decompression) the limbic structures showed nearly normal activity, whereas the cortex and reticular formation still contained more slow activity than normal. The continuous avoidance (CA) response rate returned to normal by 1 hour and 34 minutes after decompression, at which time the EEG was normal to visual inspection. Follow-up EEGs were obtained at 10 days and 6 weeks after the experiment and were found to be normal to visual inspection even though behavior had shown some decrement. The subject at that time was unusually irritable and generally hyperactive when compared to his pre-exposure general behavior. After three months this subsided and was indistinguishable from pre-exposure behavior.

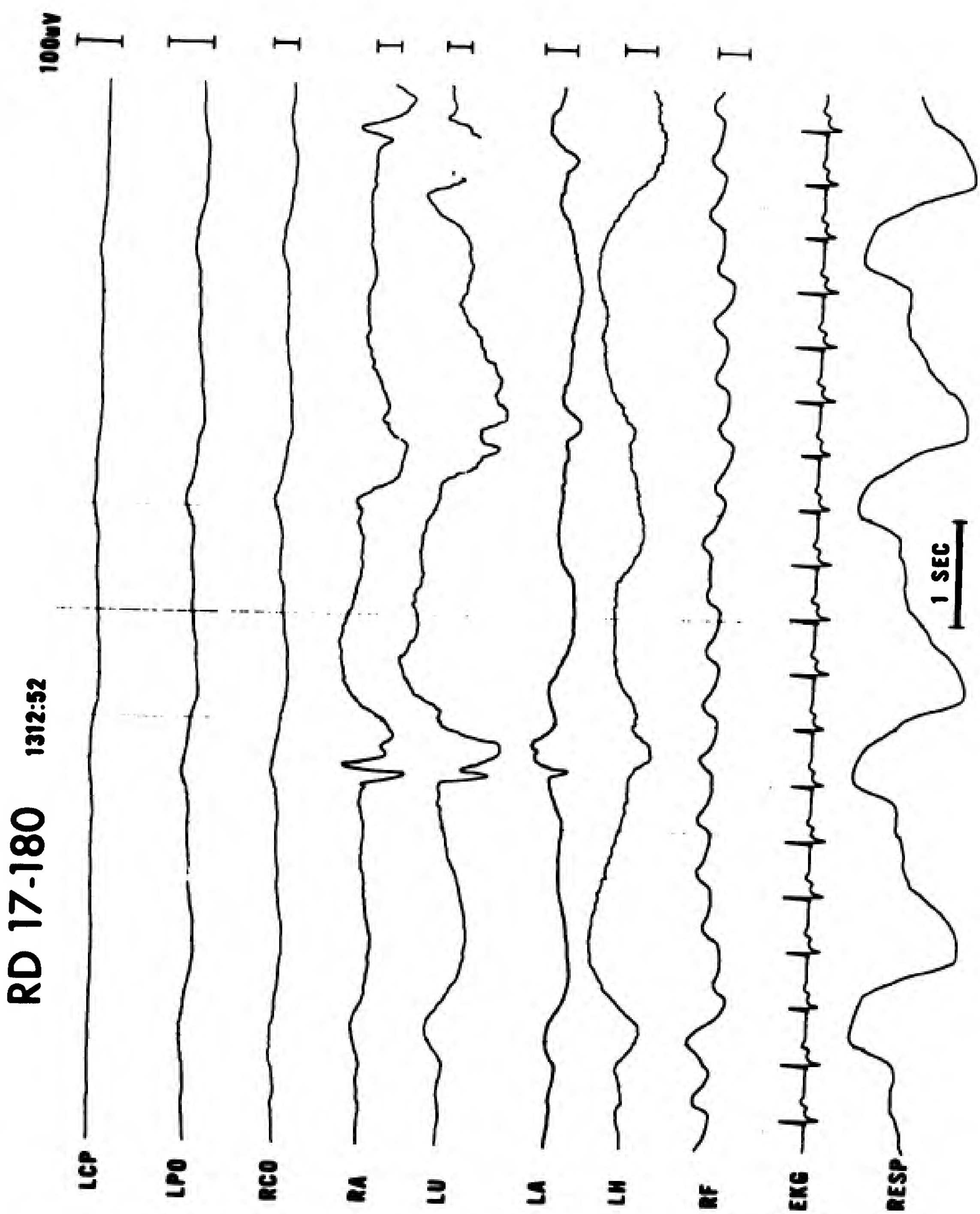

Figure 13. EEG Record at Decompression plus 4 Minutes and 51 Seconds.

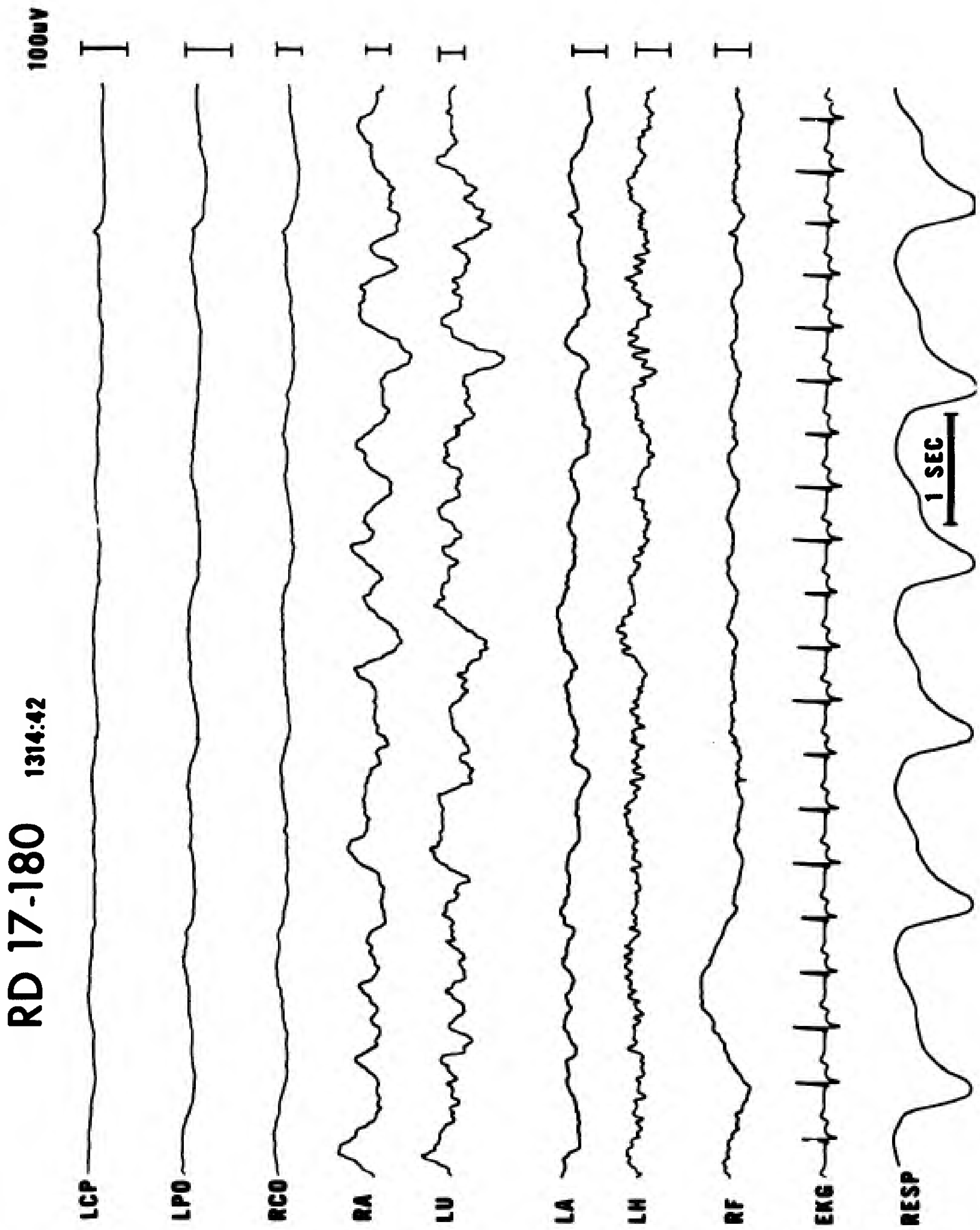

Figure 14. EEG Record at Decompression plus 6 Minutes and 41 Seconds.

DISCUSSION OF PHYSIOLOGICAL AND NEUROPHYSIOLOGICAL RESULTS

Previous work in dogs has indicated that within a few seconds after decompression to environmental pressures below the vapor pressure of water, blood circulation stops, although the ECG complexes continue. If circulation is indeed arrested, then there will be little opportunity for the oxygen remaining in the circulatory system to be lost through the alveoli. What oxygen there is in the exchange vessels of the central nervous system should thus be available for tissue survival. There is no data available as to the fate of the metabolic carbon dioxide transport system under these conditions. There can be no doubt that the brain is anoxic, but the degree of neuronal asphyxia remains to be determined. The skin temperature drop in the chimpanzee is probably paralleled by a drop in core temperature, a fact which has been established in dogs. It is likely that brain temperature also drops at least slightly following decompression to a near vacuum, thus decreasing the metabolic rate and therefore acting as a prophylactic against the effects of anoxia.

The two animals that developed ventricular tachycardia, one of which progressed to ventricular fibrillation and death, had both pre-decompression normal heart rates significantly higher and more variable than the remainder of the animals. This raises the question of whether a higher level of activity in the sympathetic or other regulatory systems might increase cardiac sensitivity to anoxia with resultant arrhythmias. The cardiac sensitizing effects of the catechol amines and resultant arrhythmias are well known.

CONCLUSIONS

The results from 18 decompression experiments have established as well as substantiated the fact that chimpanzees can survive sudden exposures to near vacuum for up to 3-1/2 minutes and recover within 4 hours to once again satisfactorily perform complex behavioral schedules. However, as encouraging as these results may be -- unless the subject is in perfect health -- decompression to a near vacuum, regardless of length of exposure, can pose a major threat to life. In additic 1, a slight performance decrement as well as increased irritability and hyperactivity for weeks after the experiment as exemplified by one chimpanzee which was exposed to 3 minutes of near vacuum, may be important from the standpoint of extrapolation to man, when these small indicators might have significant ramifications particularly in the crowded and stressful social environment of a space vehicle.

ABSTRACT

Seventeen chimpanzees were decompressed in 18 separate tests from 179 mm. Hg (breathing 100 percent oxygen) to less than 2 mm. Hg in 0.8 seconds and remained at this altitude from 5 to 210 seconds. After recom-

pression with 100 percent oxygen to 179 mm. Hg, the subjects were maintained at this pressure environment for 4 to 24 hours post decompression. Results of these tests, some of which were of replicatory nature, have established and substantiated the fact that chimpanzees can survive sudden exposure to a near vacuum and recover within 4 hours to once again satisfactorily perform complex behavioral schedules on which they have had extensive training. One subject of questionable fitness expired following a 90-second exposure to a near vacuum.

EKG, respiration, and skin temperature were recorded as standard procedure from all subjects, some of which were instrumented for EEG. All subjects demonstrated tachycardia immediately following decompression which was regularly followed by a rather sudden bradycardia. There was an initial drop in skin temperature immediately after decompression with an ensuing gradual fall resulting in a total decrease of 1.7 to 2.0°C. Visual inspection of the EEG as well as power spectral density computer analysis indicated the expected greater subcortical resistance to anoxia when compared to cortical responses. Evoked responses to stimulation of subcortical areas were used as indicators of excitability.

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Lex Cosmica

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LEX COSMICA

Lieutenant Colonel William R. Rule, USAF, MSC (Ret)

My remarks do not necessarily represent the views of the Air Force or the University of Missouri where I am presently serving as a member of the faculty, but are, rather, my personal thoughts and ideas. It is, I believe, appropriate that at a symposium on aerospace medicine we examine some views concerning law as it applies to space flight. The space physician will play a most important role in formulating and enforcing space or cosmic law. As only a few examples consider; prevention of contamination of space vehicles prior to take off or return from the earth or other celestial bodies, strict enforcement of quarantine regulations or developing and defining the necessary physical and mental standards for man's eligibility and capability to travel in space. It is striking in reviewing bibliographies of space law to observe how frequently the name of Dr. Hubertus Strughold appears.

It is my feeling that the phrase "space law" does not really describe all of those things which we are going to be concerned with in space flight, exploration and settlement. The late Andrew Haley coined a word, metalaw (1). Haley had a concept that the so-called golden rule of law might not necessarily be the best rule in the event that earth man some day finds intelligent life out in space. Haley suggested that an attempt by the earth man to treat such life as the earth man would desire to be treated might be deleterious to such life. He felt the more appropriate rule was to treat such intelligent life as they desire to be treated. Of course, this concept raises the immediate problem of communication and as Haley himself once said, "How does man talk to an amoeba?" Nevertheless, Haley, to the time of his death, insisted that any other rule by earth man was wrong and immoral.

In any case, the word metalaw does not appear to have gained wide acceptance, and yet, the phrase space law is probably not inclusive enough. When we talk of law and space, we are really thinking in terms of space vehicles, and earth man traveling in them out in the literal emptiness of space. We now are undoubtedly close to placing man on the moon and hopefully not too much later man on Mars. It has been doubted that the possibility of putting man on Venus is very promising with the present state of art (2), but this, too, should not be excluded in our thinking. In any case, man on the moon or man on Mars does not conceive of himself as out in spac but, rather, he is on a land mass of some sort on a moon or on a planet. It would seem that another phrase or series of words could be considered. The Latin word for law, "lex", is known to many nations and the word "cosmos" likewise is widely used internationally. It is suggested that the phrase Lex Cosmica or Cosmic Law would strike a responsive note in the ears of people of many countries. It is seriously doubted if life as we know it will be found on the moon and probably intelligent life as we understand it will not be found on Mars although it is postulated that at least microbial organisms may be found on Mars (3). Therefore, the interrelationships needing control and regulation on the moon and Mars, at least, will be those interrelationships between earth men who find themselves in this milieu. Professor Florioa Pereira, suggested in 1960 that there should be three branches of law identified: (1) space law, (2) metalaw, and (3) cosmic law (4).

Therefore, we might in the most general sense say that space law concerns itself with travel of vehicles in empty space or in earth's air space, use of communication channels, state or individual ownership and control of space vehicles and the crews while in flight, questions of damages or tort law involving space vehicles, collisions in flight or in falling and striking some portion of the earth. In this context, some of the analogies between space law and earth maritime law become more apparent.

Metalaw might be described very briefly as earth man's legal, social and moral relationships with other forms of intelligent life in space. Cosmic law should concern itself with the interrelationships of earth man, both civil and criminal, on celestial bodies in space.

Late last year in the United Nations it was finally and formerly agreed between all members, including the United States and Russia that the declaration of legal principles of the report of the United Nations Committee on the peaceful uses of outer space should be the basis for future space activities. This was a most hopeful step forward and these declarations now constitute international law to which all U.N. members have solemnly bound themselves to follow and obey. Some of these principles stated (a) the exploration and use of outer space shall be carried on for the benefit and interest of mankind, (b) that outer space and celestial bodies are free for exploration and use by all states on a basis of equality and in accordance with international law, and (c) that outer space and celestial bodies are not subject to national appropriation, by claim of sovereignty, by means or use of occupation or by any other means. In prior years the Soviet government had voiced strong objections to activities in space carried on by private agencies or non-governmental entities, rather than by governmental agencies; however in late 1963 the Soviet government did accept a new principle which states in part that the activities of non-governmental entities in outer space shall require authorization and continuing supervision by the state concerned. The American government accepted willingness to reaffirm that space operations carried out by private parties require government authorization and continuing supervision. There should be no question today but what all nation members of the U.N. are in complete agreement that no nation or state of the earth may exercise sovereignty over any area of space or celestial bodies. However, we should, I believe, examine this concept of sovereignty and attempt to see really what it means. The principle of terra nullius or "land the property of no one" is probably excluded and rather the international legal principle of terra communis or "property of all" is probably the proper view. The concept of occupancy of a celestial body confirming rights in that occupying nation to the extent of excluding all other nations is completely incompatable with the U.N. members solemnly engaging that they individually will not claim or attempt to exert sovereignty over any of the celestial bodies to the exclusion of all or any other member nation.

While there is no attempt to quarrel with the use of the word sovereignty yet, it is suggested that the phrase national appropriation might be more descriptive of the intent of the members of the U.N. General Menter on commenting on the earlier resolutions and positions in the U. N. stated,

> "The U. N. General Assembly resolutions which provide that celestial land masses are not subject to national appropriation, are not intended to preclude establishment by exploring States of settlements upon such land masses but rather to deny the right of any State to the claim of sovereignty. Such exploration and settlement will present many legal questions for resolution... Possible accords on utilization of land masses in space, including defining rights to accession of mineral or other resources therein, benefits and obligations of settlements, resolution of disputes, the governing civil and criminal laws and the governing administration"(5).

In 1961, the late Ambassador, Stevenson, stated,

> "Man should be free to venture into space on the same basis that he has ventured on the high seas - free from any restraints save those imposed by the laws of his own nation and by the rules of international law..."(6)

By now it is obvious that the United States at least will undoubtedly under its rules, regulations and laws permit private enterprise to explore celestial bodies and where resources valuable to the people of the earth are found, exploit the same. I am, of course, not saying that such exploitation when permitted would be to the exclusion of other people of the earth, but Telestar and the creation of the Communications Satellite Corporation (COMSAT) which launched the satellite would indicate the future intention of the American government to permit space activity by private American capital. If and when such exploration and exploitation of space resources by private industry of this country would be organized under U.S. law, of course, such laws and regulations would not be framed in contravention of international law in or out of the U.N. Our country recognized this when the Telestar satellite was launched and the communication channels used by Telestar were based upon the international agreements as to the use of radio beams and television channels.

Accepting the basic concept of no national appropriation of land masses on celestial bodies, areas of interest which should be jurisdictional in nature for purposes of exploitation of resources will probably have to be accepted (7). These jurisdictional areas should come through international agreements and undoubtedly regulatory bodies at the U.N. would be appropriate to assign such jurisdictional areas. Again, it is not suggested that a creation of such jurisdictional areas would be to the exclusion of all other nations thus exploring, but, they must undoubtedly be created. With possibility of colonization of the Moon and Mars or even other celestial bodies, consideration must be given to the preservation of law and order and mankind has not changed enough in the last five hundred years to hope that there will be no requirement for police, courts and probably prisons or jails. This maintenance of such units controlled by the individual states within its jurisdictional enclave is not without precedence on the earth and we saw, for example, in international law, the creation of extraterritorial courts both in China and Turkey in the earlier days in history. Of course, the analogy is historically unfortunate due to the fact that these extraterritorial courts were imposed by strong powers on weaker and then more backward states, but nevertheless the courts did function and in the case of American extraterritorial courts had jurisdiction to try Americans for offenses committed beyond the sovereignty of the United States.

The entire legal concept of man's activity on celestial bodies other than the earth have indeed presented serious legal problems. Many ideas of earth international law simply will not apply. The theories of the sovereignty of the state over its territory, international law concerning exploration, colonization and incorporations of new and unknown areas of land on the earth by the exploring and occupying state are both illogical and undoubtedly wrong in concepts of exploration of the moon and of planets.

It is a happy development in the interrelationships of the earth states to see that the two nations, Russia and the United States, who have the most imminent possibility of moon exploration, have expressed a unanimity of opinion through the solemn engagement entered into at the United Nations with all other members that the moon and the planets shall not fall within the sovereignty of any one nation and shall be used for the benefit of all earth nations.

The concepts of sovereignty in connection with both air and space law are indeed varied and changing. The old view in Roman Law, English Common Law, and in Russian Law was that the state exercises sovereignty over its land and the area above its land. However, this concept with the advent of manned balloon flights and later flights of manned airplanes was changed and various limitations of a nation's sovereignty arose. The scientist and the jurist are still not in complete agreement as to what these limitations are but such things as the Karmen line (8) has been suggested, a distance above the earth of 186 miles (9), or as some thinkers believe that the limitation should not be in actual measurement but a limitation based on the ability of that state to control the air space above it (10). The various concepts all have merit but I think most jurists would agree that whatever the limitation of sovereignty is, that under no conditions would it extend as far as the moon or, for that matter, within the gravitational ambit of the moon. Accepting this to be good law both from the standpoint of international law and state law then, for us at least under American law, it must also be accepted that at present an American committing a crime on the moon could not be tried for that crime upon his return to the United States. The well-known Russian jurist, Korovan, in accepting that no sovereignty would exist in celestial bodies pointed out that this indeed created a great legal vacuum (11).

Criminal codes are based upon the morals, ethics, political structure and religion of each individual state. The law of crime and the sanctions imposed upon violators of such criminal codes arise from the wishes of the citizens of that state and their cultural backgrounds. Few nations exist without police, prisons, prosecutors, judges and sometimes executioners, however, it would be difficult to find two criminal codes of separate nations which are exactly alike. Of course, there are general acceptances of certain events which constitute a crime nearly everywhere such as murder, but again the sanctions applied vary tremendously. It is not to be assumed that the citizens of any one state would be prepared to undergo trial and possible sanctions under the laws of a state other than their own unless such crime were committed within the sovereignty of this foreign and trying state (12). It has been observed that agreements have not always been obtained in the U.N. on desired objectives and it is suggested that this might be true in an effort to reach agreements on criminal laws, tribunals, and sanctions. John A. Johnson, General Counsel for NASA, said,

> "While international regulation and control of many space activities is possible, and in some instances is highly desirable, I believe the adoption of any international standard of criminal responsibility in outer space will be remote"(13).

What then, are our solutions, a legal vacuum and legal chaos in outer space, an attempt to create some sort of international tribunal applying codes which may be impossible of adoption because of failure of agreement between nations - or an extension, not of sovereignty but jurisdiction over the citizens of the state by that state for offenses committed on celestial bodies. It is suggested that the third solution should be looked at. Admittedly it is quite foreign to our normal concepts of criminal law to assess responsibility where sovereignty over the area in which the act was committed does not exist, but, reassessments are undoubtedly necessary here and it is suggested that legislation could make this possible, at least as far as American citizens are concerned.

From the standpoint of civil law equally severe problems present themselves. General Menter was undoubtedly correct in stating that there must be law and order, concerning utilization of land masses, right for prospecting and utilization of resources found, some basis of arbitration for disputes concerning such resources and administration and courts which have authority and the power to regulate and determine such disputes. Note that the Communication Satellite Corporation was organized not under rules or resolutions within the framework of the U.N. but rather it was incorporated under the laws of District of Columbia in the United States. It would appear that such individuals who engage in discovery and exploitation of space resources and are organized under the laws of the United States as enterprises, partnerships or corporations can only look to the laws of the place in which they were chartered as a guide for their operations and functioning in such exploration and exploitation of resources discovered.

Again it is to be hoped that the tribunals for guiding, advising and when necessary enforcing rules of law and order in the exploitation of space resources can be established at an international level, but to this point of time, we have not seen in or out of the U.N. serious effort in this direction. While our obvious first choice, and more proper one, are enclaves or extraterritorial courts on celestial bodies operating under the flag of the U.N. or other international organizations, alternates should be considered. It is submitted that consideration of such alternatives is in no way evidence of bad faith in the part of the American government in entering into agreements at the U.N. that no nation shall exercise sovereignty over space or celestial bodies. Beyond any question of a doubt the words of President Johnson uttered in 1958 when he was a United States Senator represent today the honest and sincere view of the American Government. The President then Senator, said,

> "We of the United States do not acknowledge that there are land-lords of outer space who can presume to bargain with the nations of the earth on the price of an access to this new domain"(14).

We are politically a divided world today and the United States and the people of western Europe are committed to systems of private enterprise and the recognition of the existence of capital and labor working together for the production of profit to those who invest their efforts, time and money. On the other hand a very large block of people in the world are presently committed to a system known generally as communism and in which private capital and private enterprise are quite generally unrecognized and profit, if any, accures to the state and not the individual. While exploitation of space resources should be for the benefit of the entire people of the world, yet such exploitation will require considerable expenditure of funds and effort by all states or individuals desiring or having the capability of engaging in space travel and exploration and even settlement on celestial bodies. It is only fair to ask the question with this world wide divergence as to profit motives, how can we reasonably hope for total agreements on joint exploitations of a resource from a celestial body by a communist and democratic state. Obviously we would have legal chaos, a complete disagreement or thirdly and the least desirable, imposition of one state system upon the system of another state. It would appear that enclaves set up separately under the conflicting systems should be considered. Such enclaves should not have the right to exclude citizens of other earth nations, but where such an enclave is recognized it is suggested that within such geographic limits the judicial jurisdiction and the laws of the state operating the enclave should be paramount.

I believe a desired goal would be for the creation of codes of law both Civil and Criminal concerning the conduct of man and his interrelationships on the celestial bodies and further that such codes should be enforced by international police forces and international courts. However, in the past the operation of police forces or military forces to enforce peace or law and order under the flag of the United Nations has not always been successful. The history of the U.N. sponsored forces in Crete and along the Israel-Arab frontiers has been reasonably good. On the other hand the U.N. efforts in the Congo did not appear to have been too successful. In fairness to the U.N. it must be recognized that national aims of some member states or nations has seriously hampered the activities of the U.N. both as to providing adequate forces, and from the viewpoint of budgetary considerations. The history of international tribunals such as the International Court has been somewhat equivocal. The International Court in many instances has functioned well as a tribunal of arbitration between sovereign states or nations who have come into conflict on points of interest. However, the flaws in the International Court or so-called World Court have been apparent, first this tribunal has rarely adjudicated differences between individual citizens of separate states and secondly, the court has no power to impose its judgment upon the nations who are parties to suits before the tribunals. Because of the last it has been observed that plaintiff or defendent nations before the tribunal have not always followed the judgment of the tribunal where the judgment appeared to be against the national interest of the nation involved. Further, international law with the notable exception of piracy and war crimes has rarely concerned itself with criminal acts of individuals.

At this time it would appear that lex cosmica or cosmic law as differentiated from space law might well come into force. We accept as a principle of both national and international law that no one nation will exercise sovereignty over the celestial bodies which hopefully will soon be explored. On the other hand it should be noted in the resolutions in the U.N. concerning the use of outer space while sovereignty was denied to all, in no resolution has it appeared either in word or by implication that sovereignty should rest with the United Nations or any other international body of the earth.

This, of course, brings us back to the legal vacuum which is seriously concerning the jurists of many countries in the world today. By way of repetition, while admitting the best solution would be codes of law, both criminal and civil, based upon international agreements a review of past history indicated that this may not be possible. It should not be overlooked that agreements have not always been arrived at in the United Nations or prior to that in the old League of Nations. Therefore, consideration must be given to the application of national cosmic law to some interrelationships of man in his exploration and occupancy of celestial bodies. It is suggested that we may desire to create extraterritorial courts on the celestial bodies being explored and possibly settled upon by earth men and this would not require a grant of sovereignty to any nation but at a maximum judicial jurisdiction. This should be considered at least for the citizens of the state exercising judicial jurisdiction. The Universe is so vast and the possibilities for space travel exploration and settlement are so large that it can only be assumed that there is more than enough room for any nation of the earth wishing to travel in space, explore and possibly settle their citizens upon a celestial body. While there have been people and nations grouping for international cooperation in space travel the much greater tendency has been for unilateral action by separate states (15).

In a look at the future there exists the possibility of Space Commonwealths. These could be communities or even governments of free people commonly associated together and self-sustaining, making the untapped resources of the celestial body they occupy available for the benefit of all mankind.

The utopian idea could come about when man rises above the present evils of the earth but such a dream, and dream it is, for the foreseeable future must first be preceded by Law and Order through Lex Cosmica. The nations of the earth must somehow agree on formulations of Cosmic Law or utter chaos and conflict could destroy all our plans, hopes and aspirations.

It is, I think, fitting to close this paper with the words of Andrew Haley.

> "We believe space exploration and settlement will dignify and enrich mankind, erasing forever devastating economic problems and affording vistas of the mysteries of creation immeasurably more challenging and interesting than we now conceive of, and so engender a measure of tolerance and compassion that man will rise above his past"(16).

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Nonpathologic Hypercapnia in Man

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NONPATHOLOGIC HYPERCAPNIA IN MAN

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In recent years it has become increasingly important to gain knowledge concerning man's ability to perform adequately when exposed to different levels of carbon dioxide, particularly on a chronic basis. The requirement for this knowledge was generated first by the nuclear submarine, followed closely by the development of vehicles for prolonged space flight. Due to the relatively small free air volume in the latter, the possibility of carbon dioxide buildup, for various reasons, is a real one. While one might assume that the study of man's response to hypercapneic environments has been exhausted by numerous investigators, a detailed review of the literature reveals very few chronic experiments. In many of the chronic studies that have been done, complicating factors of abnormally low or high oxygen tensions, high temperature and high relative humidity contribute to a lack of clear delineation of carbon dioxide effects per se. With these thoughts in mind, we will briefly review the expected physiologic changes in high ambient carbon dioxide levels, including those pertinent manned experiments in order to give a background of the overall knowledge pertaining to normal man and carbon dioxide tolerance. Finally, we will present data obtained on this question at the USAF School of Aerospace Medicine in the past two years.

Figure 1 reviews some of the more basic aspects of carbon dioxide metabolism. Carbon dioxide is continuously formed in cells where it follows diffusion gradients into the blood stream and is carried to the lungs where it diffuses into the alveoli of the lung and is removed. In the steady state, it becomes apparent that the CO_2 eliminated by alveolar ventilation must equal the CO_2 produced by metabolism.

1. Carbon Dioxide (CO_2) Formed in Cells Continuously From Carbon Containing Foods.

2. CO_2 in Cells $\xrightarrow{\text{Diffusion}}$ Blood $\xrightarrow{\text{Diffusion}}$ Lungs $\nearrow$

3. Normal CO_2 Tension Maintained if:

   Production of CO_2 = Removal of CO_2

Figure 1. Carbon Dioxide Formation and Removal.

The basic carbon dioxide, carbonic acid relationships are illustrated in figure 2. As depicted, carbon dioxide and water are removed from the lung--the dissociation of carbonic acid to hydrogen ion and bicarbonate also occurs and is balanced by renal mechanisms affecting H^+ excretion and/or bicarbonate reabsorption. Utilizing the laws of mass action, it becomes apparent that when man is subjected to higher ambient carbon dioxide levels, the carbon dioxide concentration on the left side of the equation is increased and the reaction is forced to the right with resultant increases in H^+ concentration and bicarbonate. Therefore, one would expect to see an increase in the hydrogen ion concentration (decrease in arterial pH) and some elevation of the serum bicarbonate. After several days, renal mechanisms build up the serum bicarbonate to buffer more adequately near the increased acidity of the blood, resulting in the pH being returned to normal.

LUNG: RESPIRATORY

$$\begin{array}{c}\downarrow\uparrow\\ CO_2\end{array} + H_2O \rightleftharpoons H_2CO_3 \leftrightharpoons H^+ + HCO_3$$

Kidneys
GI Tract
Cell Metabolism, etc.

Figure 2. Carbon Dioxide-Carbonic Acid Relationships.

Figure 3 portrays the ways in which an excessive acid load, such as that produced by high CO_2, can be partially neutralized or buffered by the four available body mechanisms. Approximately half of the acid load is buffered by the extracellular serum bicarbonate stores which are effective instantaneously. The increased ventilation brought about by the change in either the PCO_2 or the pH helps guard against excessive elevation of alveolar carbon dioxide tensions. Intracellular buffering takes several hours to occur and is brought about as many of the excess hydrogen ions diffuse into cells to be bound chemically with proteins and other moieties. It is apparent then, that the extracellular pH has been defended both by extracellular and intracellular means and respiratory adaptation.

BUFFERING OF EXCESS ACID LOAD

Instantaneous - Extracellular Buffering

10-30 Minutes - Respiratory Buffering

2-4 Hours - Intracellular Buffering

Hours to Days - Renal Buffering

Figure 3.

The kidney, however, is the only means by which the excess acid load may be eliminated from the body permanently. A small amount of acid is eliminated daily as a free hydrogen ion though this is quantitatively minute. The two forms in which most of the hydrogen ion excretion is brought about is in the form of ammonium (NH_4^+) and titratable acidity (T. A.).

In studies involving excessive acid loads such as acid infusions, the net hydrogen ion excretion will increase, usually in the form of increased excretion of urinary ammonium (10). In dog studies carried out at 7% and 10% carbon dioxide for long periods of time (14), there is an increase in net 24-hour hydrogen ion excretion as renal adaptation takes place. Adaptation is also greatly helped by the renal absorption and "saving" of urinary bicarbonate to increase the available body buffers. This increase in bicarbonate reabsorption by the kidney is directly related to elevations in arterial P_{CO_2} (7).

A simplified schematic of the ammonium and titratable acid excretion by the kidney is shown in figure 4. The ammonia in the kidney tubule cell diffuses into the tubule containing urine with the free hydrogen ion and combines to form the ammonium ion in which form it is excreted. In a similar fashion excessive H^+ ion in the renal cell diffuses into the urine and combines with available phosphate buffers to be excreted. In this manner, the kidney normally gets rid of 50-100 MEq. of H^+ ion daily. Utilizing the formula $NH_4^+ + T.A. - HCO_3^-$, one can calculate the net H^+ ion excretion for 24-hour periods.

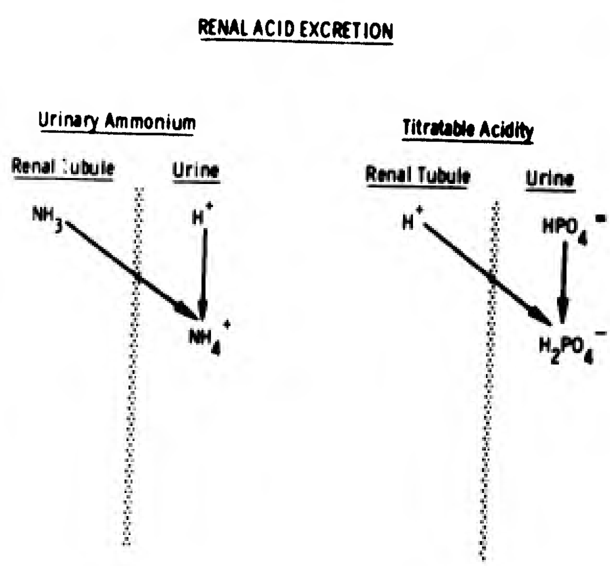

Figure 4. Schematic of the Two Important Means of Hydrogen Ion Excretion by the Kidney.

In reviewing what has been learned in acute hypercapnia studies, a host of experiments are available and encompass work from 1911 to the present time. Most studies have followed acid-base parameters and respiratory measurements. Because of our interest in man's performance in various CO_2 environments, psychomotor studies are of importance in determining operational capabilities. Fortunately, some of the studies (2, 3, 16) have included tasks such as measurements of letter cancelling ability, hand steadiness, strength, reaction times and card sorting to name but a few.

Overall physiologic changes as seen in the acute studies are illustrated (fig. 5) and generally reflect the information gained in most experiments. Immediately after exposure to the hypercapneic environment, the minute ventilation, tidal volume and alveolar carbon dioxide are elevated commensurate with the concentration of CO_2 in the atmosphere. With the elevated carbon dioxide tension, there is an immediate increased acidity of the blood as measured by a reduction in the arterial pH.

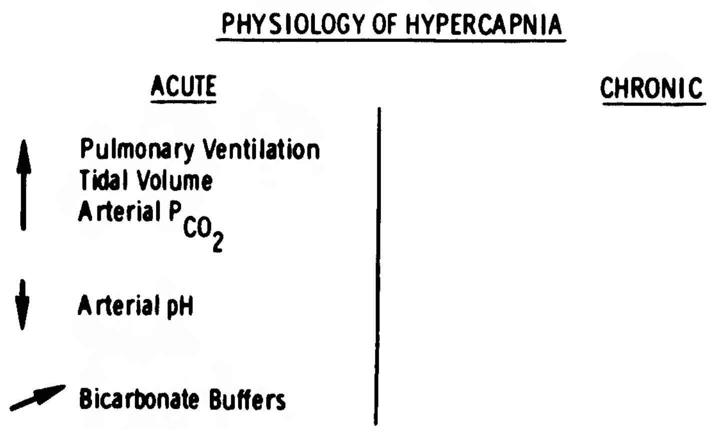

Figure 5. Respiratory and Extracellular Acid-Base Changes with Acute Hypercapnia.

Acute studies have shown that 1% (13) and 1.5% CO_2 (5, 6) are tolerated quite comfortably with very little change in pulmonary ventilation. Minor increases are seen in alveolar carbon dioxide tension and minute ventilation at 2% CO_2 (8). At these relatively low carbon dioxide levels, however, most experimental subjects are not aware of breathing an abnormal gas mixture. Experience in 3% carbon dioxide shows readily measurable increases in pulmonary ventilation, tidal volume and arterial P_{CO_2} (3). Although methodology is questionable in several of these studies, acid-base measurements have shown only small changes.

No discussion of acute hypercapnia physiology would be complete without briefly reviewing the work reported by Brackett, Cohen and Schwartz (1). In this study, seven volunteers tolerated levels of 7% CO_2 for ninety minutes and 10% CO_2 for -5125 minutes. As one might predict, these high levels produced large elevations of arterial P_{CO_2} and a marked respiratory acidosis.

In conjunction with some of the foregoing studies, a number of detailed psychomotor and performance tasks have been carried out. From the available data in different experiments done by Consolazio (2), Cutler (3) and White (16), it would appear that there is little performance and psychomotor decrement before reaching levels of 5% carbon dioxide.

Though these acute studies are important and of major physiologic interest, chronic exposures to carbon dioxide are more pertinent to a discussion of tolerable atmospheres for prolonged space flight.

The available literature concerning normal man's adaptation to chronically elevated carbon dioxide tensions is quite limited. This is most likely secondary to the obvious problems confronting the investigator including logistics, availability of human volunteers and proper environmental facilities.

Table I lists most of the long-term carbon dioxide studies that have been carried out using normal man. Note that at higher levels of carbon

CHRONIC HYPERCAPNIA STUDIES

% CO_2	P_{CO_2}	Duration	Investigator
1.0	7-8	30 Days	Russia
1.5	11-12	42 Days	USN
2.0	15	30 Days	Russia
3.0	21	5 Days	USAF
4.0	31	5 Days	USAF
5.3	38	3-4 Days	USN

Table I. Chronic Hypercapnia Studies in Normal Man.

dioxide, the duration of the studies become shorter indicating the increased difficulty for both subject and investigator.

Before discussing what has been learned from the few available chronic studies, we will reiterate expected physiologic changes (fig. 6). Note that in the chronic exposure, the minute ventilation, tidal volume and arterial P_{CO_2} remain elevated as in the acute situation. The arterial pH, however, can be expected to return to near normal levels by the fourth to fifth day as buffers build up.

PHYSIOLOGY OF HYPERCAPNIA

ACUTE		CHRONIC	
↑	Pulmonary Ventilation Tidal Volume Arterial P_{CO_2}	↑	Pulmonary Ventilation Tidal Volume Arterial P_{CO_2}
↓	Arterial pH	→	Arterial pH
↗	Bicarbonate Buffers	↑	Bicarbonate Buffers

Figure 6. Physiology of Acute and Chronic Hypercapnia in Normal Man.

Though six chronic studies have been carried out, only a few are worthy of comment. Due to reporting techniques and lack of detailed description regarding methodology, the only benefit derived from the Soviet studies relate to reported psychomotor performance. Evidently, no changes were recorded (17).

"Operation Hideout" was a prolonged 42-day experiment carried out by the Navy at 1.5% carbon dioxide. Excellent respiratory data is available for review and showed only mild but persistent elevations in alveolar P_{CO_2} and minute ventilation. The authors reported a state of prolonged, uncompensated acidosis which is not similar to the experience of other investigators. Psychiatric and psychomotor measurements carried out during this experiment were multiple and detailed. They were interpreted as showing no performance decrement during the time of carbon dioxide exposure (12).

Marked respiratory changes were seen in an interesting series of studies carried out by Consolazio and co-workers in atmospheres ranging from 4% to 5% carbon dioxide (2). No detailed acid-base studies were done, but the experiment was quite significant in that a large number of psychomotor and performance studies were carried out. At these levels no significant psychomotor or performance changes were recorded. In addition, the Navy investigators involved felt that all subjects were quite able to carry out any assigned naval tasks.

These studies are in direct conflict with the observations recorded by Schaefer and co-workers during World War II (12). As allied anti-submarine patrols became more efficient, German submarines had to remain submerged for longer periods of time, thereby, sustaining carbon dioxide levels from 3 to 3.5%. Though these submarine studies were conducted under operational conditions and thus poorly controlled, definite decrements were reported in letter cancelling studies and geometric tracing. Mention was also made of swings of euphoria and depression, the latter usually occurring after approximately 72 hours in CO_2. Later laboratory studies (12) were also reported to show biphasic responses over 4-6 days in 3% CO_2. Again, impaired attentiveness, decrements in hand steadiness and letter cancelling tests were reported.

Unfortunately, in most of these earlier studies, difficulty with environmental conditions and the possible buildup of contaminants such as carbon monoxide and methane make a critical analysis more difficult. In addition, the problems surrounding acid-base methodology have left many questions concerning the investigation only partially answered.

From the foregoing limited information, it is obvious that more data is needed to determine man's physiologic and performance adaptation to induced chronic hypercapnia. In order to better understand this problem peculiar to sealed environments, we have made some detailed investigations in 3% and 4% carbon dioxide. As these experiments were comprehensive in nature, all possible variables were monitored. Important acid-base, electrolyte and mineral metabolism parameters were studied, along with psychomotor testing, respiratory measurements and exercise programs. Additional studies included electroencephalograms, hematology and liver function studies to insure test subject safety.

The subjects were volunteers from the Lackland Air Force Base facility, having completed a six-week basic training course. After an initial physical examination and blood chemistry evaluation, the subjects were placed on a specially prepared liquid diet (4) containing constant and adequate amounts of electrolytes. A fixed diet was necessary as daily 24-hour urines were collected for chemical analysis. By starting the diet four days prior to the control period, the subjects had achieved a steady state as far as electrolyte and H^+ excretion was concerned by the start of the control period. The study was then carried out with a five-day control period in normal air, five days in the experimental atmosphere and a five-day recovery period (fig. 7). In this way, we not only studied changes occurring during the exposure to carbon dioxide but also physiologic events occurring after carbon dioxide removal.

STUDY FORMAT

1. Subjects -- male volunteers -- ages 18-25.
2. Diet
   --2600 calories/4 feedings
   --100 mEq NaCl
   --30 mEq K^+
3.

	Control	Experimental	Recovery
Pre-Diet 4 Days	5 Days	5 Days	5 Days

Figure 7. Format for 3% and 4% Carbon Dioxide Experiments.

The space simulator that was utilized in the carbon dioxide study is pictured in figure 8. Its double-walled configuration assures any leaks to be outward so that a stable atmosphere can be maintained. Complete testing and exercise facilities including the psychomotor apparatus were inside the chamber.

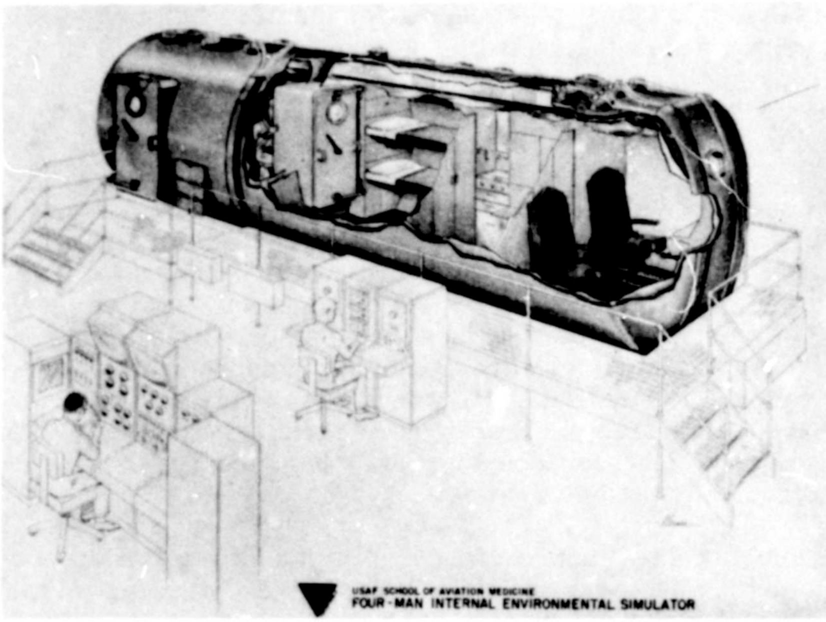

Figure 8. Four-Man Space Simulator.

The atmospheric conditions for both studies were as shown in Table II with a total pressure of 700 mm. Hg in the 3% CO_2 and 748 mm. Hg in the 4% CO_2 study. Temperature and relative humidity remained constant and normal. CO_2 in the control and recovery phases of the study was held at less than 0. 5%.

SUMMARY OF ENVIRONMENTAL CONDITIONS

	3% CO_2	4% CO_2
Total Pressure mm Hg	700 ± 1	748 ± 2
Alveolar P_{O_2} mm Hg	103 ± 5	105 ± 5

Table II. Total Pressure and Alveolar Oxygen Tension During Chronic Hypercapnia Studies.

Because of the increased respiratory minute volume known to occur with elevated levels of carbon dioxide, the Otis-Rahn alveolar formula was used to adjust inspired oxygen tension to approximate normal alveolar pressures. Note that the measured alveolar P_{AO_2}'s during the studies ranged from 100 to 110 mm. Hg--well within normal limits.

Table III lists the metabolic studies which were carried out. Venous bloods were drawn fasting and analyzed for the variables outlined here. Creatinine clearances were calculated daily.

METABOLIC STUDIES

Blood

a. Venous — Na, K, Cl, CO_2, Ca, Mg, P_{O_4}, Creatinine

b. "Arterialized" Capillary Blood — P_{CO_2}, pH

} Daily

Urine

a. Na, K, Cl, Ca, Mg, P_{O_4}, Creatinine

b. NH_4^+, HCO_3^-, Titratable Acidity, pH

c. 24-hour hydrogen ion excretion

NH_4^+ + T. A. - HCO_3 = 24 H^+ excretion

} 24-Hour Excretion

Table III. Metabolic Studies Done in 3% and 4% Carbon Dioxide Experiments.

In addition to venous blood samples, daily "arterialized" capillary blood samples were collected from the ear lobe which had been heated to approximately 45°C. Free flowing blood was collected anaerobically in a capillary tube, and P_{CO_2} and pH determinations were carried out within 20 minutes. Alveolar gas samples were collected simultaneously utilizing the Rahn sampler.

Twenty-four hour urines were collected under oil and the volume measured. To assess renal response to the induced respiratory acidosis, urine was analyzed for HN_4^+, phosphate, bicarbonate, and pH. These measurements, in conjunction with arterial pH, permitted the calculation of titratable acidity and 24-hour hydrogen ion excretion.

As shown in Table IV the basal pulmonary studies carried out included alveolar gas sampling, minute ventilation, oxygen consumption and carbon dioxide production.

BASAL CARDIOPULMONARY STUDIES
Minute Ventilation
Oxygen Consumption
Carbon Dioxide Production
Maximum Breathing Capacity
Vital Capacity
Timed Vital Capacity
12-Lead Electrocardiogram

Table IV. Cardiopulmonary Studies in 3% and 4% Carbon Dioxide Experiments.

Numerous miscellaneous tests were performed including liver function studies, hematology, and renal studies (Table V). All of these parameters were followed during both the 3% and 4% carbon dioxide tests, and all remained quite normal. Protein bound iodine determinations were also done during control and experimental periods and were not affected by the atmosphere.

Table V.

MISCELLANEOUS STUDIES

Liver Function	Hematology	Renal
-Bilirubin	-Hemoglobin	-BUN
Direct	-Hematocrit	-Serum Creatinine
Indirect	-Red Blood Cell Count	-Urine Creatinine
-SGOT	-Red Cell Morphology	Creatinine Clearance
-SGPT	-White Blood Cell Count	-Renal Sediment Exam
-Alkaline Phosphatase	with Differential	-Urine Culture
-Total Protein	-Reticulocyte Count	
-Serum Protein		
Electrophoretic Study		

To study performance capability, a large battery of psychomotor and psychological tests were performed daily on the subjects in both studies. These tasks included measuring problem solving ability, vigilance, reaction time, hand steadiness, and memory. Many of these tasks were programmed into a psychomotor testing unit designed to simulate some of the problems encountered in flying a spacecraft. In addition to this, repetitive psychological tests of types reported in earlier studies were also included in an attempt to verify or negate earlier reports in the literature. These included tests of letter cancelling and tracing of geometric figures.

In both carbon dioxide studies, the subjects were not told when the CO_2 would be increased. This was actually done over a 6-hour period while the subjects were asleep. When questioned about any noticeable changes, they were aware of an increase in the rate and depth of breathing in 3% CO_2. None of them, however, felt this to be particularly uncomfortable. Over the five-day experimental period there were no complaints or problems concerning sleep or carrying out normal tasks.

In contrast to this there was no question that the environment was altered with the addition of 4% carbon dioxide. All subjects were quite aware of an increased rate and depth of breathing, particularly accentuated by relatively mild exercise such as preparing meals and making beds. In both studies the subjects complained of mild, throbbing frontal headaches usually starting during the first few hours of exposure. In two of the cases a mild analgesic was needed to alleviate this. It is felt that these headaches were probably vascular in nature and related to known increased cerebral blood flow at the 3% and 4% carbon dioxide levels (9). The subjects did not complain of headaches after the first two days of exposure and these did not interfere with sleep or normal tasks.

The 3% carbon dioxide environment generally reflected only a mild stimulus to ventilation in the basal state. Increases in ventilation ranged from one to five liters per minute depending on the individual tested. As expected, more marked changes were seen in minute ventilation at 4% carbon dioxide, increasing from control values of 7-8 1/min. to 13-14 1/min. In both studies the elevated pulmonary ventilation was brought about more by an increase in tidal volume than by changes in respiratory rate. No significant differences were seen with reference to oxygen consumption and carbon dioxide production. Pulmonary function studies were unaffected by the carbon dioxide atmosphere. After the carbon dioxide phase of the experiments were over, an abrupt return to normal ventilation and tidal volume was seen in all subjects.

Table VI outlines the exercise protocol carried out in both studies. Planned duration in the 3% study was one hour which was reduced to ten minutes in the 4% study. The workload on a bicycle ergometer was the same

EXERCISE STUDIES

3% CO_2	4% CO_2
Duration = One Hour	Duration = 10 Minutes
Subjects = Seven	Subjects = Four

Workload = 100 watts at 60 rpm
Minute Ventilation
Cardiac Rate
Psychomotor Performance

Table VI. Bicycle Ergometer Exercise Studies.

in both experiments. This was considered a moderate exercise stimulus as the pulse responses varied from 120 to 140 beats/min. in the control periods. Along with the cardiac rate, minute ventilation and psychomotor performance was also followed. The psychomotor performance included tests of vigilance and reaction time.

All subjects tolerated the one-hour exercise in 3% CO_2 very well. During the CO_2 exposure, a marked increase was noted in rate and depth of breathing, but otherwise no difficulties were encountered. Originally, a 20-minute exercise program was planned for 4% CO_2, but it became apparent during preliminary studies that the subjects could not accomplish this. The exercise period was then reduced to 10 minutes and this was completed only with difficulty.

Figure 9 illustrates the pulmonary ventilation in the resting state and

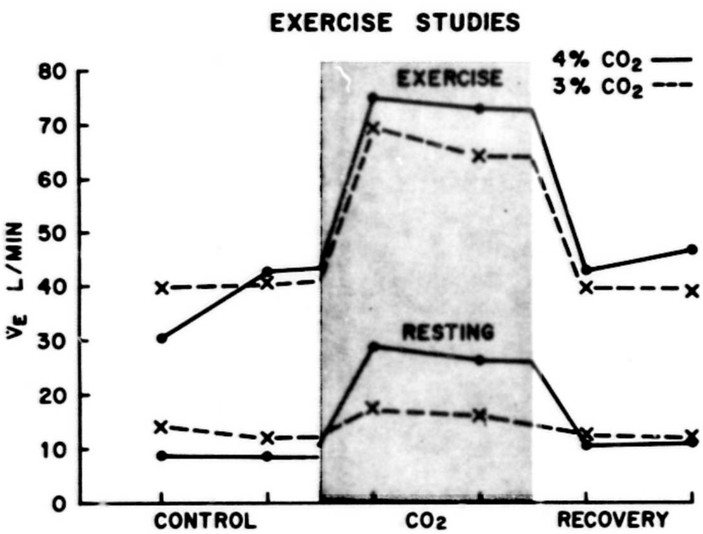

Figure 9. Ventilation Studies During Exercise.

during exercise. The exercise data points were collected at the end of the one-hour exercise period in 3% CO_2 and the 10-minute exercise period in 4% CO_2.

Note during the resting period on the ergometer in the 3% CO_2 that only a mild increase is seen in ventilation when compared to the control state. A marked change is noted in the 4% CO_2. As expected, very high pulmonary ventilatory rates are achieved during the CO_2 exercise. The main points of interest in these studies are the large differences in tolerating exercise while breathing 3% and 4% CO_2. Few problems were noted during exercise in the 3% CO_2 for one hour while an exercise period of only 10 minutes duration in 4% CO_2 was extremely difficult for the subjects.

As discussed earlier, simple psychomotor tasks mainly relating to reaction time and memory were done during exercise. No differences were found between control measurements and those done in the carbon dioxide atmosphere.

A detailed statistical analysis of all psychomotor data was done including the tests conducted three times daily. This also included the repetitive psychological measurements including letter cancelling and geometric tracing. Careful analysis of this data failed to show any performance change in carbon dioxide. Of particular interest was the continuing normal responses seen in the letter cancelling tests at both 3% and 4% CO_2. This certainly conflicts with the earlier reported German experience.

Of major interest in our series of experiments were the acid-base measurements that were made daily. Utilizing ultra-micro techniques and improved methodology we were able to study this aspect of normal man's physiologic adaptation quite closely.

The acid-base variables measured in both studies were similar and differed only in degree with respect to the CO_2 environment.

Figure 10 portrays pertinent acid-base changes seen at the 3% CO_2 level. The control data brackets the stippled area which represents the time in carbon dioxide. There is a prompt rise of 3-4 mm. Hg of the

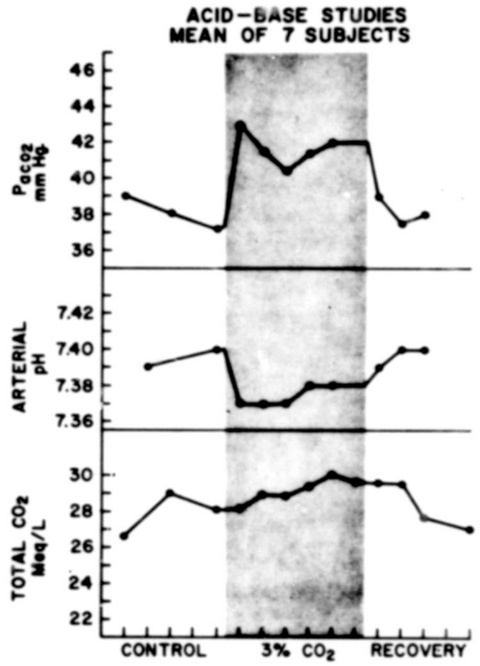

Figure 10. Pertinent Acid-Base Studies in 3% Carbon Dioxide.

arterial P_{CO_2} and this remains elevated. Note the abrupt reduction in the arterial pH from control values of 7.40 to 7.37 during the first day of CO_2. Initially the small rise in serum bicarbonate was inadequate to buffer the acute hypercapnia. By the fourth to fifth day of the study, the mild respiratory acidosis had been almost completely compensated by an increase in the serum bicarbonate.

At 4% CO_2 the acid-base changes are quite similar except in degree (figure 11). Again, we see a prompt but more marked rise in the arterial

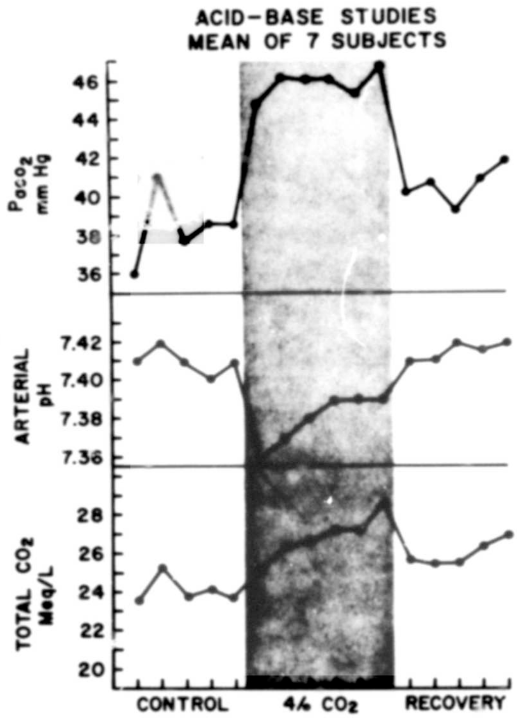

Figure 11. Pertinent Acid-Base Studies in 4% Carbon Dioxide.

P_{CO_2} from approximately 38 mm. Hg up to 48 mm. Hg. This excessive acid load has depressed the arterial pH from 7.41 down to 7.36, a change of 5 units as opposed to 3 units in the 3% studies. Note that this is inadequately buffered by the acute 1.5 mEq./1. rise in the bicarbonate illustrating the inadequate amount of buffer immediately available. By the fourth day in CO_2 the buffering capacity has been increased to the extent that arterial pH has again returned to near normal control values and is in a new chronic steady state. The elevated bicarbonate was achieved with the increased reabsorption by the kidney.

From the foregoing, it is apparent that 3% and 4% carbon dioxide is a relatively mild challenge to sedentary man's adaptive mechanisms. He is able to maintain a pH at the lower limits of normal during acute exposure and then adapt by returning to near control values. To underscore this relatively mild challenge, no renal compensation other than increased bicarbonate reabsorption was necessary. There was no change in the net 24-hour excretion of urinary ammonium or titratable acidity. As these are the only hydrogen ion excretion studies that have been done in normal man, in chronic hypercapnia, we have no other studies to compare our experience with. It would seem reasonable that net acid excretion would increase with much higher carbon dioxide levels.

Figure 12 is taken from the work carried out by Schwartz and others (1, 14, 15) and illustrates graphically the extracellular physiologic adaptation seen with stepwise increases in carbon dioxide tensions.

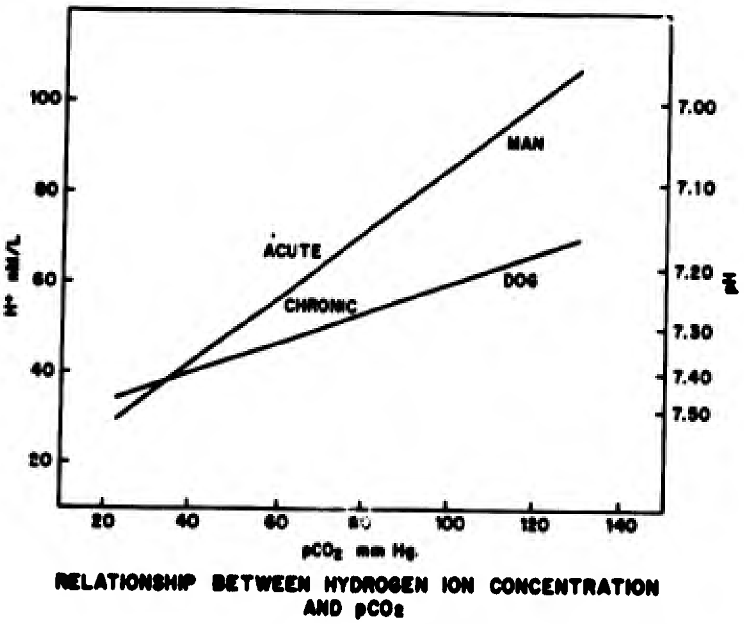

Figure 12. Acute and Chronic Studies Utilizing Dog and Man. Schwartz, et al. J. Clin. Invest., 44:296, 1965.

The H^+ concentration is plotted against the arterial P_{CO_2}. On the left side is the more familiar pH units that correspond with the hydrogen ion concentration.

The steep slope here represents acute studies carried out in normal volunteers (1). It is apparent that there is a rather marked increase in acidity (approximately 0.7 nanomoles/1.) for each mm. Hg increase in the arterial P_{CO_2}. The lower slope represents data obtained in animal studies (14) and reveals adaptation to chronic hypercapnia. Note that for each mm. of Hg increase in the arterial P_{CO_2}, the corresponding increase in acidity is much less than for the acute state.

The acid-base data we have obtained (figure 13) is unique as similar information is available only from animal work or the study of people with chronic pulmonary disease and complicating hypoxia (15). As shown in this graph, the adaptation of normal man to chronic hypercapnia is strikingly similar to the predictions based on animal work. It should be pointed out that our data has only been collected for arterial P_{CO_2}'s up to 50 mm. of Hg, and to make the H^+/P_{CO_2} relationships more meaningful, it will be necessary to perform similar investigations at higher CO_2 tensions. It is hoped that these will be carried out in the near future. To briefly summarize:

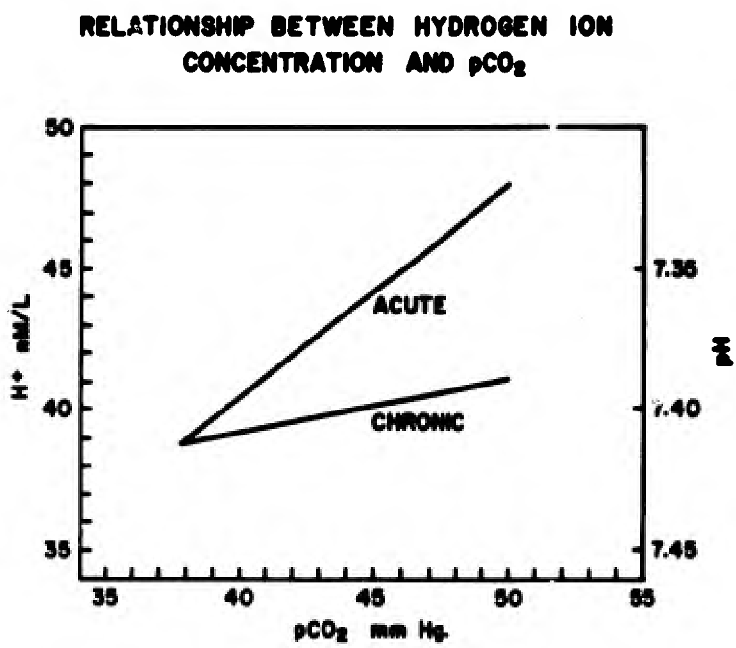

Figure 13. Acute and Chronic Studies Utilizing Normal Man. USAF 1965-1966.

By our studies we have, hopefully, clarified some of the questions which have surrounded the effects of hypercapnia on the physiology and performance of normal man.

It seems apparent that man can adapt, if necessary, to 3% and 4% carbon dioxide in the atmosphere. At these levels, we were not able to document any state of prolonged acidosis. Indeed, adaptive mechanisms returned the extracellular pH to quite near control values, as was predicted by earlier animal studies. This was achieved without increasing net renal acid excretion.

In our studies no biphasic swings of euphoria and depression were noted over the five-day period. There were no undue problems with discomfort from the atmosphere and no sleep difficulties. In addition, moderate exercise was well tolerated for one-hour periods at 3% carbon dioxide though this was no longer feasible at 4%.

Not only was physiologic adaptation accomplished but no decrements were seen in the programmed psychological and psychomotor tests.

Although we are not advocating a high carbon dioxide environment for spacecraft atmospheres, perhaps too much emphasis has been placed on the deleterious effects of this gas at even lower levels than encompassed in our study. In any event, this information should be of future value in the handling of any system failures leading to carbon dioxide buildup.

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Bends in Simulated Extravehicular Activity

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BENDS IN SIMULATED EXTRAVEHICULAR ACTIVITY

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I. INTRODUCTION

To learn how to prevent and treat decompression sickness, should it occur in space flight, experiments were designed in which individuals would be carried through atmospheric changes as might be encountered in establishing, manning, and operating an orbiting laboratory. We can now report the incidence and characteristics of decompression sickness occurring in subjects participating in these various simulated Manned Orbiting Laboratory pressure profiles, as of 24 June 1966. We also include data previously reported in a position paper dated 29 September 1965.

II. PROCEDURE

Man-experiments (388 in number) have been accomplished with 76 subjects who were experienced in high altitude chamber activities. Most of the subjects have experienced bends of some sort at one time or another. The age range of the subjects was 18 to 47 years. The experiments were accomplished at the same time of day, and a standard diet was used. With one exception, all experiments were conducted on Tuesday, Wednesday, or Thursday of each week in an attempt to avoid the influence of weekend activities. The experiments were conducted in a chamber with previously described control of atmospheric composition (7) so that, except for some of the preliminary experiments, mask breathing was necessary only during the denitrogenation portion of the profiles. Denitrogenation was accomplished by breathing 100 percent oxygen at rest through an MBU5P mask with the regulators set at approximately 4mm Hg pressure to prevent inboard leak. Subjects were not exposed to these simulated MOL flights more often than once every two weeks. A subject experiencing decompression sickness of any form in any flight was not permitted to go on a subsequent flight for 2 to 4 weeks, depending upon the severity of the disorder. The grading of bends is that used by Berry and Wayne (4): Grade 1 - intermittent or mild symptoms; grade 2 - moderate to severe symptoms not requiring abort; grade 3 - severe symptoms requiring abort of the flight; grade 4 - severe decompression sickness requiring hospitalization of hyperbaric therapy. Grade 1 bends, in our opinion, must be evaluated with caution since mild or fleeting aches and pains are observed almost daily in the average person. The profiles investigated are listed in table I. During the extravehicular activities (EVA), exercising was begun immediately upon reaching final pressure (3. 5 psia). In transfer EVA, exercise consisted of 5 deep knee bends and 5 push-ups every 5 minutes, while in work EVA, exercise consisted of the same

TABLE I. Sequence and Duration (Hours) of Exposures to Indicated Gas Pressure and Composition

Mission Profile	ATMOSPHERE: On Pad	Liftoff & Transfer Vehicle	Transfer EVA	Period in Laboratory						Work EVA
	14.5 psia 100% O_2	5 psia 100% O_2	3.5 psia 100% O_2 Exercise	7 psia 46% O_2 51% N_2	7 psia 46% O_2 51% He	7 psia 100% O_2	5 psia 100% O_2	5 psia 70% O_2 30% N_2	5 psia 70% O_2 30% He	3.5 psia 100% O_2 Exercise
1A	1.5	2.5	0.25				4			2
2A	1.5	2.5	0.25	4						2
2B	4	2.5	0.25	4						2
2B He	4	2.5	0.25		4					2
$2B_2$ He	4	2.5	0.25		4	0.5				2
2C	4	2.5	0.25	12		0.5				2
2C He	4	2.5	0.25		12	0.5				2
2Q	4	2.5		4						2
2Q He	4	2.5			4					2
2S	4	2.5						4		2
2S He	4	2.5							4	2
1S	4	2.5					4			2

exercises every 15 minutes. It is not known whether this exercise is equivalent to the work performed during weightlessness, but if not, the error should be on the safe side.

III. RESULTS AND DISCUSSION

A detailed presentation of the general results is given in table II. Specific areas of interest are also presented in tables II through IX.

A. <u>Denitrogenation Times.</u> Table III compares denitrogenation times of 1.5 hours and 4 hours. In these cases, bends occurred before the subject entered the simulated MOL atmosphere. One and one-half hours' denitrogenation resulted in 13 cases of decompression sickness out of 52 exposures, while 4 hours of denitrogenation resulted in only 10 cases of decompression sickness out of 160 exposures. In 171 additional experiments in which there were 4 hours ground level prebreathing and no transfer EVA, there was only one case of bends occurring before entry into the MOL atmosphere.

TABLE II. Cases of Decompression Sickness

Mission Profile	N	BENDS GRADE: Liftoff and Transfer Vehicle 1	2	3	Transfer EVA 1	2 (N=20)*	3	Laboratory 1	2	3	Work EVA 1	2	3 (N=19)**
1A	21		3	1	1	3		2	4	1	4	2	4
2A	31	1			6	2					6	10	3
2B	50				2						7	2	1
2B He	38				4						10	2	3
$2B_2$ He	32				1	1					6	3	1
2C	30				1								1
2C He	10				1						4		
2Q	38										6	2	1
2Q He	39	1								1	7	1	1
2S	36										3		
2S He	35										2	1	1
1S	28											1	

* N = 20
** N = 19

TABLE III. Denitrogenation Times and Bends Incidence in Transfer Vehicle and Transfer EVA

Grade of Bends	1.5 Hrs. (N = 52)	4 Hrs. (N = 160)
1	7 (13.5%)	9* (5.6%)
2	5 } (11.5%)	1* } (.6%)
3	1 }	0 }

* All occurred in Transfer EVA.

B. Preoxygenation Before the Work EVA. Table IV shows cases of bends from helium atmospheres in which 30 minutes of oxygen breathing was compared with no oxygen breathing prior to work EVA following MOL atmosphere exposure. These results indicate that benefit from the 30 min-

TABLE IV. Bends Cases After Breathing Oxygen for 30 Minutes Prior to Work EVA

2B He vs.	$2B_2$ He and 2C He	Paired Flights
No	No	12
Yes	No	8
No	Yes	4
Yes	Yes	6

utes preoxygenation was questionable in reducing the incidence of bends from the helium atmospheres. Possibly one hour would be of more benefit than 30 minutes.

C. Fate and Progression of Bends Symptoms. Table V indicates the progression or regression of the 59 cases of bends which occurred in the 308 man-flights which involved exposure to helium-oxygen or nitrogen-oxygen MOL atmospheres. The appearance of grade 1 bends was followed either by disappearance in approximately 35 percent of the cases, or with persistence as grade 1 bends in 55 percent of the cases. Only 4 cases progressed to grade 2. Of the grade 2 cases which appeared, half of them became grade 1, and half of them progressed to grade 3. There was only one instance of a grade 2 pain remaining as a grade 2 pain until the flight was terminated.

TABLE V. Fate of Bends Symptoms During Work EVA (59 Cases).

GRADE BENDS				
First Report	Subsequent Report			
	0	1	2	3
1	18	27	4	0
2	0	4	1	5

D. Helium versus Nitrogen. Paired flights were accomplished by an individual at different times (3), using helium-oxygen on one occasion and nitrogen-oxygen on the other occasion. In profiles 2B, 2Q, and 2S, comparisons were made as can be seen in tables VI and VII. In flight 2B, for example (table VI), there were 9 individuals who had bends after decompression from the helium-oxygen atmosphere and did not have bends following decompression from the nitrogen-oxygen atmosphere; whereas there was only one individual who had bends after decompression from the nitrogen-oxygen atmosphere and did not have bends after decompression from the helium-oxygen atmosphere. Altogether, there were 38 cases of bends in 148 helium-oxygen experiments, and 21 cases of bends in 150 nitrogen-oxygen experiments. These results exclude those pairs of experiments in which bends occurred prior to the work EVA.

TABLE VI. Comparison of Helium and Nitrogen Bends Cases in Work EVA

He	vs. N_2	2B	2Q	2S
No	No	19	24	28
Yes	No	9	4	2
No	Yes	1	4	1
Yes	Yes	3	4	2
	Total Pairs	32	36	33

TABLE VII. Comparison of Number and Grade of Bends Cases in Work EVA

Grade	2B		2Q		2S	
	He	N_2	He	N_2	He	N_2
1	9	3	7	6	2	3
2	1	1	1	2	1	0
3	2	0	0	0	1	0
Total Pairs	32		36		33	

E. Extent of Recompression Necessary. In 71 cases of decompression sickness in this series, the pressure of disappearance of symptoms during recompression was reported and recorded, and is indicated in table VIII. It will be noted that 21 of these cases required recompression to pressures greater than 7 psia, and 9 of these required recompression to 14.5 psia with 100 percent oxygen. Six of these 9 cases required time at ground level after

TABLE VIII. Number of Cases in Which Bends Symptoms from 3.5 psia Were Relieved at the Indicated Pressures During Recompression.

	HELIUM			NITROGEN		
Grade	<5 psia	5-7 psia	>7 psia	<5 psia	5-7 psia	>7 psia
1	11	3	4	12	9	1
2		1	1	5	5	5
3			5	1	3	5

recompression before the complete disappearance of symptoms (table IX). Thus, it appears that approximately 10 percent of the subjects with decompression sickness would require 14.5 psia pressure for relief of symptoms.

TABLE IX. Pressure of Relief in Subjects Recovering at >7 psia.

HELIUM	NITROGEN
7.6 psia	7.3 psia
9.4	8.6
9.7	9.0
10.9	10.1
11.3	10.1
14.5	11.3
14.5	13.9
14.5 + 15 minutes	14.5
14.5 + 18 minutes	14.5 + 55 minutes
14.5 + 32 minutes	14.5 + 60 minutes
	14.5 + 62 minutes

F. Treatment Profiles. In recent exploratory experiments, a few patients have been treated with 9. 5 psia, 100 percent oxygen. These cases, not included in the above data, also occurred at 3. 5 psia. Recompression treatment to 9. 5 psia was accomplished in order to simulate a 5 psia cabin pressure plus 4. 5 psia emergency suit pressure. Most of these subjects were relieved of symptoms by the use of 100 percent oxygen at 9. 5 psia. However, it was necessary to continue this oxygen-breathing period at 9. 5 psia for 4 to 5 hours before subsequent decompression to 5 psia could be accomplished over a 30-minute period without the recurrence of bends symptoms. This again is a small series of cases and insufficient for conclusive analysis. There were 3 men in this group, however, who did not respond to 100 percent oxygen at 9.5 psia and, indeed, it was necessary to use hyperbaric oxygen therapy for complete relief of symptoms (10). In all three of these individuals, 3 atmospheres absolute pressure, breathing 100 percent oxygen, was necessary to completely alleviate their symptoms. These 3 cases are not shown in tables VIII and IX. One of the subjects presented symptoms of chokes with circulatory manifestations, another presented severe chokes, and the third was a case of circulatory collapse.

G. Recurrence of Symptoms. A few experiments have been accomplished in which it was attempted to estimate the time required at MOL pressure after a subject had developed bends symptoms at suit pressure before a subsequent decompression to suit pressure could be accomplished without recurrence of symptoms. In the small number of experiments accomplished, 6, 12, and 18 hours appeared to be unsatisfactory. The time required may well be 24 to 48 hours.

H. Equipment Failures.

1. Cabin Pressurization Failure on Liftoff. In the event of cabin pressurization failure on liftoff, the astronaut would immediately thereafter be exposed to 3.5 psia suit pressure. The Air Crew Equipment Laboratory of the U. S. Navy (5, 6) showed an average of approximately 10 percent incidence of bends following 3 hours of ground level denitrogenation and subsequent decompression to 3.5 psia for a 3-hour period. It is a general impression of our group that at least 4 hours' denitrogenation would be required to give protection against this type of decompression.

2. Rupture of the Suit in EVA. Reference is made to work accomplished at the USAF School of Aerospace Medicine by Bancroft and Dunn (2), and also work accomplished at Holloman Air Force Base (8) in which rapid decompression of animals to extremely high altitudes was followed by recovery, in most instances, if the length of exposure time was kept to less than 2 minutes. Exposure of non-denitrogenated dogs to a near-vacuum for 2 to 3 minutes resulted in mortalities of about 15 to 85 percent, respectively. Denitrogenated dogs showed a slightly better survival rate. The work at Holloman Air Force Base, using a smaller number of trained chimpanzees, has resulted in a good survival rate after 3-minute exposures. This would indicate that if another person were present to assist the victim in returning to the capsule so that repressurization could be accomplished, survival is possible. The critical time period for man is not known.

IV. RECOMMENDATIONS

A. Prebreathing Times. Four hours' denitrogenation time is recommended before decompression to 5 psia or less. If the MOL atmosphere is mixed gas and the astronaut has equilibrated with this atmosphere, then one hour's oxygen breathing is recommended before EVA is attempted.

B. Time for Initial EVA. Extravehicular activity is not recommended at the times used in some of the earlier experiments. EVA at 6.5 hours or less from the beginning of denitrogenation was dangerous. An EVA taking place 10.5 hours after the beginning of denitrogenation was safer.

C. Medical Management. There are certain extremely severe manifestations of decompression sickness which are exceedingly rare and which are generally accepted as calculated risks. These cases can be treated satisfactorily only with hyperbaric therapy and, hence will be excluded from the discussion of medical management with reference to manned space flight decompression sickness.

1. If Abort is Possible. Any flight in which a subject develops signs of severe decompression sickness such as neurological symptoms, circulatory symptoms, chokes, paresthesias, and grade 3 joint pains, should be aborted. From tables VIII and IX, there is evidence that even grade 1 and 2 joint pains may require recompression to 14.5 psia. If, by combining suit pressures and MOL pressures, 14.5 psia total pressure can be provided with 100 percent oxygen breathing, this could be used for treatment in cases of mild decompression sickness. At least a 5-hour treatment period will be required before re-ascent to 5 psia can be accomplished at a slow rate (30 minutes). A repeat EVA should not then be attempted for 48 hours.

2. If Abort is Not Possible. If abort of the mission is impossible and a subject develops severe decompression sickness, then unless 3 atmospheres absolute pressure (psia) with 100 percent oxygen can be utilized, a certain amount of morbidity and possibly an extremely rare fatality could result. Historically, Adler (1) in his review reported 7 fatalities out of 400 cases of circulatory collapse at altitude. If 14.5 psia with 100 percent oxygen can be provided, it is recommended that this pressure be maintained, with oxygen breathing, for at least 5 hours with a slow decompression to MOL pressure. General supportive care may be necessary, including fluid replacement (9). In the case of severe symptoms, it would be wise to stage the decompression so that 5 to 10 hours would first be spent in a 7 psia MOL atmosphere before subsequent decompression to a 5 psia MOL atmosphere. If possible, it would be safer to maintain the MOL pressure at 7 psia until abort could be effected, and certainly there should be no more decompressions to 3.5 psia unless absolutely necessary.

D. MOL Pilot Indoctrination Flight. It is recommended that MOL pilots, as part of their training, be subjected to certain safe decompression profiles in a chamber, preferably here at the USAF School of Aerospace Medicine in the Physiology Branch. This would be valuable experience for the MOL pilots. We have confirmed, in the course of our experiments, that certain individuals appear to be unduly susceptible to decompression sickness and, thus, profiles could be devised which should be safe for each individual astronaut.

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What Has Space Experience Taught Us About Disorientation?

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WHAT HAS SPACE EXPERIENCE TAUGHT US ABOUT DISORIENTATION?

Paul A. Campbell, M.D.

Spatial orientation and its antithesis spatial disorientation has always been one of the most intriguing facets of both Aviation and Space Medicine. In the early history of aviation, disorientation was considered to be a serious limitation to flight without earthly visual reference--for example when darkness or cloud formations obscured visual references. In the pre-manned space flight era there were predictions by knowledgeable people--some of it dire--that disorientation might be a very serious limitation to manned orbital flight. As they reasoned, both visual and gravitational references would at times be lost. In retrospect, as we well know, the predictions have not been valid.

We know well that the perfection of instrument aids as well as other aids has solved most of the problems of flight without earthly reference in conventional aviation. We also know that to date little serious difficulty has been experienced during orbital flight. To cite a few figures: Orbital experience in 14 orbital flights involving 19 American astronauts totaling 1993 man hours, 41 minutes and 55 seconds (through Gemini 12) has demonstrated no difficulty. The Soviet Cosmonauts have made 8 flights involving 11 Cosmonauts totaling some 507 man hours with minor difficulties reported by Cosmonaut Gherman Titov and Cosmonaut Physician Boris Yegorov. It has been said that Cosmonaut Engineer Feoktisov and Lady Cosmonaut Valentina Tereshkova at times during their flights were not completely free of aberations of orientation. The box office score during extra vehicular activity, a situation which according to the older theories should have been a prime producer of disorientation is: Astronauts, 6 hours and 3 minutes and the Cosmonauts about 20 minutes.

Thus it seems timely to review the entire matter of disorientation and orientation in light of experience in both atmospheric and space flight, point out the evolution of the concepts, possibly point out what has been learned and then indulge in a little reevaluation.

To begin by turning back a few pages of history--and one often finds many interesting answers in history--it is quite interesting to follow the orientation concept through the major part of its evolution. It began with the work of the French physiologist Pierre Jean Marie Flourens whose classical work with pigeons of the early 1820's demonstrated the semicircular canals of the vestibular apparatus to play an important role in orientation. His results, obtained by sectioning or obliterating various elements of the vestibular system and then observing the subjects, their attitudes, gaits, flying ability, orientation etc., unfortunately went forgotten for almost half a century.

In the year 1873 Ernst Mach (2) of Prague, famous physicist and philosopher, whose name is most often associated with Mach numbers, Mach blast effects, etc., spread the spectra of the incredible breadth of his interests into the realm of biophysics. Almost simultaneously with J. Bruer of Vienna (3) and A. Crum Brown (4) of Boston, he worked out a theory concerning vestibular function. Many of the aspects of their similar theories remain reasonably valid today. Some do not. During the first quarter of the present century, Robert Barany, famous for the development of the Barany Chair and rotation studies (5, 6), G. Alexander (7), H. Brunner (8), and G. Schubert (9), all of Vienna added greatly to the stockpile of knowledge concerning vestibular reactions and who represented the famous school of thought in this particular area at that particular time. In the United States, at about the same time Isaac Jones (10), Eugene Lewis (11), Lewis Fisher (10), and a number of others furnished a good deal of basic knowledge as well as applicatory knowledge. Unfortunately, during this period, a situation of over-emphasis of the role of the vestibular apparatus in aviation and for that matter clinical medicine and neurology led to some discreditation of its value in testing and diagnosis. Vestibular responses were being used as a sort of a new peep-hold into the central nervous system. In fact some ot the normal responses, especially in the use of vestibular testing as a selection device, led to rejection of many good candidates for flying training while accepting some of the abnormal. As in most cases of overemphasis, the pendulum swung back and forth for a few oscillations and then came to rest in the mid-line of proven logic. The profound studies of J. Tait and W. McNally (11) of Canada were very helpful in placing the role of the vestibular apparatus in proper focus.

Since World War II the names of A. Graybiel (12) and associates, as well as F. Kramer, S. Gerathewohl, H. Von Beckh and others have added vast new areas of knowledge of the orientation processes in space flight. Much definitive information concerning aberrations during weightlessness have come from the experience of the Astronauts and Cosmonauts. In the Soviet Union the names of K. Chilov (13), O. Gazenko (14, 15), A. Gurjian (14), B. Yegrov, A. Popov, L. Pavlov, G. Kulikovsky are well known. In western Europe the names of N. Lansberg (16), T. Lomonaco and A. Scano (17) have prestige.

In the early 1920's, over most of the world, the concept of the orientation triad had reached the point of definitive usefulness. In a possibly over simplified generalization it alluded to the following:

The orientation function (5) (18, 19) is the result of the integrated activities of three components: 1) The visual apparatus; 2) The vestibular apparatus and 3) The combined functions of the kinesthetic, proprioceptive and tactile apparati. All three of the components are integrated in the central nervous system through their nervous connections. According to the views of the time two of the components of the triad were required to be functioning more or less perfectly if orientation was to be within an effective range. Any two would do. None was considered to be dominant over the others. Thus the clinical Romberg test was explained. To this day the Romberg test or some of its modifications are very helpful in clinical neurology as well as aviation medicine.

As applied in explanation of inability to fly in darkness or through cloud formations it was hypothesized that vision would be lost through complete darkness or cloud formations and as the aircraft was not a solid platform kinesthetic reactions would be faulty. Thus two elements of the triad would not be furnishing sufficient or correct information to the central nervous system integrator for orientation to be effective. The situation was often complicated with afterturning responses, vertigo and/or other aberrations emanating from the vestibular apparatus. Until the late nineteen-twenties flight through clouds or in total darkness was practically impossible. Under these circumstances orientation was quickly lost and disaster often followed. During the early twenties competition to see who could stay in a cloud formation for the longest time without spinning out was a common pastime of the aviators of the day -- providing the clouds were high enough. The winner usually was the one who could remain without visual references for a period of a very few minutes--usually only a minute or two.

The classical experiments of Ocker, Crane and Myers (20), in 1926 demonstrated that vision was the dominant element of the triad and if vestibular and kinesthetic information could be ignored through training and experience and if the airman could be taught to believe implicitly in the information his instruments were giving him, he could then and only then fly "blind."

Thus an experiment costing less than a dollar revolutionized aviation and resulted in instrument flight. The many, many millions of flying hours flown under instrument conditions attest the correctness of their studies and the instrument training systems which they produced. The orientation concept had also been altered by their work. It awaited the advent of space flight for further alteration.

However, extensive studies of airsickness performed during World War II at the School of Aviation Medicine at Randolph Field threw a great deal of new light on disorientation and vertigo, the role of the vestibular apparatus and other elements of the triad. Most important from this author's point of view were the following:

Through studies of large numbers of candidates for the various categories of flight it became evident--at least from the standpoint of tolerance to motion--that reactions of the members of the general population distributed themselves along a more or less classical Bell Curve (21, 22). In other words, at one end of the curve were a small number of the population relatively insensitive to motion. The large central bulge of the curve was made up of the major portion of the crewmen candidates who reacted in varying degree to motion. At the far end of the curve was a smaller number who were severely affected by just a little motion--some with the mere sight of random motion or the thought of flying in an aircraft. It was subsequently determined that there was a very strong psychogenic overlay in the latter group. From the viewpoint of selection for aircrew duties, pilot or otherwise, these people selected themselves out in very short order. They wanted to have little or nothing to do with anything with random motion--including aircraft. In that era flights in light aircraft proved to be an excellent selection device. After a few flights those seriously affected by motion or a psychogenic component, which most often was fear of flight, were very evident. Some would show rapid adaptation during their first few flights and as a number of these had excellent motivation--sufficient to put up with airsickness on their first few flights--were kept on. If they continued to improve to the point where they were experiencing no difficulty they were selected in. Many became excellent combat crewmen.

Here one must pause to point out an item of great importance as we shall show later, namely that long periods of aircraft flight experience--accumulated flying time, if you please--is a most important selection criteriod for any form of flight and most especially--exotic flight. This is extremely true if the flight time has been in high performance aircraft with extensive experience in aerobatics. These individuals have lived through a series of selection events, have done the proper thing and have lived on to fly another day. They have proven their motivation or they would have selected themselves out. They have proven their ability to react quickly and properly. They have proven themselves in many ways. As space flight is only an extension of aviation these same individuals will, wherever the human factor is involved, probably turn in the best performance record (23). One hesitates to think what might have happened if when Gemini 8 began to rotate, reaching a rotation rate* of some 50 revolutions per minute, Astronaut Armstrong had not had vast test experience and had not undergone high speed rotation in previous experience.

It is my personal opinion that the primary reason our Astronauts have been completely free of disorientation difficulties in the weightless state, whereas the Soviet Cosmonauts have had some difficulty, is simply a function of flight experience. I hesitate to think of the possible reactions astronaut physicians, astronaut physicists, astronaut geologists and astronaut

* The rates were not constant. They were in all axes but primarily in roll axis running fore and aft of spacecraft. Total time of unusual gyrations was about 25 minutes. (Personal communication with Howard Gibbons, NASA)

crewmen of other categories will have unless high performance flying experience of many hours including aerobatic training is kept as a most important criterion for selection. One cannot conceive of many situations which would be as unpleasant in the weightless state as to have a companion crewman vomiting nor so hazardous as vomiting into one's helmet.

In such a paper as this, one must stop to equate to some extent at least, motion studies and zero "g" studies. This is open to some argument but not very much as there are several common factors. The same systems are involved with zero "g" inserting itself exactly in the center of the spectrum between positive acceleration on one end and negative acceleration on the other. Zero "g" is the neutral point of the spectrum between weight acting in one direction and weight acting in the opposite direction. Possibly the central nervous system is capable of sensing this neutral point as an excitation entity and capable of accepting the condition without confusion and other conditions such as vertigo. Only detailed studies of man in orbit, in an orbital laboratory with adequate laboratory instrumentation at hand, animal experiments with a man present as well as other experiments in geotropism will give the final answers (24).

When the feasibility of manned space flight began to loom on the horizon the question of man's reaction to weightlessness, in light of knowledge then at hand, produced a huge question mark. In view of the triad concept of orientation, the possibility of disorientation and possibly resultant vertigo was raised by a number of knowledgeable scientists. If the triad concept, which had been so helpful in aviation was correct then during weightlessness the amount of information coming in from the gravi-receptors, namely the utricular portion of the vestibular apparatus, visceral, skin and deep muscle sensors would be zero and only the eyes would serve for orientation. Authors writing of the feasibility of space travel in the early part of the twentieth century were concerned with various aspects of weightlessness and in at least two instances suggested rotation as a gravity substitute. Tsiolkovskii of Russia suggested rotation by attaching two vehicles at each end of a long cable and then rotating them about a center of rotation about the midpoint of the cable. Hermann Potocnik of Austria, writing under the pseudonym of Hermann Noordung in the nineteen twenties suggested a very large wheel as the basic configuration of a space vehicle with the crew quarters placed in the circumferential rim of the wheel. The wheel was to rotate during the space voyage. The scientists of the U. S. S. R. in their excellent presentation at the Mar del Plata, COSPAR (14) meeting spoke of facilitation of the Cosmonaut Leonov's extra vehicular orientation by means of positioning a camera on the top of the spacecraft's lock arrangement which along with the coordinates afforded by the side of the spacecraft offered adequate cues for orientation.

To date neither Cosmonaut Leonov in his some twenty minutes of extra vehicular activity nor the Astronauts White, Cernan, Collins nor Aldrin have suffered from disorientation even though in at least two instances vision was seriously obscured by fogging of the face plate.

Now concerning sleep in the weightless state: If the evolving triad concepts were true, during sleep in the weightless state no information would be coming into the central integrator from the eyes. Due to weightlessness no information should be coming in from the utricular portion of the vestibular apparatus and none from the gravi-receptors of the kinesthetic, proprioceptive and/or deep muscle sensors. Consequently, according to much thinking, sleep would be difficult or impossible. But we all know it has not been difficult (25); at least not difficult from the standpoint of disorientation or dreams with a disorientation component; at least not difficult for the highly selected and highly trained astronauts who have been in space to date.

Thus, at this point in our discussion we are faced with three questions: 1) Must we change the orientation triad concept? 2) Is rapid adaptation taking place among these highly selected, highly trained, highly motivated individuals? or 3) Has some element been overlooked or not given proper emphasis. In my opinion the answer is--a little of all three.

In answer to the first question: The orientation triad concept probably applies to the greater part of our population but it must be altered to some extent when one deals with highly selected, highly trained individuals.

Concerning the second question--that of adaptation: We all recognize that space flight has already taught us that the power of adaptation to new environmental situations by the carefully selected, highly trained, highly motivated individual greatly exceeds anything heretofore suspected.

Turning to the third question: Has some element been overlooked or given improper emphasis? The answer is yes. In the past, the third element of the triad, that portion representing the sum of the kinesthetic, proprioceptive, visceral and skin sensibilities has always been placed third in order of importance. It seems to have also been relegated to third place in terms of the amount of research which has been performed in the area. The visual and vestibular systems seem always to draw most interest and support. However, space flight may well prove this lowly third member of the triad to be much more important than hitherto suspected. It may well be capable of maintaining orientation completely on its own--especially when kinesthetic, tactile, visceral and other forms of identification are maintained with the spacecraft through pressure by seat or couch restraints. This constant identification with a relatively solid, relatively stable, encasing structure in an orbital situation where a good deal of power is required to alter the orbit just a little, might be one of the major answers to our question.

For some support for this hypothesis we might turn back to studies during the late nineteen forties relative to the effects of the drug streptomycin on the eighth cranial nerve and some of its end structures (26, 27). Those clinicians who studied the effects of the drug noticed that some of the patients with obvious destruction were unable, while blindfolded, to walk across resilient surfaces such as bed mattresses strewn across the floor. In other words, with their visual cues removed by the blindfold and their vestibular cues by streptomycin they were unable to maintain orientation. They resembled tabetics in a dark room, during the days when tabes dorsalis was a common affliction. The patients would simply sit or lie down to regain orientation through identification with a stable object--namely the floor. Often, lightly touching a handrail or the use of a walking stick against a stable surface would suffice to return orientation and put an end to their spatial confusion.

Gazenko and Gurjian (14) reported that, Feoktistov and Yegorov found they could suppress disagreeable "vestibular autonomic sensations" while weightless by straining their muscles "to gain proprioceptive afferentation." They also suggested that tactile reception must play a role in the maintenance of orientation while weightless. Here, again I would like to suggest that identification with restraints, seat, etc., through skin and other receptors may have been playing a very important role. This must be the sole source of identification during sleep.

As we draw near conclusion we must point out that geotropism defined as the response of plants and animals to the earth's 1 "g" force field is a phenomenon which has affected and has played an important role in the evolutionary processes of MAN. There is much to be known of the physics, chemistry and biology of its effects. Space flight gives us another important tool with which to study the phenomena and certainly should receive detailed study in a Manned Laboratory in Space (24). Spatial orientation is one of the aspects of geotropism in which knowledge is lacking. Knowledge gained concerning orientation and the avoidance of disorientation and vertigo will be helpful in solving some of the problems which have plagued conventional aviation as well as those of space flight. Such knowledge will also have many applications in clinical medicine and its associated specialties.

Now to attempt to give a few of the answers to our complex title question: What Has Space Experience Taught Us About Disorientation? and to give a few reasons why predictions of disorientation in the weightless state have failed to materialize. The following is pertinent:

1. The importance of the third element of the orientation triad--namely the summed activities of the kinesthetic and proprioceptive senses emanating from the muscles, viscera, skin etc., has never been fully appreciated. It is much more important than we may think and may hold the key to some of the false predictions concerning effects of weightlessness. The general area should have much more research support than it has been given

in the past. In my opinion it should have equal support, for the time being at least, with research on the vestibular aspects of aviation and space flight.

2. The third element of the triad of which we have just spoken, apparently can function alone through the process of identification with the orbiting spacecraft through the medium of seats, couches, restraints, etc.

3. Extended flight experience in high performance aircraft, with many hours of instrument flight, aerobatic experience and similar type of flight is a most and possibly the most important selection device and qualification criterion for participation in space flight. Flight experience is a selection device in itself as a pilot with thousands of hours of experience has been through a process of continuing selection, or series of selection procedures since his first flight physical examination and first flight. The fact he has lived through the period proves that he has had the proper responses and has done the proper things at the proper times. He has proven himself stable, his orientation physiology stable and without aberrant or hyperactive response. He has learned to sublimate, in degree at least, such responses as fear and confusion. He has demonstrated his ability to withstand stress. Long hours of flight experience has taught him to ignore certain types of information coming into his central nervous system integrator. All of his responses have been conditioned by flight experience. Only flight experience can offer this background.

4. Man can adapt better to aberrations of "g" fields than hitherto suspected. In fact one lesson Manned Space Flight has taught all of us is that the adaptability of man to most stresses including space flight is much superior to that which was hitherto advertised by our profession. Space flight has also taught us that the space environment as it has been encountered to date is much less severe than predicted.

Finally: One should never, never discount the capability and the adaptability of MAN.

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Vestibular Experiments in Gemini Flights V and VII

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VESTIBULAR EXPERIMENTS IN GEMINI FLIGHTS V AND VII

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The vestibular organs are affected quite differently in weightlessness, emphasizing their individuality. In the absence of inertial forces there is "physiological deafferentation" of the otolith apparatus, but no corresponding dramatic effect on the semicircular canals. With movements of the head (body), the angular accelerations generated would stimulate the canals much the same as they do under terrestrial conditions, but the linear accelerations might not always constitute an adequate stimulus to the otoliths or, if they did, would not provide a cue to the upright of the spacecraft. Stated differently, when a person makes his first transition into weightlessness the normal constant stimulus to the otolith apparatus is lost for the first time; it is analogous to closing the eyes with the difference that we are habituated to eyes closed as well as eyes open. A person under these conditions constitutes not only an elegant "experimental preparation" but also one which has no counterpart under conditions where gravity due to a central field factor is present.

The great opportunities in weightlessness, to make observations and conduct research are, however, almost matched by the great experimental difficulties, at least in present day spacecraft. In the Gemini flights, despite the obvious constraints, it was considered feasible to conduct an inflight experiment dealing with space perception and to carry out preflight and postflight measurements of ocular counterrolling, a test of otolith function. Chief attention will be given to the inflight experiment.

SPACE PERCEPTION

The purpose of this experiment was to compare the influence of nonvisual sensory inputs on the visually perceived direction of space under terrestrial and weightless conditions. The astronauts' task was to set a luminous line to the horizontal in an otherwise dark visual field; preflight and postflight it was set to the Earth horizontal, and inflight to an element in the spacecraft which was horizontal with respect to the astronaut. This basic procedure was introduced by Aubert (1) who along with Muller (2) demonstrated the well-known E-and A-phenomena observed when man is tilted away from the upright in the frontal plane. Subsequently, their findings were extended by many investigators not only by positioning the subject with respect to gravity (3-8) but, also through the use of a human centrifuge by manipulating the gravitoinertial force vector with respect to man (9-21).

Inasmuch as these studies set the stage for our inflight experiment and the results of these studies were essential to their interpretation, a brief review is obligatory.

BACKGROUND STUDIES

In figure 1 is shown a simplified analysis of cues to space perception

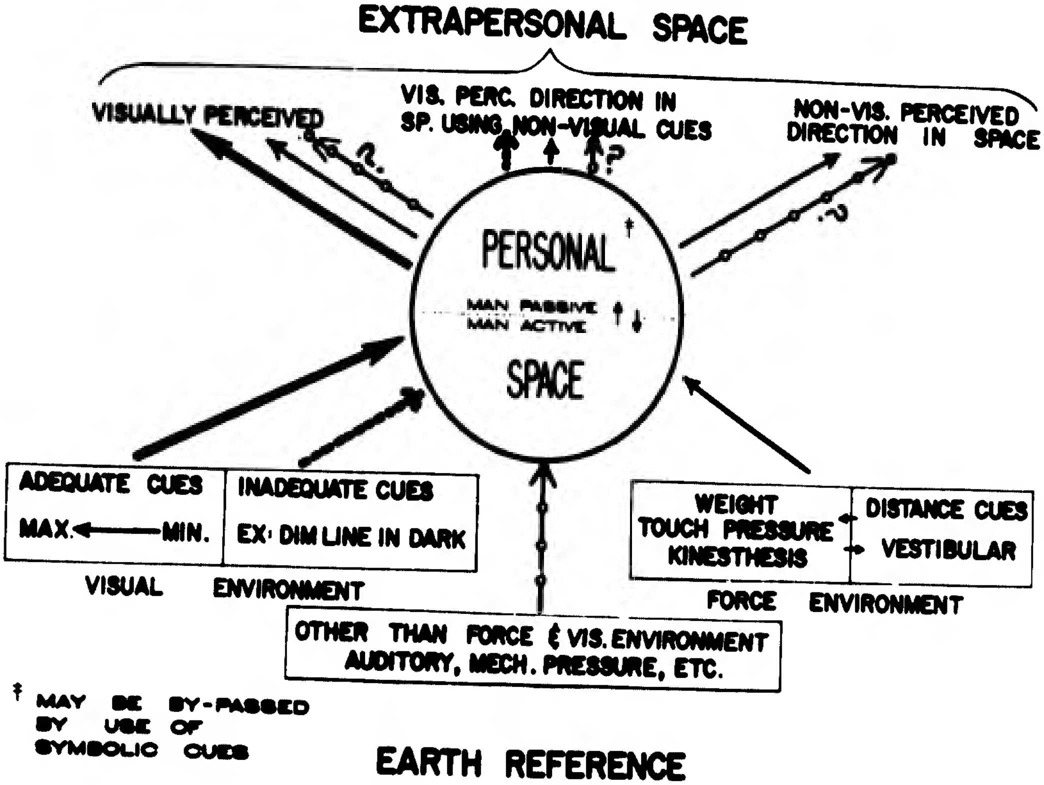


Figure 1. Cues influencing perception of force environments.

provided under terrestrial conditions and some of the possibilities for interaction among them. In general, manipulation of the gravitoinertial force environment is more difficult than is that of the visual environment, and this greater difficulty is enhanced by the several sensory systems responding, directly or indirectly, to gravitoinertial stimulation. The major nonvisual cues to the upright have their origin in the distance receptors in the otolith organs and in sensory receptors responding to mechanical force giving rise to tactile, deep pressure, and kinesthetic sensations which, for convenience, will be termed TPK receptors, and which, directly or indirectly, may be stimulated by weight. By testing both normal subjects and persons with bilateral loss of labyrinthine function (L-D subjects) exposed under normal (dry) conditions or submerged in water (wet), it was possible to determine the reactions of persons with signals from 1) otolith and TPK receptors, 2) otolith only, 3) TPK only, and 4) neither.

Visual cues are eliminated when the subject's eyes are closed or he is in darkness, although visual memory remains. The visual field may be structured to provide correct or incorrect cues to the visual upright or simply inadequate cues; the last type of cues is represented by the broken lines in figure 1. Within this category of "inadequate cues," moreover, there is the extraordinary possibility of using a fixation target by which the subject can indicate the upright or horizontal. A dim line of light that can be rotated clockwise or counterclockwise serves this purpose (22). Using such a target device enables the experimenter to investigate nonvisual influences on the visually perceived direction of space; these inputs articulate rather than interact with visual inputs.

In this summary and in reporting the Gemini findings we will be dealing with experimental situations in which the subject estimates the direction of extrapersonal space with reference to himself. In the interest of brevity references to interactions between visual and nonvisual inputs are not included here, but it is worth pointing out that in studying these "interactions," the point of departure at one extreme is represented by the illustrations of influences to follow.

Certain Effects of Lateral Tilt in the Gravitational and Gravitoinertial Fields

Seated upright in a tilt chair normal subjects in the dark are able to set a luminous line approximately to the gravitational horizontal but manifest a characteristic bias as they are tilted leftward or rightward through 90°. The bias appears at tilts of 15° to 20° as an overcompensation which, with large angles of tilt, gives way to an undercompensation, termed, respectively, the E-and A-phenomena. In L-D subjects the bias is greater than in control subjects, the E and E patterns different, and the intraindividual variance in the settings greater when they are positioned near the upright but similar when they are near the horizontal. With the subject lying on his side (fig. 2) not only is the A-phenomenon prominent but also, for some subjects, the line appears slowly to oscillate, a form of apparent motion.

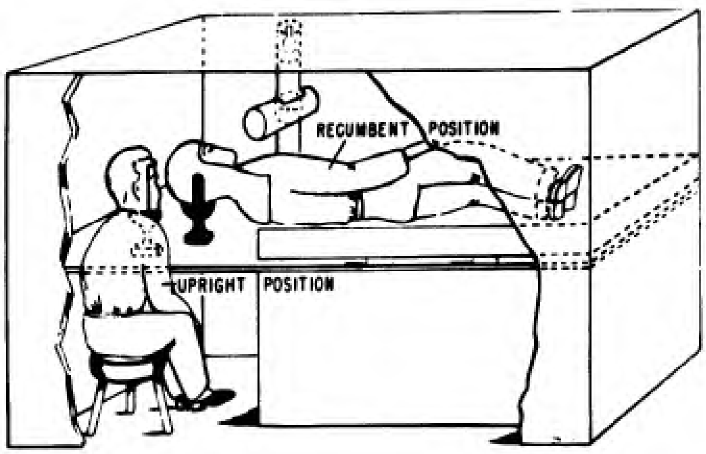


Figure 2.
Diagram of apparatus used to determine location of horizontal with subject in upright or recumbent position.

The settings of a Mercury astronaut, of a normal, and of an L-D subject are shown in figure 3. The estimations of the astronaut were typical for one other while those of the normal and the L-D subjects represented the modes of nine and ten subjects, respectively; both groups manifested great individual variance (7).

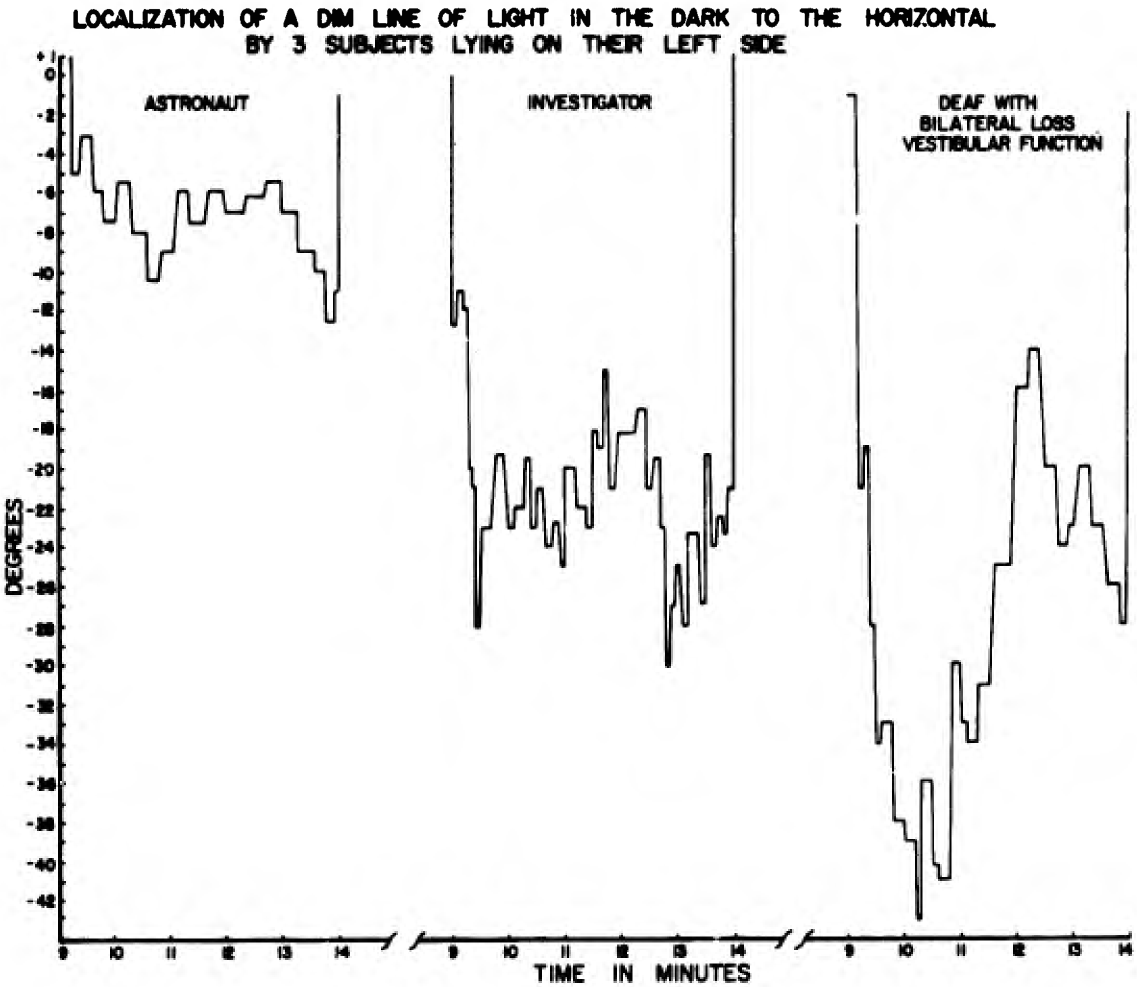


Figure 3. Continuous settings of a dim line of light in the dark to the horizontal by three subjects lying on their left side.

This bias as a function of increasing G load was measured on the centrifuge by controlling the deviation of a freely swinging platform from the gravitoinertial upright (8). In figure 4 the family of curves obtained from eight normal subjects shows the increase in bias with increasing magnitude of force, and in figure 5 are the findings under similar conditions in two subjects without vestibular function. Note that the change from the E-to A-phenomenon occurs with smaller angles of tilt in L-D subjects compared with normal subjects, the bias tends to be greater, and the variance in the settings far greater when near the upright.

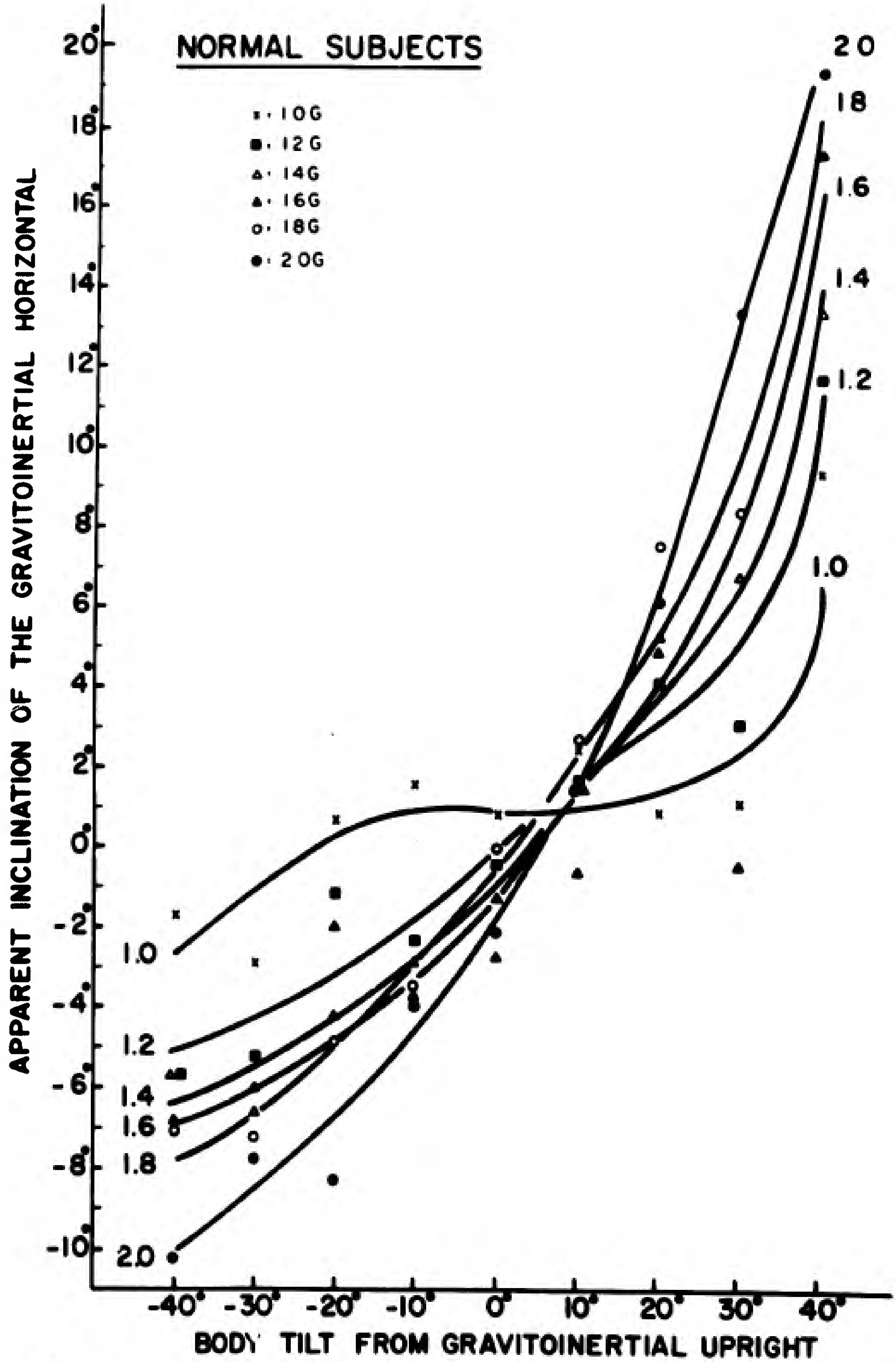


Figure 4. Change in E-phenomenon as a function of increasing G level in normal subjects.

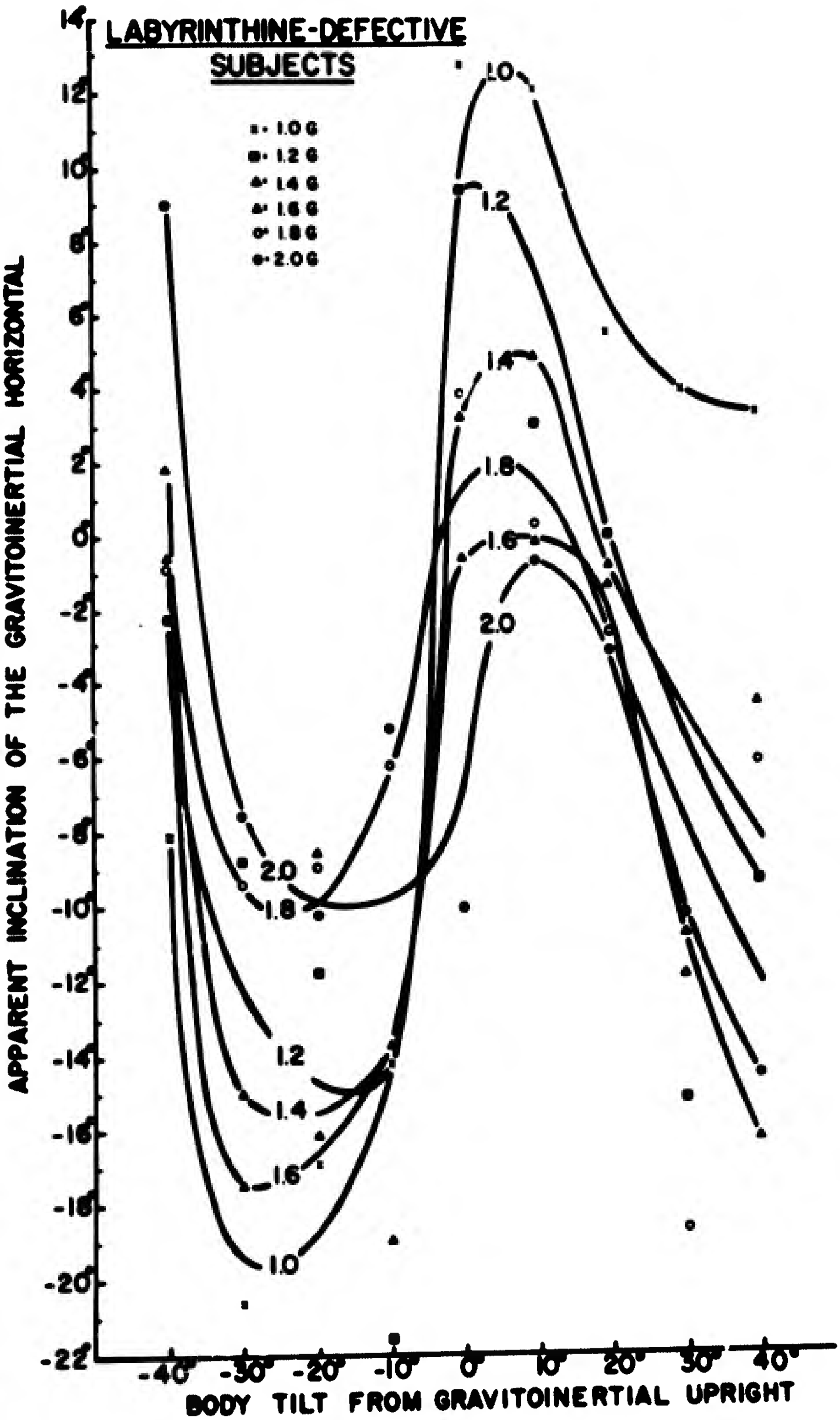
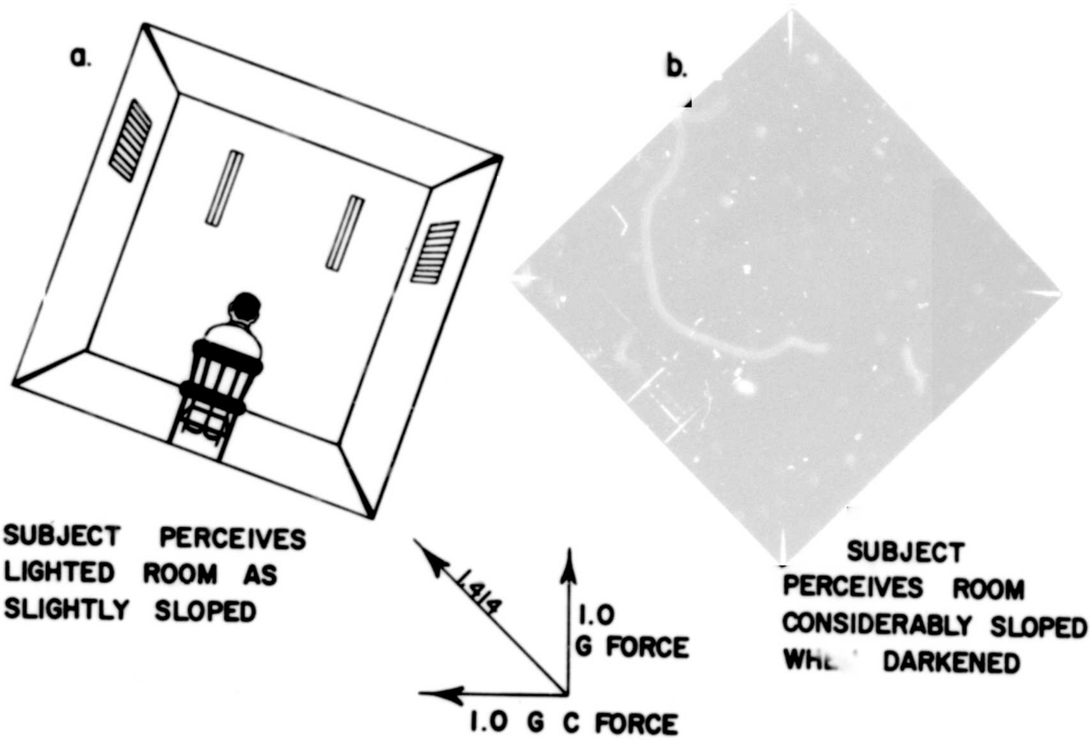


Figure 5. Change in E- and A-phenomena as a function of increasing G level in L-D subjects.

Certain Effects of Changing the Force Vector with Reference to the Subject on a Centrifuge

In figure 6 a subject is shown seated facing the direction of rotation while exposed to a centripetal force of 1.0 g unit. A naive subject with eyes closed feels as if he is tilted to the right in an upright room. A sophisticated subject is also aware of the tilt but will realize his position has not changed with reference to the room. Both subjects, if viewing a luminous line in the dark while suddenly subjected to a centripetal force of 1.0 g unit, would perceive the line as rotating slowly clockwise from the horizontal position through an arc usually greater than 45°. This is an illusory or apparent motion representing influences of cues from the force environment on visual spatial localization. If the subject is requested to set the line to the Earth horizontal, he rotates it counterclockwise from its original setting toward the gravitoinertial horizontal, usually overcompensating at this level of force; grasping a swivel rod with eyes closed, he also sets this near the gravitoinertial horizontal. The results are scored in terms of correspondence of the settings to the gravitoinertial horizontal.



DEPICTING THE ILLUSORY TILT OF A PHYSICALLY UPRIGHT ROOM PERCEIVED BY A SUBJECT ON A HUMAN CENTRIFUGE

Figure 6. Naive subject facing the direction of rotation fixating a luminous line in the dark regards himself as tilted in an upright room.

The effects of having the subject delay in opening his eyes are shown in figure 7. This demonstrates that visual perception is not essential for the

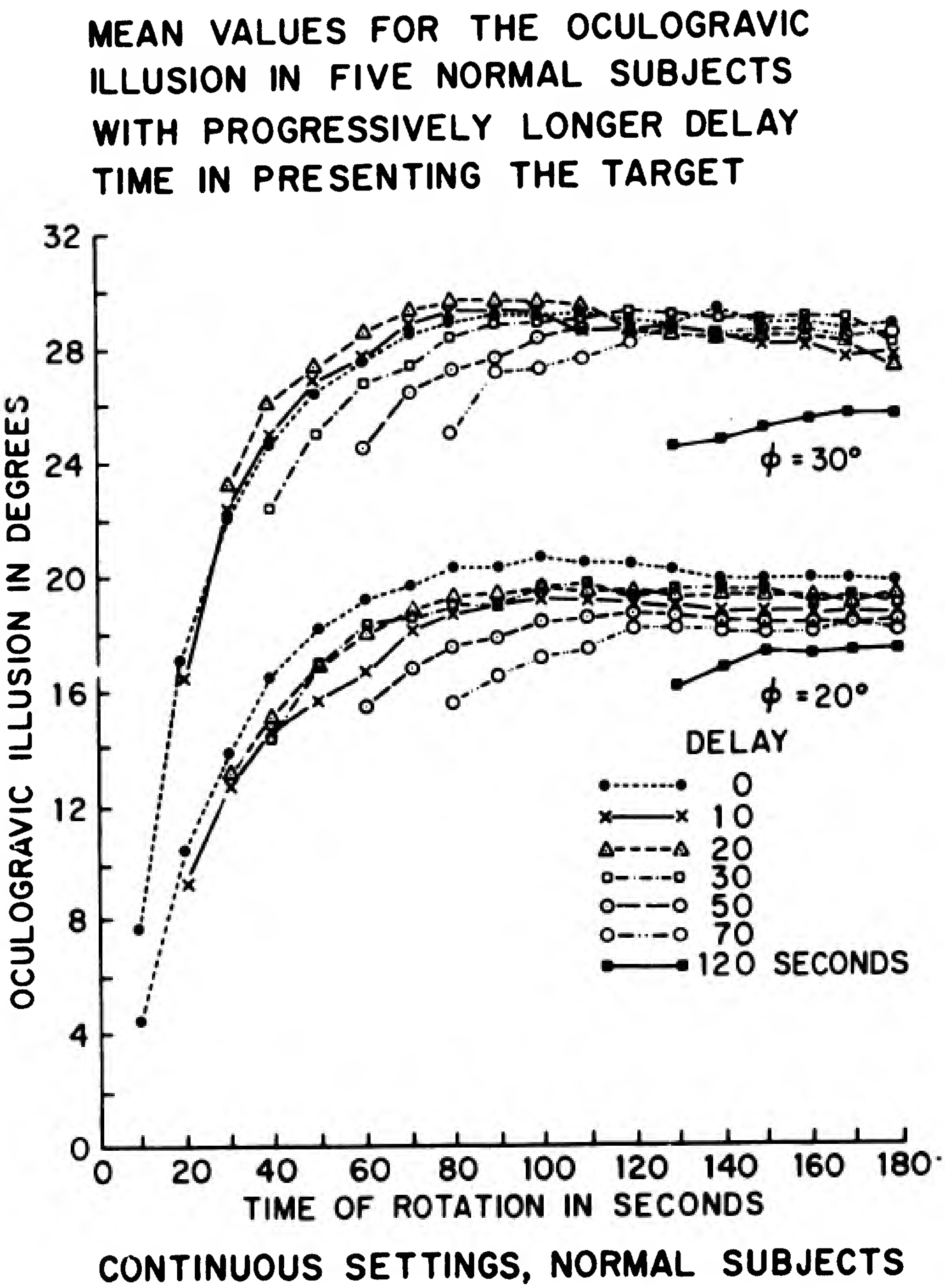
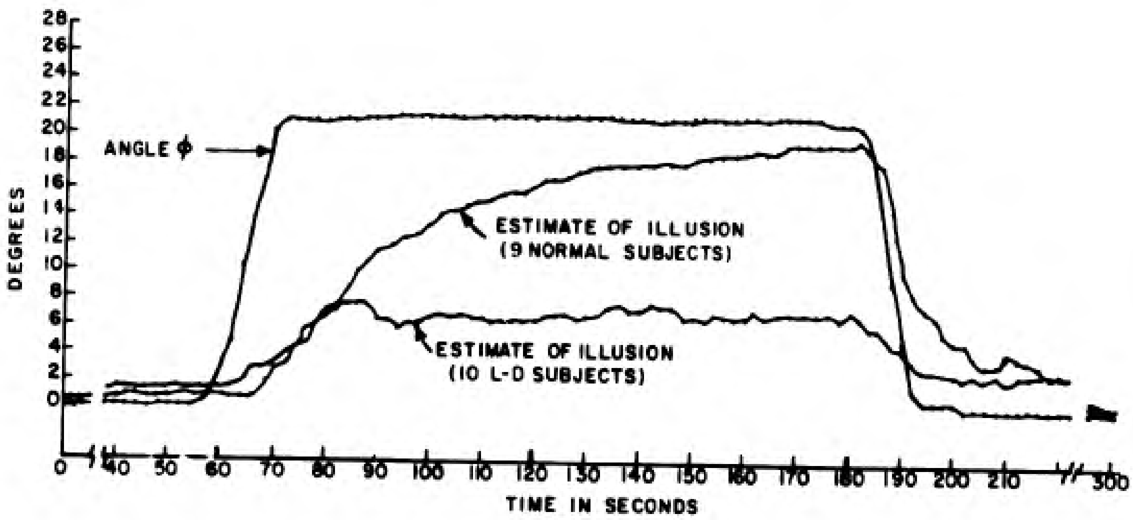


Figure 7. Mean values for the oculogravic illusion in five normal subjects with progressively longer delay time in presenting the target.

integrative action, although it tends to favor it slightly. Vision is essential only to display the effects of otolith and TPK receptor influences.

The settings by normal subjects and by persons with bilateral labyrinthine defects (18) who were requested to maintain the line at the horizontal continuously throughout an experimental trial in which they were subjected to a change in direction of gravitoinertial force of about 20^{o} are shown in figure 8. Note the delay or lag between the change in force vector and the apparent rotation of the line, indicating, presumably, the complex nature of this integrative mechanism (14).

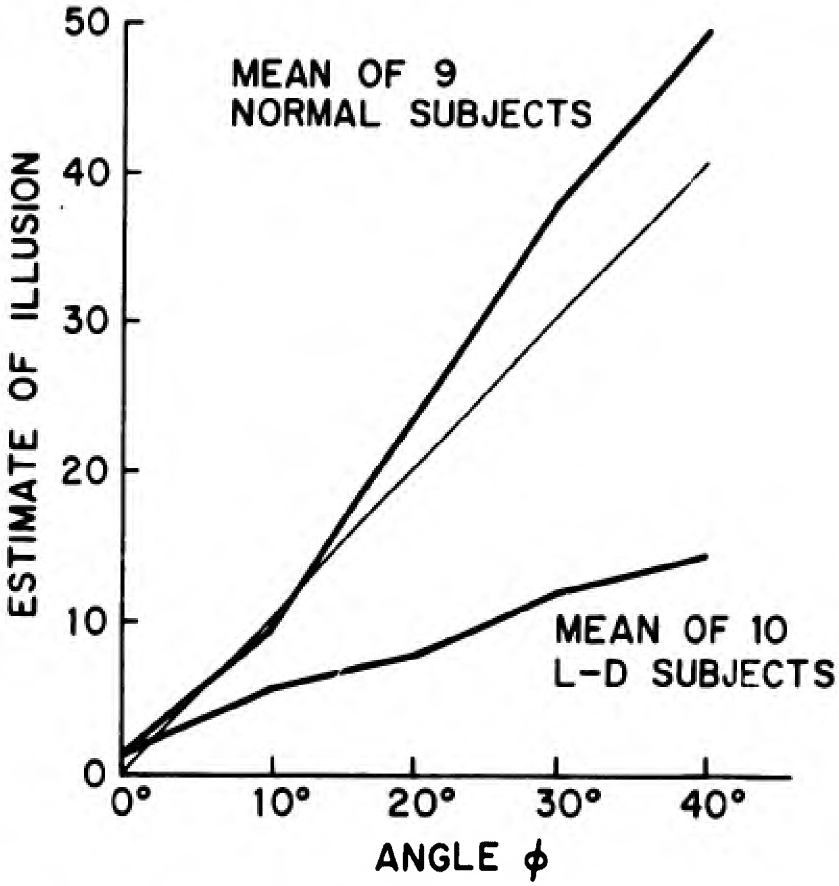


CHANGE IN SETTING OF STAR AS FUNCTION OF TIME COMPARED WITH CHANGE IN DIRECTION OF RESULTANT FORCE OF 20°. CURVES DEPICT MEAN VALUES

Figure 8.

Change in setting of star as function of time compared with change in direction of resultant force of 20^{o}. Curves depict mean values.

In figure 9 is shown a comparison between the settings of naive normal subjects and L-D subjects exposed to gravitoinertial forces corresponding to deviations from the gravitational vertical (angle phi) of 10^{o}, 20^{o}, 30^{o}, and 40^{o} (18). The variance was great in the ten L-D's but not in the normal subjects. The group differences were attributed to the presence and absence of vestibular, and more likely otolith, function.



ESTIMATES OF THE OCULOGRAVIC ILLUSION BY NORMAL AND L-D SUBJECTS. SINGLE SETTINGS OF STAR.

Figure 9. Estimates of the oculogravic illusion by normal and L-D subjects.

The L-D subjects over a period of time demonstrated "improvement" in the correspondence of their settings with the gravitoinertial horizontal. In addition to a possible practice effect, although the means of monitoring were not evident, the settings were greatly improved with prolonged exposure (17) and by encasing the subjects in Fiberglas molds. Some of these factors were evident in the experimental findings upon comparing the settings of the lun nous line between normal and L-D subjects when exposed to identical changes in the gravitoinertial upright, once when submerged to the neck, and again under atmospheric conditions (21). The use of Fiberglas molds tended to maximize the area of good contact with the centrifuge, but under water these contacts were minimal.

The curves in figure 10 summarize the findings. Three normal subjects manifested little difference in setting the line to the gravitoinertial horizontal when dry or wet. On the other hand, the L-D subjects manifested a great difference; submerged they set the line very close to the Earth horizontal which coincided closely with their internal horizontal coordinate; when dry, the settings were qualitatively similar but quantitatively about half the value indicated by the normal subjects. Put in other terms, the loss of cues from the TPK receptor organs had only a slight effect in the normal subjects inasmuch as the distance receptors in the otolith organs were functioning normally, the quantitatively slight decrease might be said to represent the contribution of the TPK receptors under dry conditions. When the L-D subjects were under dry conditions, they demonstrated that the TPK receptor organs provided good cues to the force environment despite the absence of distance receptors, and their settings were a measure of these cues alone; underwater, these cues were greatly diminished, and their influence on the visually perceived direction of space minimal.

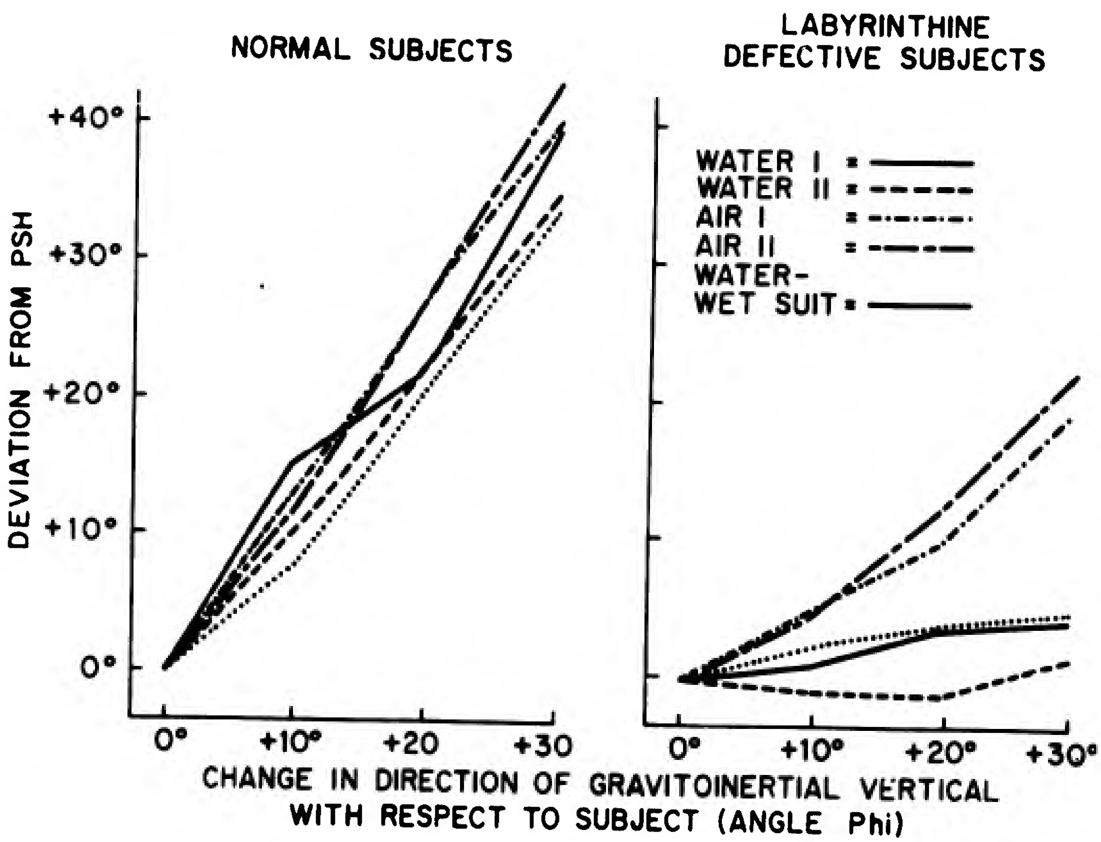


Figure 10. Subjects' estimates of horizontality under static conditions and after changes in direction of gravitoinertial horizontal, both under dry and wet conditions.

Comment

These findings indicate that, under the experimental conditions described, the best concordance between nonvisual and visual cues to the gravitational vertical is provided to normal persons when they are upright or nearly upright. Presumably this is the result of much practice with excellent monitoring possibilities. The same is true for persons who have lost labyrinthine (otolith) function, with the difference that accuracy is reduced and variance greater. With the subject tilted away from the gravitational upright the modulating influence of the otoliths is shown, becoming least evident with normal subjects lying on their side where their settings were similar to those made by L-D subjects. Tilting away from the gravitoinertial upright demonstrated an increase in the bias as a function of increasing g load, at least in normal subjects.

Tilting the gravitoinertial upright with respect to the subject demonstrated greater and more predictable influences in normal compared with L-D subjects. Under similar conditions but with the subjects submerged up to their neck, the settings are little affected in normal but greatly affected in L-D subjects.

Insofar as these findings may be extrapolated to weightlessness, it would appear that lifting the gravitational load from the otoliths would abolish their influence on the visually perceived direction of space provided that this did not result in any functional disturbance, especially of central origin. Lifting the g load from the TPK receptors responding to weight should reduce their influence also although these receptors would still respond to mechanical forces. If such agravic touch, pressure, and kinesthetic inputs were sufficient to influence the perceived direction of space, the unusual pattern of these inputs would be expected to result in great variance in the responses. It was with these considerations in mind that we suggested the experiment now to be described.

THE INFLIGHT EXPERIMENT

Procedure

The four astronauts aged 36 to 39 were in excellent general health. Particulars regarding their status throughout the entire GT V and VII flights are available in NASA publications.

The Force Environment. The likelihood that the high G loadings on launch and re-entry significantly affected the labyrinthine systems was extremely small in view of studies on man (23) and animals (24-26). The effects of the sudden transitions into and out of weightlessness, although appreciable from the behavioral standpoint, would almost certainly have disappeared before our experimental trials were made either aloft or postflight.

The possible effects of prolonged weightlessness should have been demonstrable, if present, in the case of the inflight experiment but were problemic in the case of the preflight and postflight experiments.

The poverty of cues from the several sensory systems under the experimental conditions aloft is summarized in table I. Inasmuch as the head was fixed in the GT VII, and held motionless in the GT V experiment, neither the canals nor otoliths was stimulated, leaving only agravic mechanical forces acting. The astronaut's direct contact with his environment stimulated touch and pressure receptors, and agravic stereognostic and kinesthetic cues were available.

PERCEPTION Extrapersonal Space (EPS)

<table>
<tr><td colspan="2" rowspan="2">SENSORY SYSTEMS</td><td colspan="2">NATURAL COND.</td><td colspan="2">WEIGHTLESS SPACECRAFT [3]</td></tr>
<tr><td colspan="2">PHYSIOL. STIMULUS</td><td>PHYS STIM.</td><td>CONTRIB. TO E.P.S.</td></tr>
<tr><td colspan="2">VISUAL</td><td colspan="2">VISUAL ENVIRONMENT</td><td>TARGET</td><td>INADEQUATE [4]</td></tr>
<tr><td rowspan="2">VESTIB-ULAR</td><td>CANAL.</td><td rowspan="2">GIFE [1]</td><td>ANGULAR [2]</td><td>I.F. $\gtrless$ THRESH.</td><td>? NIL</td></tr>
<tr><td>OTOLITH</td><td>LINEAR</td><td>I.F. $\gtrless$ THRESH</td><td>NIL</td></tr>
<tr><td rowspan="2">TACTILE</td><td>TOUCH</td><td rowspan="3">MECH. FORCES</td><td>GIFE (wt.)</td><td>AGRAVIC T</td><td rowspan="3">POSTURE
AGRAVIC STEREOGNOSIS: COUCH, ROD ETC.</td></tr>
<tr><td>PRESS.</td><td rowspan="2">OTHER THAN GIFE (wt.)[5]</td><td>AGRAVIC P</td></tr>
<tr><td colspan="2">KINESTHETIC</td><td>AGRAVIC Jt C&D</td></tr>
<tr><td colspan="2">AUDITORY</td><td colspan="2">SOUND PRESSURE</td><td>AMBIENT</td><td>? INADEQUATE</td></tr>
</table>

1. Gravitoinertial force environment. 2. ? Linear forces under special circumstances
3. Astronaut secured in couch; fixates line in dark. 4. Visual memory a factor.
5. Joint Capsule Compression & Displacement

Table I. Sensory systems involved in the perception of extrapersonal space in natural habitat and under weightless conditions.

Equipment. The goggle device used represented a modification and miniaturization of a target-device previously described (22). It consisted essentially of a collimated line of light in an otherwise dark field. This "line" could be rotated about its center by means of a knurled knob. A digital readout of "line" position was easily seen and was accurate within $\pm$ 0.25°.

The goggle device was monocular and fabricated in duplicate so that the astronaut in the lefthand seat used the right eye with the readout visible to the astronaut on his right, and vice versa. The readout was adjusted for each flight so that the instrument's zero was represented by a value other than zero or 180° to eliminate or reduce the possible influence of knowledge of the settings upon subsequent judgments. Horizontally with respect to the apparatus was 61.3° for the astronaut on the left and 98.8° for the astronaut on the right in the Gemini V, and 76.6° and 101.6° for the left and right Gemini VII astronauts, respectively.

It was necessary to incorporate the device with the Vision Tester which was used in another experiment. The device was held at the proper position, with the lines of sight coincident with the optic axes of the instrument, by means of a bite-board individually fitted to the subject. A head brace, as shown in figure 11, was provided to connect the bite-board of the instrument to the map board slot of the spacecraft and thereby eliminate any rolling movement or displacement of the zero target setting for horizontal with respect to the spacecraft; a limited amount of freedom around its pitch axis was permitted by the folding configuration of the brace as designed for storage purposes. This method of fixing the Vision Tester to the spacecraft was not used in the GT V mission, but a similar positioning of the instrument was achieved by having the subject sit erect in his seat with his head aligned with the head rest.

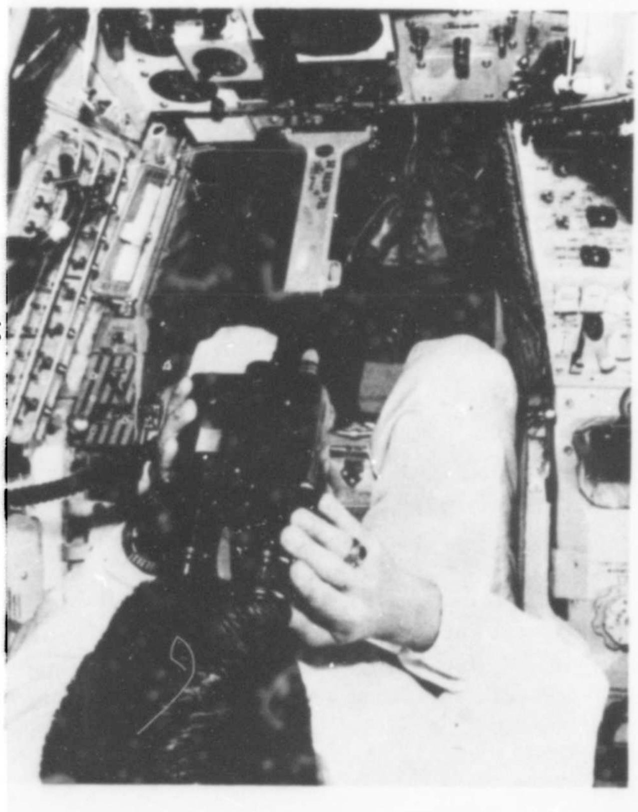


Figure 11.

Photograph illustrating the vision tester and its use within the spacecraft. Note head brace connecting the biteboard of the Vision Tester to the instrument panel.

Method. The preflight testing of the Gemini V crew was accomplished sixteen days prior to their flight. The Gemini VII crew were similarly tested on two different occasions, nineteen and six weeks prior to their flight.

Preflight and postflight, the measurements were made with the subject rigidly secured in the upright position. The experimenter offset the line clockwise or counterclockwise in variable amounts, then the subject set it to what he regarded as horizontal. This was repeated five or more times.

The method inflight was as follows: Immediately after completion of the visual acuity experiment, and without removing the instrument from his face, the subject prepared for making his judgments of horizontality by occluding the left eyepiece and turning on the luminous target before the opposite eye. The target appeared against a completely dark background. The observer astronaut offset the line, and the subject's task was to set it parallel to an element of the spacecraft panel which was horizontal with respect to himself. When satisfied with the setting, he closed his eyes and removed his hand from the knurled knob. This served as a signal to the observer to record the setting and offset the target. Upon completion of a test session by the first subject, the Vision Tester was handed to the other pilot, and the same sequence was carried out after completion of the visual acuity test.

This procedure was scheduled to be repeated five times during each of the daily test sessions. In the interest of conserving vital spacecraft power during the early part of the Gemini V flight, no settings were made; for the same reason during revolutions 24, 39, and 54 only one judgment of horizontality was made by each subject.

Results

None of the astronauts expressed any difficulty in carrying out the experimental task either under gravitational or weightless conditions. On the contrary, all regarded the task as an easy one, and this was reflected by the fact that the settings were made quickly. All stated that they clearly had in mind the spacecraft reference in making the settings.

In figure 12 are shown the values representing the settings of the two GT V astronauts. The striking feature is the difference in estimations of horizontality by the pilot A obtained inflight as compared with preflight and postflight. Postflight variance for this pilot was significantly greater than the variances for each of the inflight measurement groups and was also significantly greater than preflight variance. The estimates of pilot B revealed no systematic differences except that the postflight variance was greater than was the preflight variance.

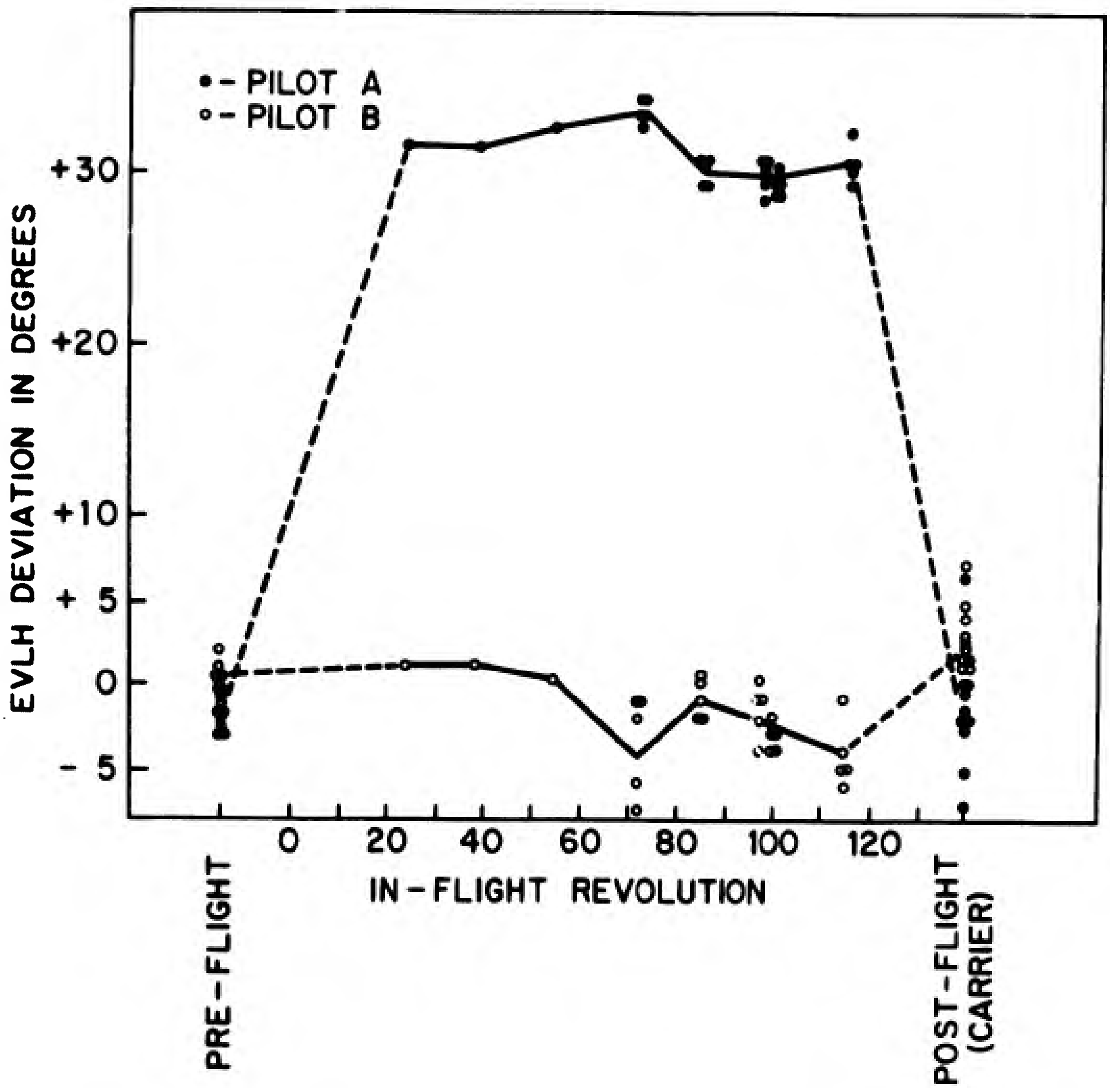


Figure 12. Settings of luminous line in darkness made by crew of Gemini V preflight and postflight (earth horizontal) and inflight (horizontal of element in spacecraft).

The findings obtained on the GT VII astronauts are shown in figure 13. For pilot C there is no systematic variance differences among the preflight, postflight and inflight measurements. For pilot D variance of preflight measurements was significantly greater than variances for all other sets of measurements, including postflight. Postflight variance was significantly greater for this pilot than the variances for nine of the fourteen sets of measurements obtained during orbital flight.

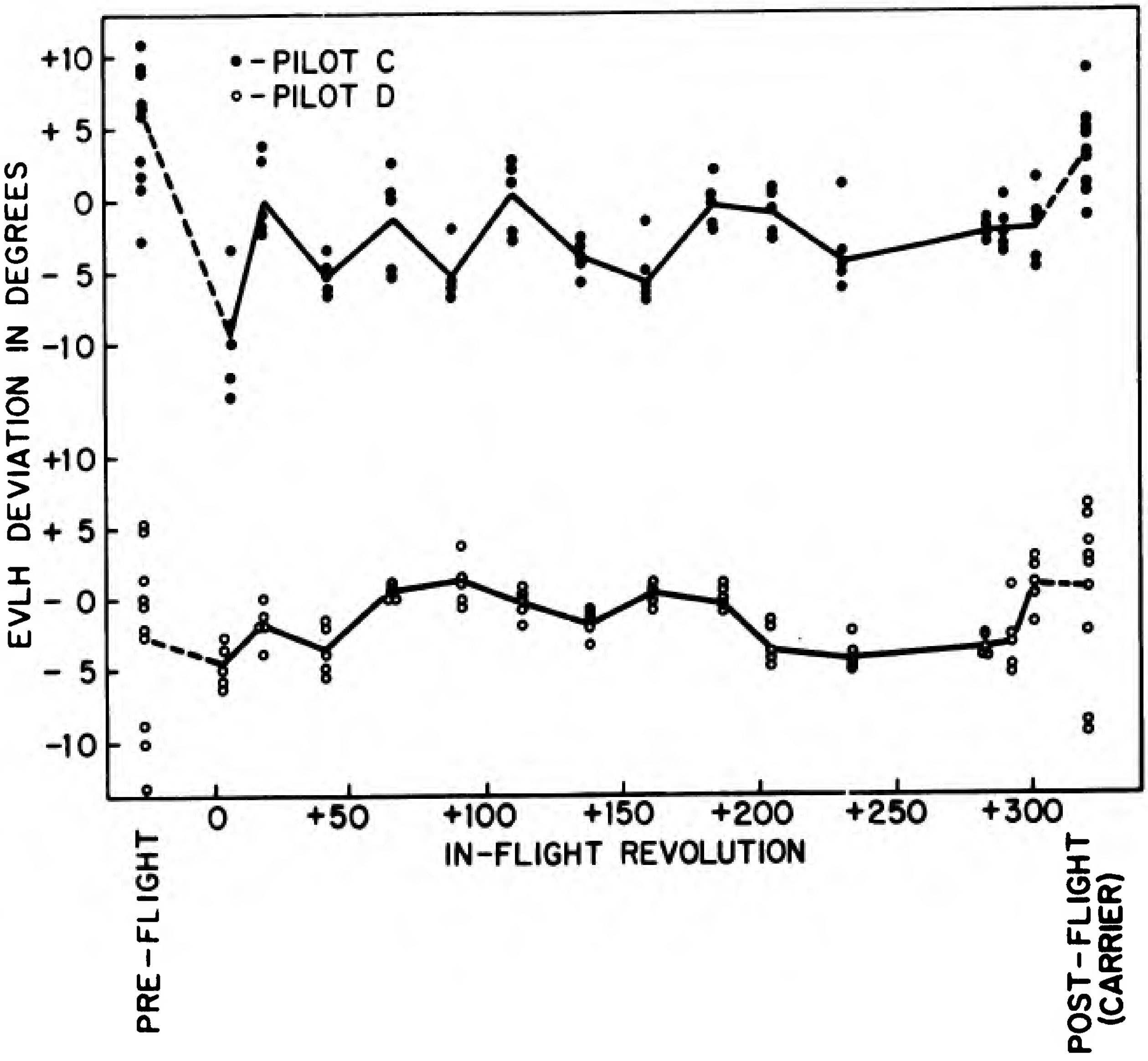


Figure 13. Settings of luminous line in darkness made by crew of Gemini VII preflight and postflight (earth horizontal) and inflight (horizontal of element in spacecraft).

Discussion

In discussing the results, it has been kept in mind that the GT V and GT VII experiments were conducted under field conditions. The astronauts were usually under time-stress and sometimes under load-stress as well. Moreover, the constraints were such that only a limited number of experimental trials were feasible. Thus it is assumed that, with long practice and under ideal laboratory conditions, their performance would, if anything, be improved. This was considered when drawing comparisons between earlier ground-based experiments and those in GT V and GT VII flights.

The preflight settings were made under external conditions which provided maximal concordance of cues between the visual and gravitational upright, namely, subject upright with head and body firmly fixed on a stable platform. The postflight settings aboard an aircraft carrier at sea were made under excellent weather conditions, and previous experience had demonstrated that the slightly unstable platform would have very little effect on the measurements obtained. The postflight intratrial variance compared with that preflight was greater for both astronauts in GT V, but in GT VII the variance was the same for one astronaut and smaller for the other. Both the variance and accuracy of the settings were in the expected range, taking all factors into account.

The finding that the intratest variance of inflight settings never exceeded and often was smaller than the preflight and postflight settings proves that during the test periods, influences sufficient to produce a bias were either constant or, more likely, minimal. This conclusion is supported by the fact that the intertrial variance also was small, smaller than would be expected under terrestrial but otherwise comparable conditions with the possible exception of pilot B in GT V where it was not feasible to use a "biting" board. These small variances manifested aloft have important implications both with regard to the inflight and ground-based experiments.

In weightlessness the lifting of the gravitational stimulus to the otoliths did not result in any detectable disturbance of central nervous system integrative processes. Moreover the astronauts' settings did not reflect in the increased variance manifested by persons with loss of otolith function under terrestrial conditions.

Stated in another way, the loss of sensory information from the otolith organs and other receptor organs stimulated by gravity following transition into weightlessness did not appear to influence visual mechanisms concerned with the perceived direction of space. Indeed, it remains to be demonstrated if agravic sensory inputs impressed on the astronaut are influential in this regard. If this conclusion is correct, that the influence of agravic cues on visually perceived direction in space is small, then this influence should be even less discernable when adequate visual cues are present. Thus, in the interaction between visual and nonvisual cues under weightlessness conditions, nonvisual cues would have less influences than under terrestrial conditions.

The small variances manifested in weightlessness contrasted strongly with those observed in subjects under many different circumstances in the laboratory, testifying to the fact that these variances were the positive results of sensory inputs. This applies to L-D subjects under all experimental situations, except, possibly, when they are submerged in water. It applies to normal subjects probably under all circumstances except possibly when the subject is near the gravitational upright.

With regard to the accuracy of the settings in terms of the external reference, the performance inflight was excellent except for that of pilot A; his settings differed from those of the other three in that they were approximately 30 degrees clockwise with respect to the external horizontal reference. The question arises whether these settings represented a systematic procedural error, a bias, or the use of a symbolic cue, thus "bypassing" the use of posture or personal space. The same goggle device was used postflight; hence, a mechanical error was ruled out. Inasmuch as the task involved setting the line to a horizontal cabin reference coinciding with the astronaut's body horizontal, the difference would be small if the body reference was chosen. Our experience is so limited that we cannot even determine whether a bias of this magnitude based on nonvisual sensory inputs under agravic conditions is possible. The settings do not seem to have the typical characteristics of biases manifested under terrestrial conditions, but this does not rule out the possibility. This can of course be put to test whenever it becomes feasible in weightlessness to manipulate sensory cues and investigate their effects on spatial localization.

An attempt will be made to consider the inflight findings in their entirety with regard to the structuring of personal and extrapersonal space (27).

If it is assumed that the astronauts used the external reference in making the settings, their consistency in doing this as well as their accuracy, with the one exception noted above, suggests that agravic sensory inputs provided by contact with their environment were sufficient not only to orient them in their supporting couch but also to provide them a stable anchorage on which to base their estimates of an external reference regarded as separate from themselves and wholly dependent on visual memory. Whether their meager sensory input would serve as adequate primitive sense experience out of which to construct a concept of physical space (28) is unknown, but, once this concept has been established, a greatly reduced number of cues must suffice. From a practical standpoint these findings suggest that, in darkness, the astronaut may have not only an accurate awareness of external spatial coordinates based on meager postural cues but also may be less susceptible to bias errors in the absence of a structu visual field than under terrestrial conditions.

OTOLITH FUNCTION AS DETERMINED BY OCULAR COUNTERROLLING

Direct testing of the function of the otolith organs, analogous to tests of vision or hearing, is not performed routinely because of the great difficulties involved. The difficulties include manipulating the physiological stimulus and lack of a specific, accurate indicator. Among the methods used, estimation of the oculogravic illusion with the subject submerged to reduce nonotolith sensory inputs and ocular counterrolling with head fixed to reduce influences from "cervical reflexes" are in all likelihood the most accurate. Only the latter is practical, and the most accurate measurements of the ocular counterrolling or ocular torsions have been made using "landmarks" in the fundus (29) or artificial (30) or natural (31) external markings.

In figure 14 is shown the change in position of the eye as a function of lateral tilt from the upright; the measurements were made from photographs of the face obtained with the subject in the upright and tilt positions (32). The reliability of the method was established by using normal and L-D subjects. When normal subjects were exposed to changes in direction and magnitude of force on a human centrifuge, the amount of the roll increased and was found to be a function of the laterally acting (shearing) force. When L-D subjects were exposed to identical gravitoinertial forces, there was no increase in ocular torsion above control values which would have been expected if nonotolith sensory mechanisms were acting.

a. SUBJECT UPRIGHT

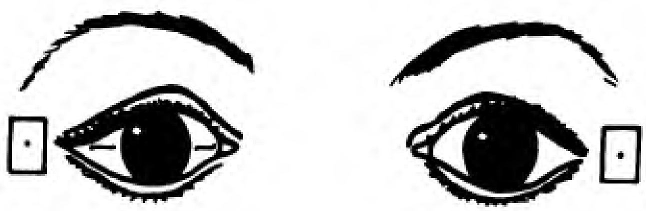


Figure 14a. Showing sutures in conjunctiva and markers at outer canthi;

b. SUBJECT TILTED RIGHT 75°

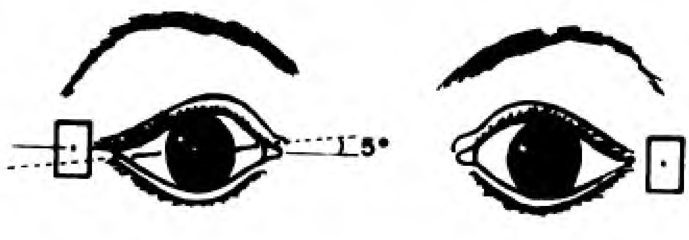


Figure 14b. Demonstrating counterroll of eye with lateral tilt.

It would have been of interest to determine any changes in ocular counterrolling as a function of exposure aloft in the Gemini flight, but for obvious reasons this was out of the question. Measurements were made, however, preflight and postflight.

APPARATUS AND PROCEDURE

The apparatus used for measuring ocular counterrolling is essentially a tilt device on which a camera system is mounted (fig. 15). The main supporting part of this device acts as a carrier for the stretcher-like section. This section contains Velcro straps and a saddle mount to secure the subject in a standing position within the device and can be rotated laterally to $\pm 90^{\circ}$ about the optic axis of the camera system and, when the subject is properly adjusted, also about the visual axis of his right or left eye. A custom fitted bite-board was also used in counterrolling testing to fix the subject's head with respect to the camera recording system.

COUNTERROLLING TEST DEVICE

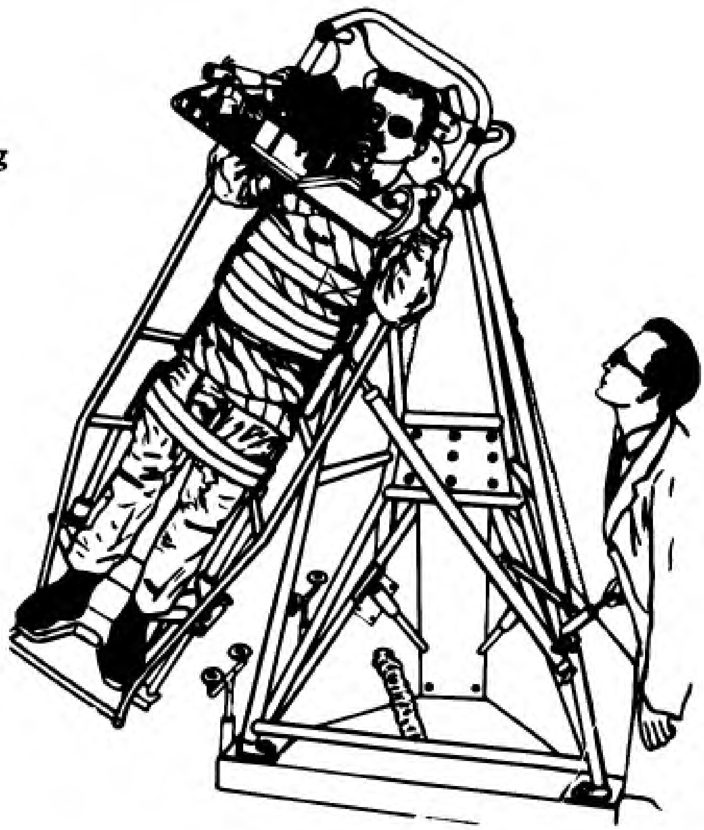


Figure 15. Counterrolling test device.

The camera system used to photograph the natural iris landmarks includes a motor driven 35-mm camera with bellows extension and an electronic flash unit. A console located at the base of the tilt device contains a bank of power packs which supply the electronic flash, a timer control mechanism, and controls for the flashing, roundfixation light which surrounds the camera lens. A triaxial accelerometer unit which senses and relays signals of linear acceleration to a Consolidated Electrodynamics Corporation galvanometer recorder was mounted to the head portion of the device for shipboard use.

A test cubicle 12 feet x 16 feet x 10 feet insulated against outside sounds, light, and temperature was constructed for carrying out the postflight tests of spatial localization and counterrolling onboard the recovery aircraft carrier.

Immediately prior to the preflight and postflight testing one drop of 1% pilocarpine hydrochloride ophthalmic solution was instilled in the subject's eye opposite to the one he used for making visual orientation judgments. These judgments were made first. Then the subject remained in the upright position in the tilt device, the Vision Tester and its bite-board were removed, and preparations were made for photographically recording the eye position associated with a given position of body tilt. The counterrolling bite-board was inserted in the subject's mouth, and the position of his appropriate eye was adjusted so that it coincided with the optic axis of the camera system when he fixated the center of the flashing red ring of light. Six photographic recordings were made at this position; then the subject was slowly tilted in his lateral plane to each of four other positions ($\pm 25^{\circ}$, $\pm 50^{\circ}$), and the same photographic procedure was repeated.

The accelerometer system was used postflight during all testing to continuously record motions of the recovery ship around its roll, pitch and yaw axes inasmuch as the values were small and plus and minus values tended to cancel out, they were considered to have very little or no significance.

Postflight examinations were begun for pilots A, B, C, D approximately six, five, six, four and one-half hours, respectively, following recovery of the pilots at sea.

RESULTS

The counterrolling measurements are summarized in figures 16 and 17. It should be noted that it was necessary to reject a number of photographs obtained in the GT V experiment for technical reasons which accounts for the incomplete curves. The values for pilots A and B were in the lower range of those from a random group of 100 normal persons while the values for pilots C and D were in the mid-range. No significant differences were found between the preflight and postflight values of any of the four astronauts; the differences manifested were no greater than might be expected.

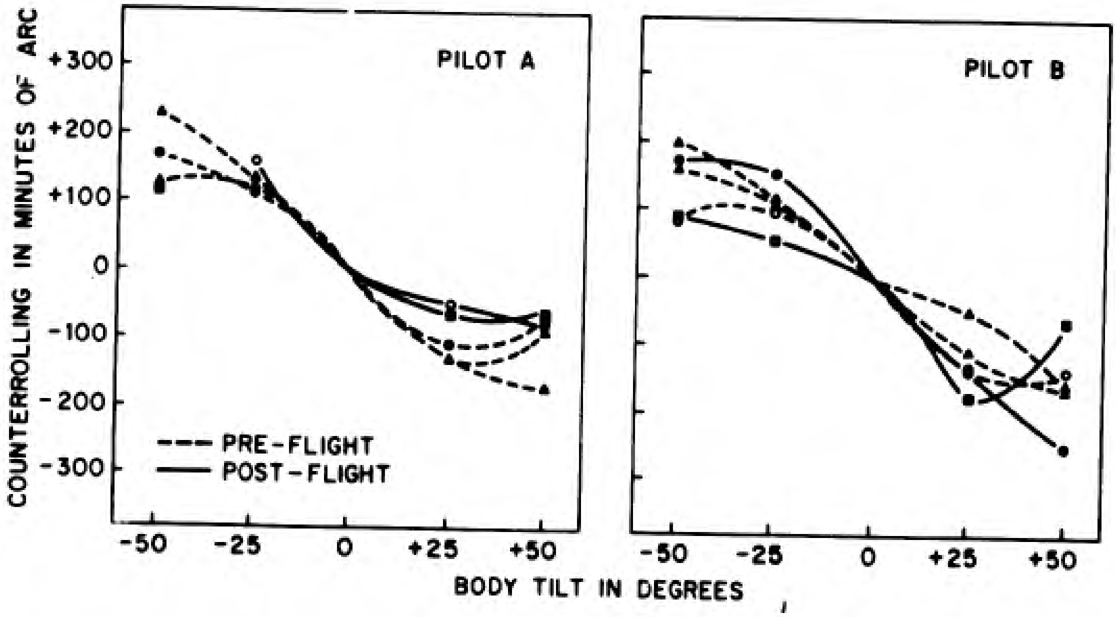


Figure 16. Ocular counterrolling measurements of the Gemini V crew obtained preflight and postflight.

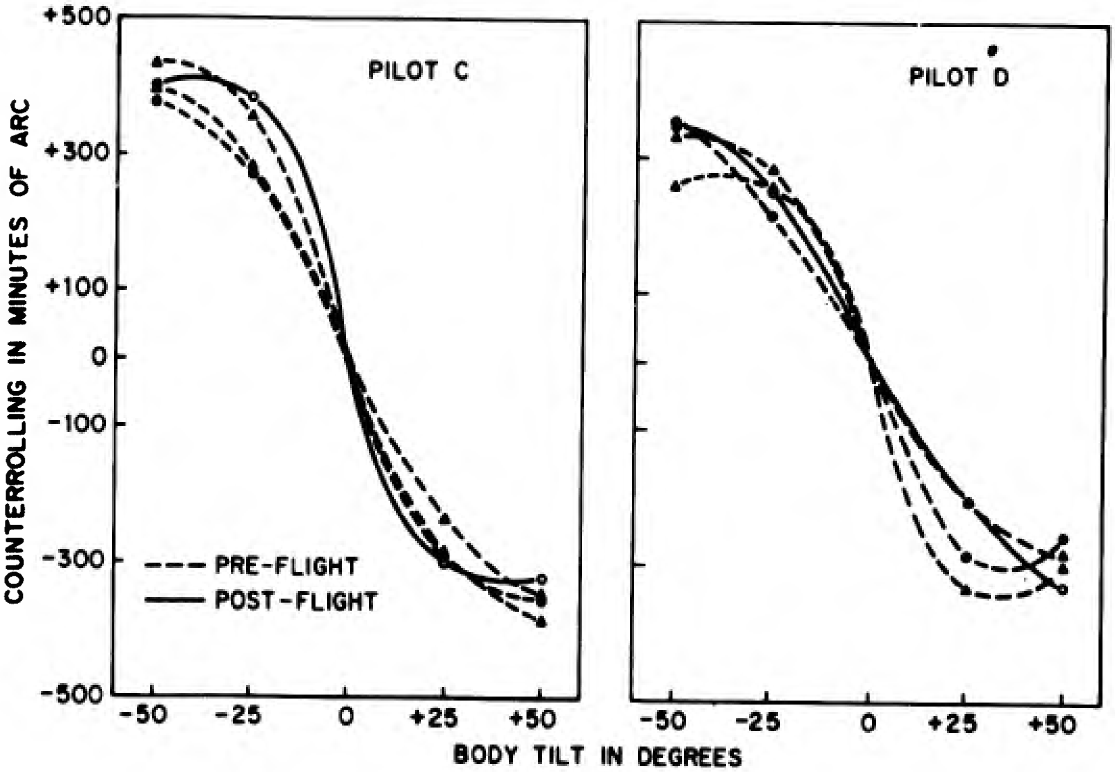


Figure 17. Ocular counterrolling measurements of the Gemini VII crew obtained preflight and postflight.

DISCUSSION

The failure to find any significant changes in the preflight and postflight counterrolling values was not surprising. The findings suggest that either no measurable changes in counterrolling response occurred as a result of prolonged exposures in a weightlessness spacecraft or, if they did, they did not persist for periods of four and one-half to six hours. One feature worthy of comment is the relatively small counterrolling values in pilots A and B. Inquiry did not disclose any common factor associated with the flight which might account for these low values.

SUMMARY AND CONCLUSIONS

Two experiments were carried out involving the otolith apparatus on the astronauts who were exposed to weightlessness for periods of eight days in GT V and fourteen days in GT VII.

One experiment dealt with nonvisual influences which might affect egocentric visual localization of the horizontal. The astronauts' task was to set a dim line of light, in an otherwise dark field, to an external horizontal reference; in weightlessness this reference was the recollection of an element of the spacecraft horizontal with respect to their seat; preflight and postflight it was their recollection of things horizontal with reference to the Earth while they were in a device upright with respect to gravity.

Previous studies using a similar procedure and involving normal subjects under terrestrial conditions had demonstrated that a high degree of accuracy in making the settings was possible only when subjects were at or near the gravitational upright. With increasing tilt away from the upright in the frontal plane, variance in the settings increased and the characteristic E and A bias appeared, culminating in gross inaccuracies when the subjects were lying on their side. Moreover, subjects with loss of vestibular (otolith) function manifested greater variance and greater inaccuracy in their settings with reference to the external spatial coordinates than did normal subjects. The implications were that both otolith and nonotolith sensory mechanisms influenced the visually perceived direction of space and that accuracy in making the settings was influenced unfavorably when persons either lost the function of the otoliths or were tilted away from the gravitational upright, or both.

Although the number of settings made by the astronauts were few, yet the results were fairly clear-cut and were discussed in terms of the accuracy with regard to the external reference and their intratrial and intertrial variance. Comparisons were made between the astronauts' inflight and preflight and postflight settings and between the settings made by the astronauts and by subjects in earlier experiments.

The outstanding inflight findings were the small intratest and intertest variances manifested by all of the astronauts and the high degree of accuracy in the settings made by three of the four astronauts. These results suggest that lifting the gravitational load from the otolith organs did not result in any disturbance of central nervous system integrative processes which might have influenced the visually perceived direction of space. Moreover, the combination of removal of otolith modulating effects on tactile and kinesthetic sensory systems and the unusual pattern of agravic pressure and kinesthetic sensory inputs, factors which might be expected to increase variances in settings, did not do so. Whether agravic sensory information of this nature can influence, in a positive manner, the setting of a dim line of light in darkness remains to be demonstrated.

From the theoretical point of view these findings imply that the E and A phenomena and the oculogravic illusion are the positive results of sensory inputs mainly of otolith and tactile and kinesthetic origin, responding, respectively, to gravitoinertial accelerations and weight. Moreover, in these experiments there was no evidence that lifting the normal stimulus to the otolith organs and to receptor organs responding to weight led to symptoms characteristic of a disturbance in central nervous system integrative patterns.

From a practical standpoint these findings suggest that, in darkness, the astronaut may have not only an accurate awareness of external spatial coordinates based on meager postural cues but also may be less susceptible to nonvisual influences than under terrestrial conditions. A single exception to the "rule" requires further investigation.

The second experiment consisted in the preflight and postflight measurement of ocular counterrolling which depends, for the greater part at least, on a reflex response having its genesis in the otolith apparatus. No significant differences between preflight and postflight responses were demonstrated.

ACKNOWLEDGMENTS

The success of these experiments was in large part dependent upon the subjects involved, astronauts Frank Borman, Charles Conrad, Gordon Cooper, and James Lovell. These men deserve special commendation for their efforts in gathering research data under the stresses and strains incidental to spaceflights. The help of many persons both at the Manned Spacecraft Center and the Naval Aerospace Medical Institute not listed as authors is appreciated. The financial assistance provided by the Office of Advanced Research and Technology made possible many of the background studies and that provided by Space Medicine, Manned Spacecraft Center, the spaceflight experiments.

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Human Tolerance of Prolonged Exposure to a Rotating Environment

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THE HUMAN TOLERANCE OF PROLONGED EXPOSURE TO A ROTATING ENVIRONMENT

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The purpose of this paper is to review the relatively recent research seeking to define the human tolerance to prolonged constant angular velocities of a magnitude that might be used in a rotating spacecraft.

Whether the astronaut can live and function for months or years in a weightless state remains to be seen. Some problems associated with prolonged weightlessness such as circulatory deconditioning, bone demineralization, wasting of muscle mass and diminished stimulation of the otolith apparatus, may require separate, individual solutions involving a significant portion of the astronauts' time and a certain amount of apparatus. An alternative, however, would be to provide the astronauts with a prolonged acceleration which would serve as an artificial gravity. It is impractical to use a prolonged linear acceleration due to the excessive terminal velocity. The logical choice is a centripetal acceleration and several engineers have addressed themselves to the design criteria for spacecraft which would rotate (1-3). Until rather recently information concerning the human tolerance to prolonged rotation was scarce, and to begin design of a rotating spacecraft without more information would be hazardous. To obtain this information it was necessary to conduct a group of experiments utilizing rotating environments. An early experiment involved two days exposure at various angular velocities to outline the general nature of man's capability to adapt to a rotating environment. Later experiments for longer exposure periods established 1.0 rpm as an angular velocity to which almost any subject could adapt, 3.0 rpm as an angular velocity to which normal subjects could adapt without difficulty, and 10.0 rpm as an angular velocity to which even highly selected subjects have difficulty adapting. In spite of certain significant theoretical differences in the stimulus environment between the erect subject on the earth-based rotating platform and the astronauts in the plane of rotation of a rotating spacecraft, there is some evidence that the adaptation in subjects erect and in the plane of rotation is similar in many respects at least on an earth-based rotating platform. The practical nature of these experiments is considerable in that to postulate 2.0 rpm as a maximum angular velocity, it would require almost a 750-foot radius to generate 1.0 G at the periphery. However, to assume 8.0 rpm as a maximum angular velocity it would require only about a 50-foot radius to generate the same 1.0 G at the periphery.

In 1959 there was limited information in the literature concerning human tolerance to prolonged rotation. With the exception of some early animal experiments using white rats (4-6), and a report from Johnsville in which one human subject was rotated for 24 hours at 2.0 G (7), specific study of this problem had not been undertaken. In view of the likelihood that rotation might be employed to generate an artificial gravity in manned orbiting spacecraft, the need for information about the human response to prolonged, continuous rotation became a matter of pressing practical concern. In response to this need, the then U. S. Naval School of Aviation Medicine started a long-range research program to seek information in this area.

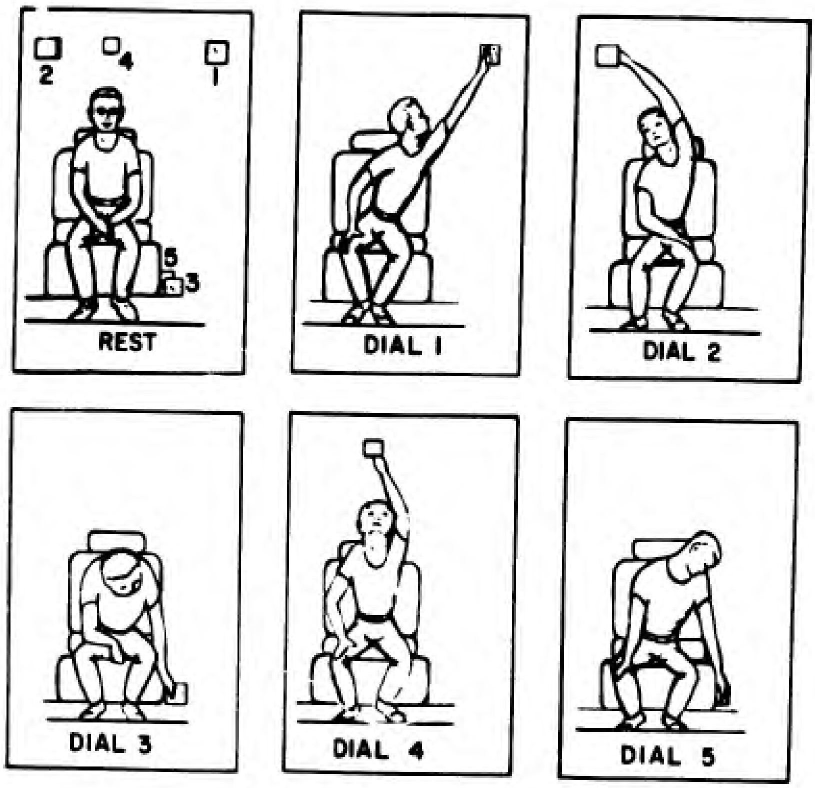
An early investigation consisted of exposing six healthy, young males to two days of continuous rotation at constant angular velocities of 1.71, 2.22, 3.82, 5.44 and 10.0 revolutions per minute (8).

The apparatus employed in this experiment is known as the "Pensacola Slow Rotation Room" (SRR). This device (9) consists of a 46-ton flywheel upon which is mounted an essentially circular, light-tight room that is fifteen feet in diameter with a ceiling height of seven feet. The device is powered by an industrial natural gas burning engine. The drive train consists of two cascade-mounted five-speed transmissions. The clutch and brake are air-powered while the throttle is hydraulically controlled. Long-term angular velocity control is $\pm$ 2.5%. Sliprings supply electrical power and transmit data to the control room where recording facilities are located. The SRR contains a refrigerator, sink, cooking facilities, toilet, gear storage and sleeping space for five people.

The subjects consisted of six volunteer healthy males ranging in age from 19 to 44 years. The 44-year-old subject had a long history of recurrent inner ear infections and upon whom bilateral mastoidectomy had been previously performed. He was clinically deaf and failed to show any evidence of semicircular canal function in that he failed to perceive the oculogyral illusion and failed to demonstrate nystagmus when exposed to high angular accelerations or to caloric stimulation with ice water. This subject was felt to have minimal or absent otolith function in that one year before the experiment he failed to demonstrate ocular counterrolling and at the time of the present experiment he did not perceive the oculogravic illusion (10, 11). This individual served as a control subject in each of the rotational experiments. Four of the remaining five subjects were felt to have normal semicircular canal function on the basis of caloric stimulation and perception of the oculogyral illusion. The fifth subject had a somewhat hypoactive caloric response bilaterally. All five normal subjects had an absent or minimal history of motion sickness and all of them demonstrated less than normal susceptibility to motion devices.

The subjects were given a variety of tasks, some of which were designed to induce head movement and, therefore, stimulate the canals, and other tests which might measure any deterioration of performance due to the canal stimulation. Those daily tasks designed to induce head or body movements included the demonstration of the oculogyral illusion, a body sway test which is a modified Romberg test, a heel-to-toe walking test, a ball-throwing exercise, a dart-throwing exercise and the Dial Test (12). The Dial Test (fig. 1) consists of locating five dials about a seated subject such that he must turn to his left and back to adjust the first dial, lean forward and turn to his right for the second dial, lean down and to the left for the third dial, straight backward for the fourth dial and to his left and down for the fifth dial. The dials are always set in the above order and the actual values to be set by the subject are given to him from a conventional magnetic tape recorder. In this experiment the individual settings were spaced four seconds apart for each sequence of five settings. Individual sequences were separated by a sixty-second rest period. Ten sequences (50 settings) were performed daily in two groups of five each. Those tasks not involving head or body movement included routine electrocardiography, blood pressure determinations, a card-sorting task, opening ten combination locks as rapidly as possible, an estimate of hand steadiness using a stylus in various sized holes (Whipple Steadiness Test), the use of a hand dynamometer and a series of arithmetic computations. Each forty-eight hour rotational test period was preceded by a prerotational static period to familiarize the subject with the procedures and collect control data. A similiar period followed the cessation of rotation. In each rotational experiment at the above mentioned constant angular velocities, two normal subjects were accompanied by the labyrinthine-defective control subject and an on-board experimenter who observed the subjects and administered the

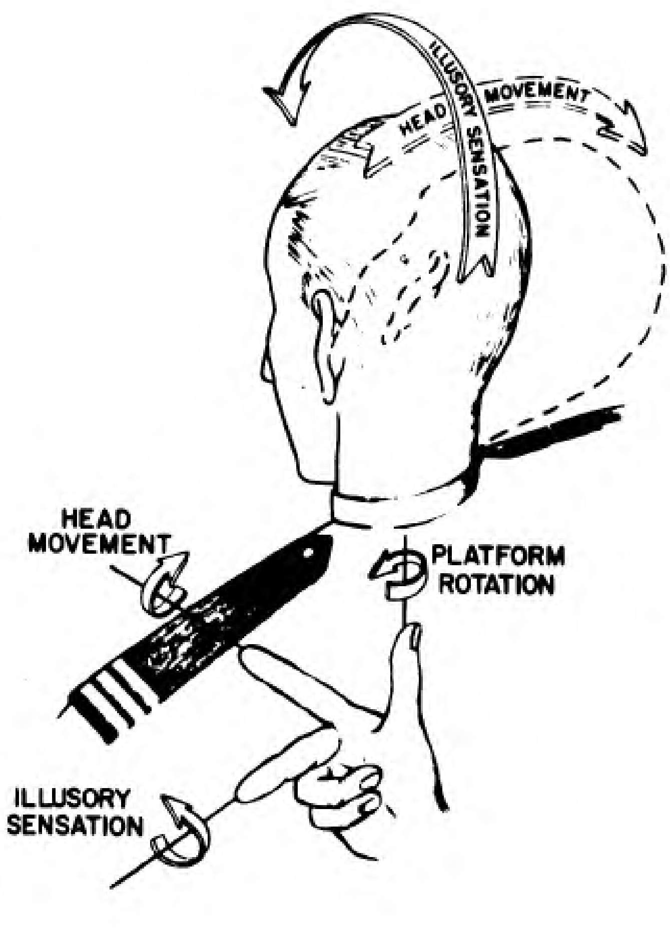
Figure 1



DIAL SETTING SEQUENCE IN SLOW ROTATION ROOM

Since the experiment employs constant angular velocities, there would be no angular acceleration once the centrifuge had attained the desired angular velocity. The primary stimulus associated with head movement, as in the demonstration of the oculogyral illusion, would be an angular Coriolis acceleration. This is a cross-coupled gyroscopic acceleration following the right-hand rule (fig. 2) where the thumb represents the vector of the spinning platform, the index finger represents the vector of the angular distorting torque (head movement) and the third finger represents the vector of the resulting precession (acceleration imparted to the semicircular canals) (13). An example would be the subject who while standing erect on a counterclockwise rotating platform of constant angular velocity would tilt his head from the upright to his right shoulder. The signal from the subject's semicircular canals indicates that he not only tilted his head to his right shoulder but has simultaneously pitched far forward. In conflict with this input are the visual, proprioceptive and intellectual signals indicating that only the intended head tilt to the right shoulder has taken place. This conflict of normally synergistic inputs is probably quite important in producing the later canal sickness syndrome. The symptoms may range from mild malaise to frank prostration. Subjects may complain of dizziness, "stomach awareness," drowsiness, nausea, fatigue and apathy. Signs of the syndrome include cold sweating, pallor, vomiting, restriction of activity and the accompanying ataxia.

Figure 2



If the same subject were to walk along a radium he would experience a linear Coriolis acceleration which in the above situation would cause him to sway to his right as he moved toward the center and to his left as he moved toward the periphery. It is important to note that if the subject were to remain motionless, he would experience neither of the above stimuli and his only unusual sensation would be due to the centripetal acceleration. His response to this would be to lean slightly toward the center of the room so as to align himself with the gravitoinertial vertical.

The symptoms of these various constant angular velocities are as follows:

a) At 1.7 rpm two normal subjects who had less than normal susceptibility to motion sickness and an on-board experimenter experienced mild symptoms of canal sickness but adapted within the first day. The labyrinthine-defective control subject did not complain but had some slight difficulty in walking.

b) At 2.2 rpm the stress response was not found to be significantly different from the results at 1.7 rpm.

c) At 3.8 rpm two normal subjects who were not readily susceptible to motion sickness experienced mild symptoms and adaptation was not achieved in one of the subjects until the second day. Again the control (L-D) subject had no symptoms but all had difficulty walking. The normal subjects experienced an increased fatigue.

d) At 5.4 rpm only the control (L-D) subject experienced no symptoms. All of the subjects and the on-board observers experienced prominent, incapacitating symptoms of canal sickness. The severity and time course of the symptoms were variable between individuals. All subjects restricted their head movements, complained of fatigue and slept as much as possible. Walking was difficult for all on-board personnel. At the cessation of rotation all experienced ataxia and some had recurrent canal sickness symptoms. Some of the subjects were not adapted at the end of the second day of rotation. Again the control (L-D) subject had no symptoms of canal sickness but did have some difficulty walking during rotation.

e) The personnel selected for the 10.0 rpm run were felt to be the least susceptible to motion sickness from the available subjects. One subject had few symptoms of canal sickness but complained continually that he was sleepy and preferred not to engage in any of the experimental procedures. The other subject and the on-board observer experienced severe symptoms and although they restricted their head movements to avoid the bizarre stimulation, they found it difficult to continue the experiment. Again the control (L-D) subject had no symptoms but had difficulty walking. Without heavy reliance on the control subject, it would probably have been impossible to complete the experiment. Adaptation to rotation was questionably complete at the end of forty-eight hours and upon the cessation of rotation, all experienced significant, albeit transient, ataxia.

Concerning the various tasks which involved head or body movement (14), there was a gradual disappearance of the oculogyral illusion which reappeared with head movements directly after the cessation of rotation. The body sway (modified Romberg) when standing on both feet showed a modest deterioration at higher angular velocities and moderate instability upon the cessation of rotation.

When standing on one foot the results were more variable, but the subjects experienced prominent difficulty under rotation and directly after stopping. The results of heel-to-toe walking were similar to the body sway. It is interesting that the control (L-D) subject did not experience the marked ataxia problem of the normal subjects upon the cessation of rotation. The results of the ball- and dart-throwing tasks were highly variable and difficult to assess. The results of the Dial Test are difficult to judge since it represented such a stress that on many occasions the test was halted prematurely due to the onset of canal sickness symptoms in the subject.

Regarding the tests involving little movement, there were minor alterations of the ECG and blood pressure, but these were felt to be of little significance. Rotation had little, if any, effect on hand steadiness, strength of grip or the opening of combination locks. The results of the card-sorting and arithmetic tests indicated a simple learning process could continue under rotation with perhaps a temporary deterioration at the start of rotation.

To summarize these results, persons of low susceptibility to motion sickness adapted to 5.4 rpm but not to 10.0 rpm. Persons with normal susceptibility experienced prominent symptoms at 5.4 rpm and lower angular velocities with some mild symptoms being encountered at the slowest experimental velocity, 1.7 rpm. There was significant variation in the severity of symptoms and the time course of adaptation from subject to subject. Mild to moderate symptoms recurred upon the cessation of rotation but readaptation was rapid. A labyrinthine-defective subject was present at each velocity studied. He experienced ataxia in a pattern similar to the normal subjects with not so prominent a postrotation ataxia, but he at no time experienced the symptoms or demonstrated the signs of canal sickness.

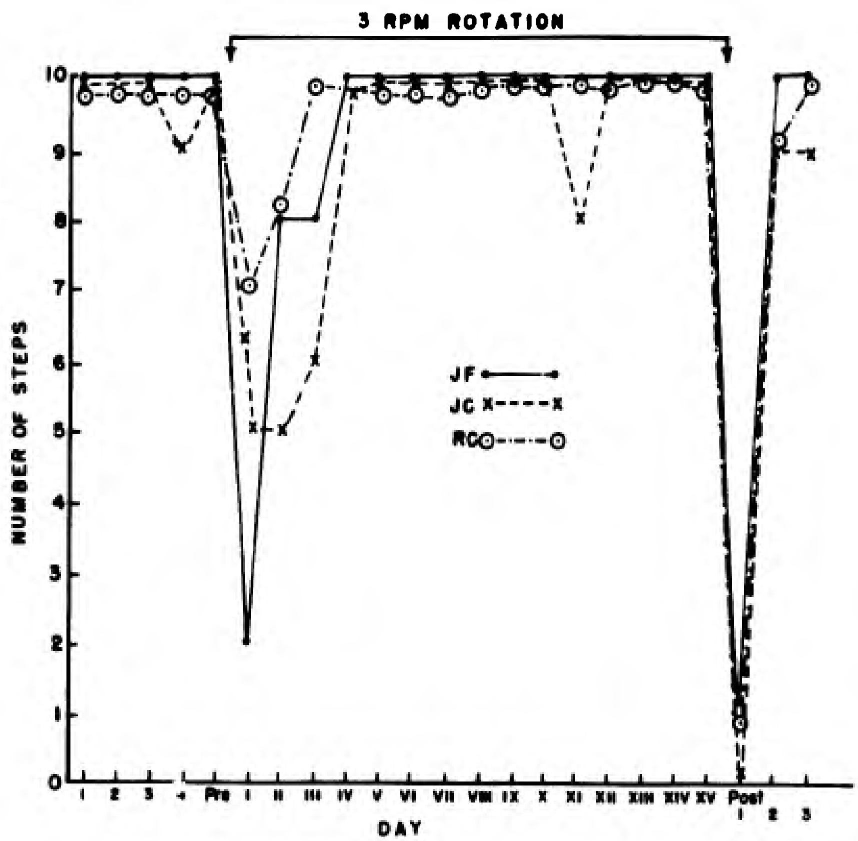
In the preceding experiment (8) mild symptoms were encountered at the slowest angular velocity studied, 1.7 rpm. The subjects in this case were known to have less than normal susceptibility to motion sickness. It would be desirable to know at what angular velocity susceptible individuals could adapt without significant symptoms. With this in mind a series of pilot studies were done on the SRR which indicated that 1.0 rpm might be tolerable to the most susceptible subjects. To more carefully investigate this assumption, four subjects of normal susceptibility were exposed to constant rotation at 1.0 rpm for fifty hours (15). The testing procedures were very similar to those of the preceding experiment. Two of the four subjects reported the oculogyral illusion soon after the start of rotation and this disappeared within hours. Shortly after stopping the room three of the four subjects reported a postrotational oculogyral illusion. At the start of rotation all subjects experienced some difficulty walking heel-to-toe with their eyes closed, but readily adapted to control levels. Three of the four experienced transient postrotational difficulty with the same test. The remainder of the test procedures showed no effects of rotation. Symptoms of canal sickness were not encountered, and the subjects performed all assigned tasks well. It was felt that 1.0 rpm was near the threshold for the perception of the oculogyral illusion and at this angular velocity the head movements employed to elicit this illusion were not associated with uncomfortable symptoms. Further testing involved two subjects who had been found to have abnormally high susceptibility to canal sickness in earlier experiments. These subjects were rotated at 1.0 rpm for thirty hours using essentially the same experimental design as above. The subjects remained asymptomatic and the results are similar to the first run at 1.00 rpm. As a final test, two subjects with lifelong histories of motion sickness were exposed to 1.0 rpm for 4.5 hours. Both subjects reported the oculogyral illusion initially, but this disappeared within two hours. One subject initially complained of a slight malaise, and the other of a headache. Later these symptoms subsided and the subjects remained otherwise asymptomatic. Walking heel-to-toe was difficult at the start of rotation, improved during rotation, and at the cessation of rotation it transiently deteriorated to the level present at the start of rotation. The remainder of the procedure showed no effects of rotation. In summary, it seemed that 1.0 rpm represented an angular velocity to which even the most susceptible subject could readily adapt.

It was found in the first experiment (8) that mild symptoms were encountered at 1.7 and 2.2 rpm and that severe symptoms were encountered at 5.4 rpm during forty-eight hours of rotation. To investigate an intermediate speed for a much longer period of time appeared to be a logical next step. The experiment performed consisted of continuously rotating three normal subjects and an on-board observer for two weeks at 3.0 rpm (16).

The experimental design was similar to that of the above mentioned experiment (8). The subjects were three young volunteer males who had no history of difficulty or disease related to the VIII nerve and who demonstrated the usual sensitivity to caloric stimulation (17). The on-board tests could be divided into two large groups: the first group monitored any alteration in physiologic function and simple reactions; the second group of tests monitored higher CNS function involving complex tasks. The first group of tests consisted of standard electrocardiograms, routine blood pressure determinations, a step test (18), determinations of urinary catecholamines (19) and corticosteroids (20), a weight-lifting task, the Oculogyral Illusion (21), the Rail Walking Test (22), a Heel-to-Toe Walking Test (15), a pastpointing test, measurements of ocular accommodation and convergence, and photoelectric measurement of the Achilles reflex. The second group of tests included a conceptual reasoning test (23), a sequence response test, a series of arithmetic computations, and an audio vigilance test. A four-day prerotation and a four-day postrotation control period allowed adequate acquisition of control data to compare with the perrotational results. The Dial Test (12) was employed to induce head movement. Rotation was continuous except for two or three brief stops daily to allow experiments to come aboard, to load groceries and to unload refuse. These stops were limited to fifteen minutes or less during which time the subjects remained motionless.

The results indicate that there was no significant deterioration of psychological or physiological function during the two weeks of rotation. All subjects experienced transient but significant difficulty on the Rail Test (fig. 3) at the onset and cessation of rotation. With the exception of one subject experiencing "stomach awareness" at the onset of rotation, symptoms of canal sickness were not encountered.

Figure 3



Graybiel-Fregly Posture Test - Total Number of Steps Walking Heel-to-Toe on 1 1/4" Rail with Eyes Open

It was impossible to detect any change attributable to rotation in the electrocardiograms, blood pressure determinations, step test, urinary catecholamines and corticosteroids, weight-lifting and ocular accommodations and convergence. The conceptual reasoning and the sequence response tests showed no deterioration at the onset of rotation, during rotation and at the cessation of rotation; learning trends on both of these tests continued throughout rotation (fig. 4). The Math Test showed some slight decrement on the first day of rotation but returned to prerotational level by the second day of rotation. The results of the oculogyral illusion are inconclusive due to the low magnitude of the illusion at 3.0 rpm and a lack of sophistication on the part of the subjects. The results of the pastpointing, Achilles reflex monitoring and the audiovigilance test were inconclusive due to excessive variance between observations and technical difficulties. Thus, it would seem that routine, unselected, normal subjects tolerated a constant angular velocity of 3.0 rpm for two weeks without any significant decrement of function.

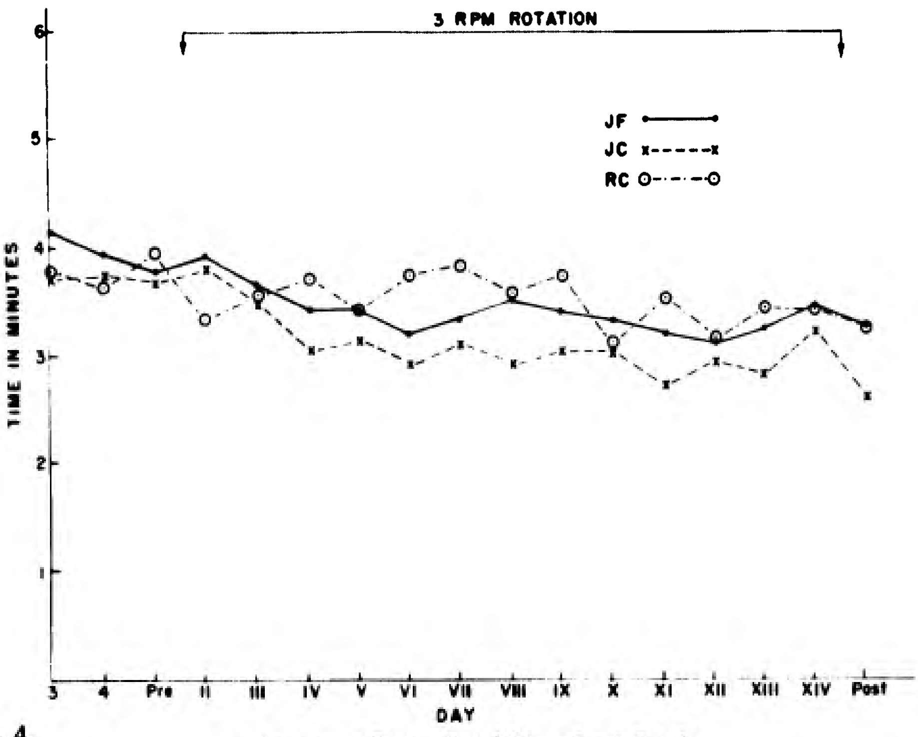


Figure 4

Sequence Test-- Total Time for 5 Trials

Having shown that normal subjects experienced no symptomatic or functional difficulties during two weeks at 3.0 rpm, it seemed reasonable to investigate what might be a maximum tolerable angular velocity for highly selected subjects similar in background to astronaut candidates. The experiment performed consisted of exposing four aviators and an on-board observer to 10.0 rpm for twelve days (24).

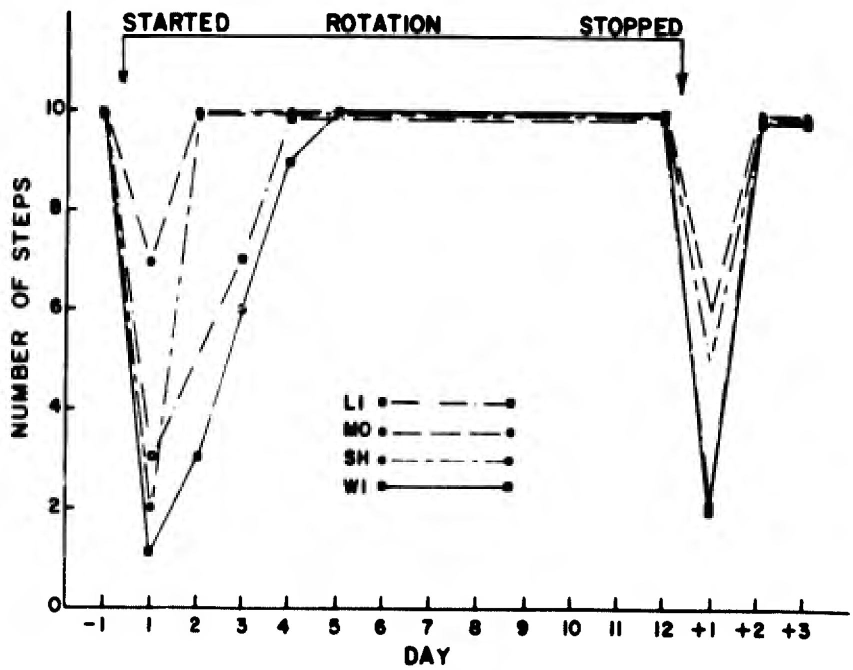
The rotational device employed was again the Slow Rotation Room (9) and the experimental design was similar to the above experiments. However, in choosing 10 rpm, a certain amount of difficulty was anticipated and therefore an elaborate variety of laboratory determinations, clinical studies and psychophysiological tests were included in the experimental design. The volunteer subjects were aviators who had completed the acrobatic stage of flight training. The subjects were carefully evaluated physically with particular attention to the inner ear. On the basis of caloric stimulation (17), a brief vestibular disorientation test (25, 26), a Standard Pattern of Acrobatics (27), and a Rorschach Test scored in an unusual way (28), the subjects displayed essentially normal responses but suggestive of below-normal susceptibility to motion sickness. The subjects were also ranked by each of the above tests in order to study the predictive value of the individual tests. The rotational routine was similar to earlier experiments with a four-day prerotational control period, twelve days of perrotational testing and a two-day postrotational control period. It was again necessary to make three brief stops daily to allow test personnel access and to load and unload supplies. During this time the subjects remained motionless so as not to lose their adaptation.

The experimental results may be divided into four large areas: subjects' symptoms and objective signs noted by the on-board observer, various clinical studies, many laboratory determinations and a series of psychophysiological tests.

Prominent symptomatology was encountered in all of the subjects. At the onset of rotation, all experienced immediate difficulty in walking and other body movements. The usual symptoms of canal sickness appeared after a delay in spite of the subjects' wearing orthopedic neck braces to reduce head movement. Subject Mo, who experienced the most severe symptoms, became sick within 35 minutes and experienced eight vomiting episodes ending the evening of Day 2. During this time he lost six pounds. His appetite did not return until Day 3 and he did not regain his weight until Day 8. Subject Sh experienced somewhat lesser symptoms. He became sick within one hour, but vomited only once during the afternoon of Day 1. During the first two days he lost three pounds. His appetite returned on Day 3 and he regained his weight by Day 4. Subject Li experienced lesser symptoms; he did not vomit in spite of his nausea, but he transiently lost two pounds primarily due to voluntary water restriction. He slept at every opportunity during the first two days. He regained his weight and appetite by Day 3. Subject Wi who had the least symptoms, experiencing only mild nausea during the first three hours, was the only subject to gain weight during the first two days. During this time he gained two pounds, one of which he lost on the following day. The Vestibular Disorientation Test correctly ranked the subjects as to their susceptibility to canal sickness. All of the subjects experienced long-term fatigue with a considerable restriction of physical activity. Free time was spent napping or doing something requiring no significant mental concentration. By Day 12 none of these resistant subjects had fully adapted. The reaction of stopping was less symptomatic than starting. Immediately upon stopping there was a significant ataxia which improved within hours. Only one subject (Sh) complained of "stomach awareness."

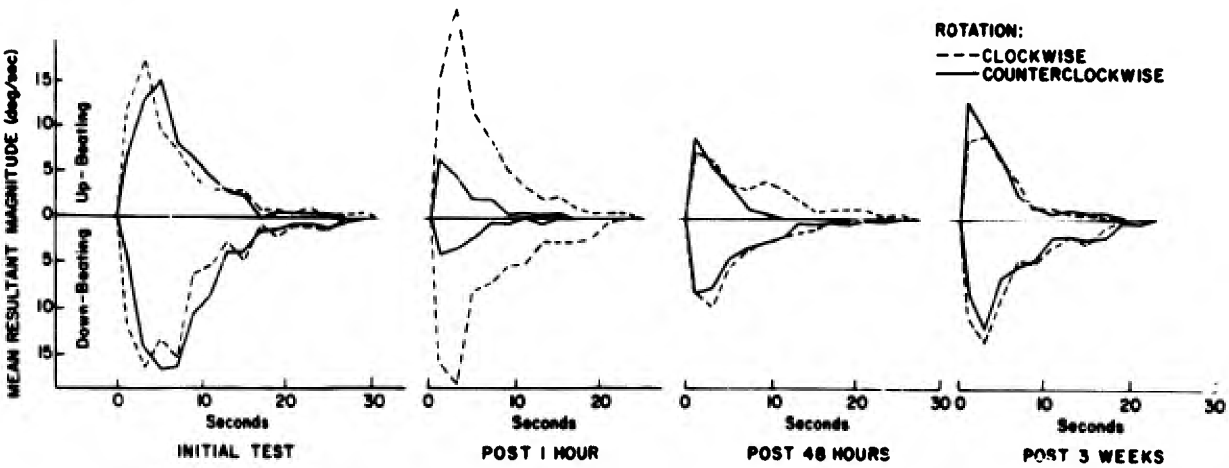
The results of the clinical studies are interesting. To assess any alterations in postural equilibrium, the Graybiel-Fregly Rail Test (22) was administered on Day 7 (7 days prerotation) and again on Day +3 (3 days post-rotation). Perrotation the subjects were daily given a standing heel-to-toe, eyes closed, arms folded task and a walking heel-to-toe test (fig. 5). The results are similar to earlier experiments, but it is interesting to note that subject Mo, who had the most severe symptoms of canal sickness, had the least difficulty with the heel-to-toe walking task. It is equally interesting that subject Wi, who had the least symptoms of canal sickness, experienced the most difficulty in walking heel-to-toe. The explanation is not clear and the occurrence may be accidental. In the above experiment at 3.0 rpm (16) similar difficulty was encountered in the heel-to-toe walking task (fig. 3); yet the symptoms of canal sickness were absent. Thus it seems clear that the adaptation to rotation as measured by the heel-to-toe walking task is significantly different from that measured by the symptoms of canal sickness. The results of the Rail Test are unchanged from control data except for the Stand Eyes Closed Test in which three of the four subjects did poorly when compared to prerotational controls. This suggests that they had not yet fully recovered from their exposure to rotation on the third postrotational day.

Figure 5



HEEL TO TOE WALKING SCORES FOR FOUR SUBJECTS

Nystagmography was conducted just prior to rotation and at 2 hours, 2 days and at three weeks after rotation. The results (fig. 6) (29) indicate that there was a marked reduction in the nystagmus in the accustomed direction of rotation upon stopping. At forty-eight hours, the responses were equal but both reduced in amplitude; some suppression was still present at three weeks postrotationally. The mechanism of this suppression is not clear. The nystagmus generated by acceleration and deceleration was not affected by the twelve days of rotation, indicating that the habituation is rather specific. It is also interesting to note that the amount of nystagmus did not correlate with the symptoms of canal sickness. Subject Mo, who had the most severe symptoms, yielded the least amount of nystagmus. The Coriolis Illusion was performed on Days 1, 3, 6, 10 and on the first postrotational day. Three of the four subjects had complete adaptation by Day 3. The subject Li, who had restrained his head movements the most, was completely adapted by Day 6. The illusion transiently reappeared upon the cessation of rotation, indicating a conditioned response. Subject Mo experienced an almost perfect reversal of magnitude and direction, implying that the mechanisms of perrotational adaptation are compensatory in nature (30). Several visual tests were performed which did not reveal any prominent effect of rotation; however, there was a decrease in the flicker fusion test in two subjects who had the more severe canal sickness symptoms. It has



been reported that caloric stimulation will depress the critical fusion frequency (31). Whether the depression of CFF is specific or a nonspecific component of the fatigue state is not clear. Several cardiovascular tests including routine pulse and blood pressure determinations, standard electrocardiograms and a tilt test failed to reveal any significant effect of rotation.

Several unexpected findings were encountered in the laboratory determinations. Several serum enzymes were daily monitored (glutamic-oxaloacetic acid transaminase, alkaline phosphatase and lactic dehydrogenase).

Although the SGOT and alkaline phosphatase levels remained within normal limits, the LDH levels (fig. 7) rose at the onset of rotation, fell to control levels on Days 2 and 3, and then again increased gradually over the duration of the run, with a fall toward control levels at the cessation of rotation.

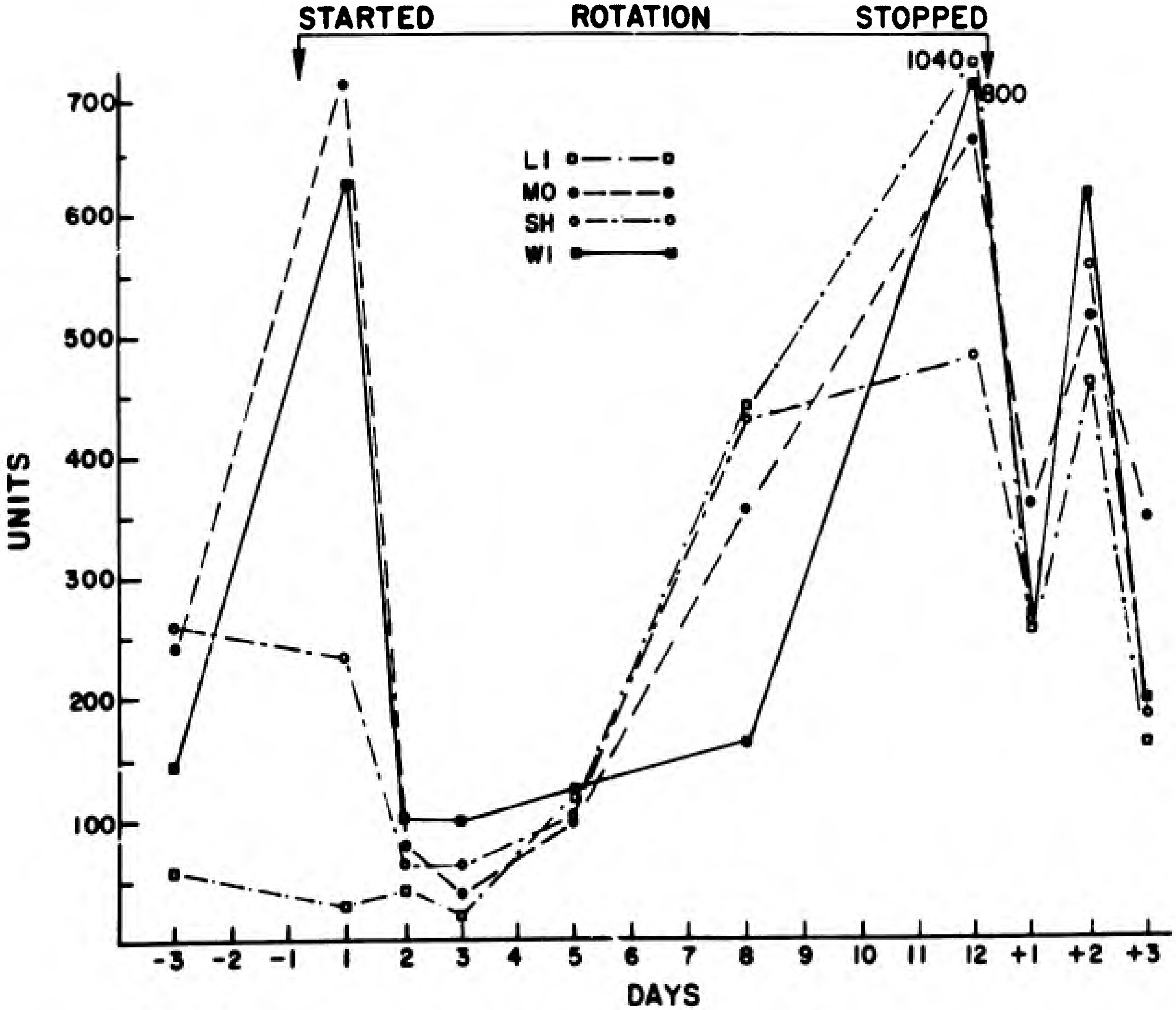


Figure 7 Lactic Dehydrogenase Response of Four Men

One explanation might be that there was an increased muscle tonus secondary to the bizarre semicircular canal stimulation or to the postural difficulties encountered in the rotating environment. It is interesting that the LDH levels generally followed the activity of the subjects: an initial increased level of activity during the delay before the onset of canal sickness followed by a sharp restriction in activity with the onset of nausea and a gradual increase in activity as further adaptation ensued. Another rather unexpected finding was an initial decrease in the rate of glucose removal from the blood followed by a significant increase above control levels (fig. 8). There was

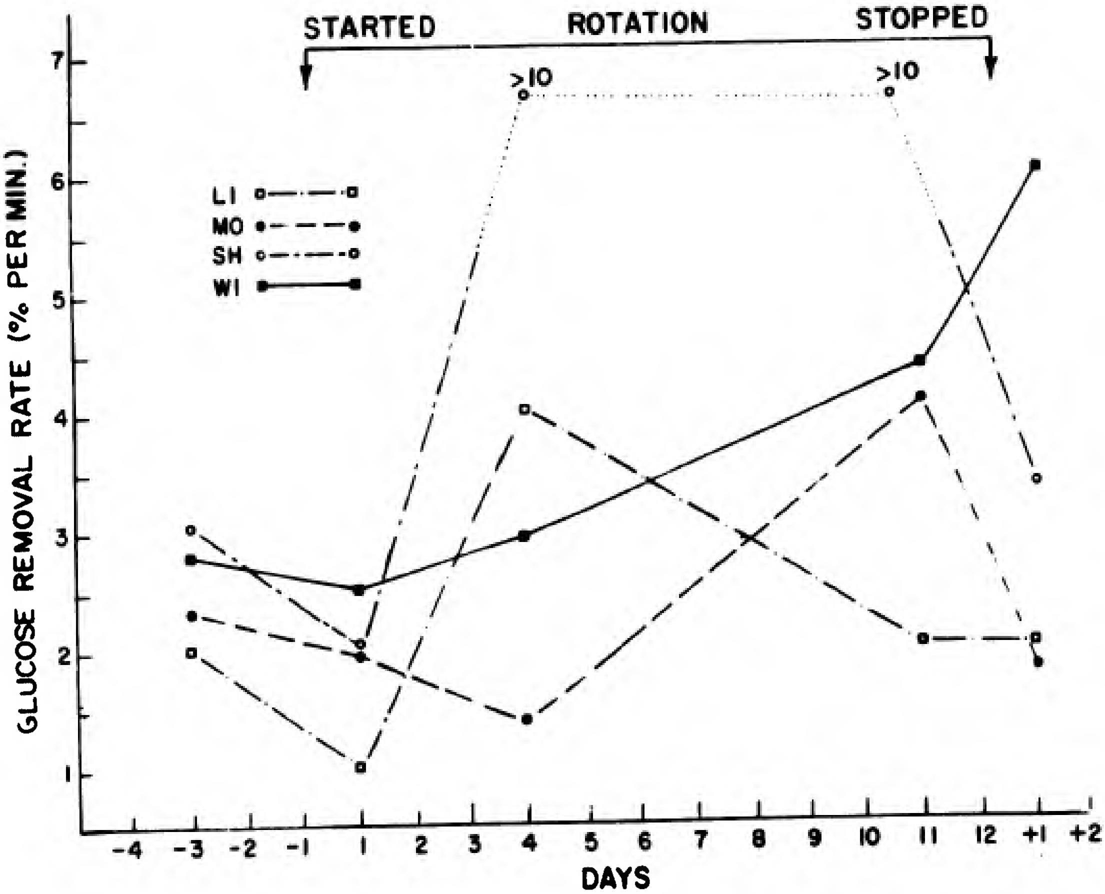


Figure 8 Glucose Removal Rate of Four Subjects

considerable variation among subjects; yet they all experienced the same trend but at different rates during rotation. The explanation for this is not clear. It was anticipated that urinary catechols and corticoids would follow the symptoms of the nausea syndrome; however, this did not prove to be the case. Neither serum nor urinary catecholamines were elevated. Urinary corticoids failed to rise when the nausea syndrome was prominent shortly after the onset of rotation but did elevate significantly toward the end of rotation when the subjects were increasing their physical activity (fig. 9). It has been shown that an antidiuresis accompanies motion sickness (32), and there was indeed a decrease in urine volume and sodium excretion shortly after the onset of rotation. It is interesting to note that the adaptation to the antidiuretic effect required longer than the adaptation to the nausea syndrome. With the exception of a transiently lowered pCO_2 for subject Mo who vomited eight times in Days 1 and 2, the remainder of the blood chemistries and counts indicated no significant alteration attributable to rotation.

To more carefully monitor the subjects' psychological behavior, an elaborate variety of psychophysiological tests were included in the experi-

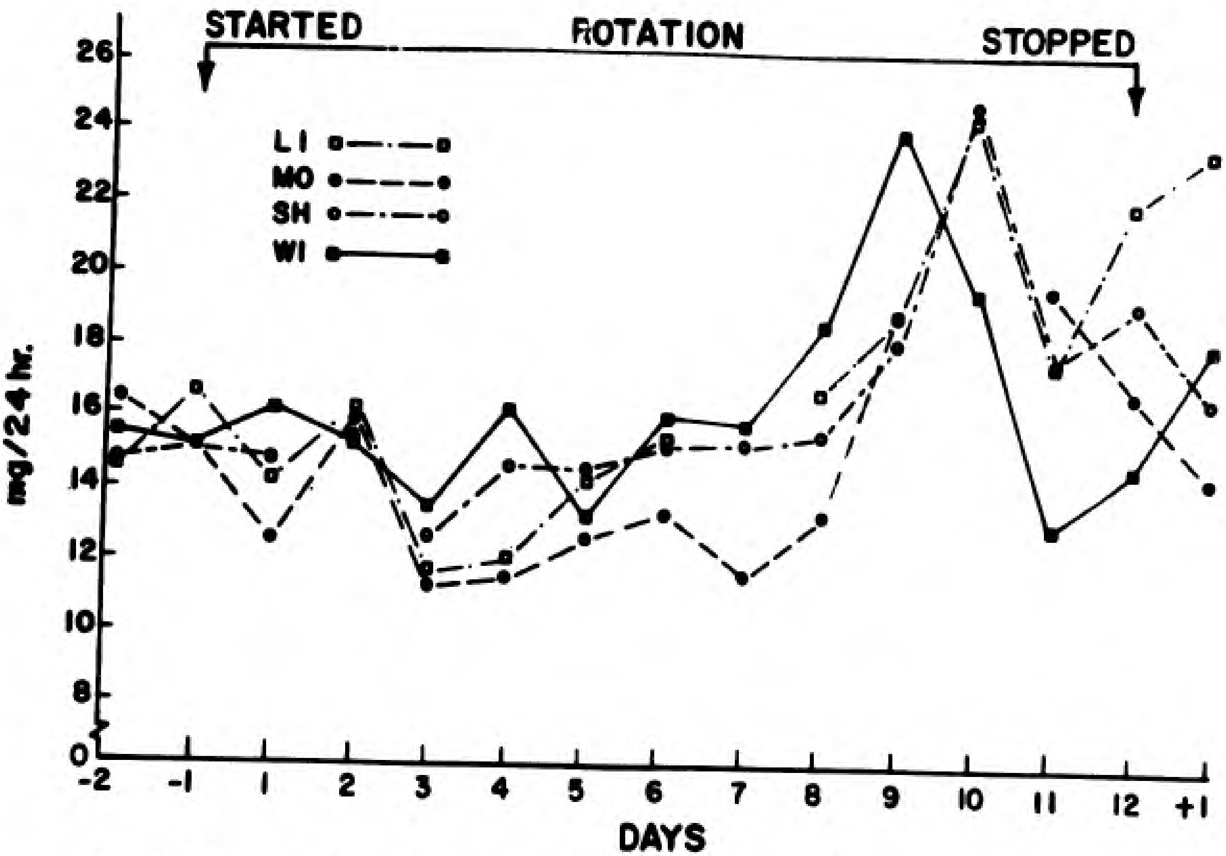


Figure 9 Urine Corticosteroid Excretion of Four Subjects

mental design. With the exception of minor, transient decrements in performance at the beginning and end of rotation, no significant changes attributable to prolonged rotation were encountered.

Thus, four carefully selected subjects perhaps did not fully adapt to 10.0 rpm in twelve days of rotation. Significant physiologic changes were associated with the stress of prolonged rotation. Although the psychophysiological tests indicated only transient decrements in performance associated with the onset and cessation of rotation, the subjects felt their ability to make sophisticated decisions had been compromised, especially at the onset of rotation.

The stimulus environment with an erect subject on the SRR is different in several important respects from that of a manned rotating spacecraft (33). On the SRR a given head tilt relative to the subject's body will produce the same response regardless of which direction the subject is facing relative to the center of rotation. In the rotating spacecraft the man will be in the plane of rotation, and the response elicited by a given head movement will depend on the direction the man is facing when he performs the movement. This particular stimulus environment is impossible to produce on earth for any length of time. To locate the man in the plane of rotation of the SRR is not difficult, but the presence of gravity appears to modulate the response of the semicircular canals so as to reduce the nystagmus and suppress the sensation of rotation upon deceleration (34). Furthermore, the adaptation on the SSR is accompanied by rather specific compensatory reactions (30) and there is little transfer of adaptation from one specific, practiced head movement to another specific, unpracticed head movement (35). Since in the rotating spacecraft a particular head movement will yield a variety of responses depending on the direction the subject is facing, it is difficult to imagine how specific compensatory reactions might develop. At the same time, the limited transfer of adaptation from one head movement to another suggests that each bizarre canal response will have to be dealt with individually by the central nervous system. In spite of these theoretical differences, the initial examination of data from experiments which are still in progress, indicates that adaptation in the plane of rotation is similar in many respects to adaptation in the erect position, at least on a ground-based rotating platform (36).

A related problem, upon which research has hardly begun, is the acquisition of basic information about the nature of the adaptation process. With this information it might be possible to precondition susceptible personnel prior to launch and later recondition them to the earth environment prior to re-entry.

Some years ago R. L. Noble published an interesting paper about adaptation in dogs to a simple swing (37). He concluded:

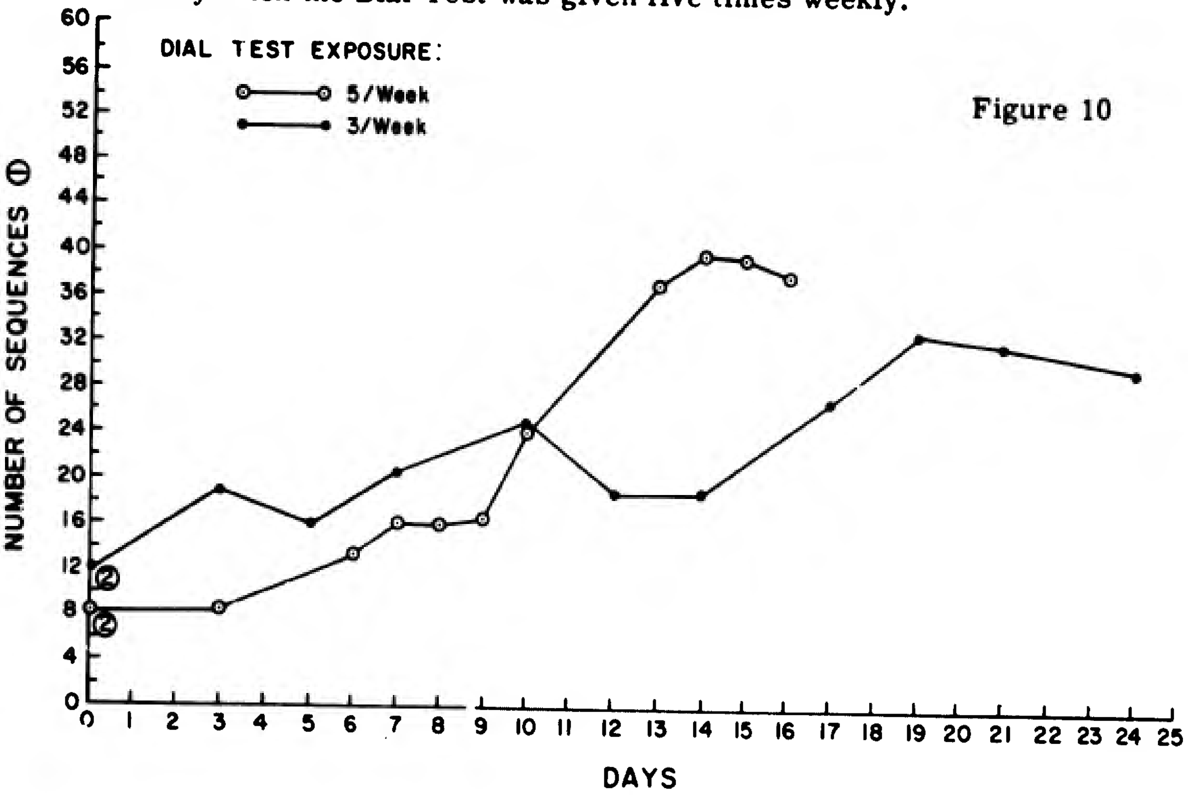
1) The degree of adaptation was much greater in the dogs who initially were highly susceptible.

2) The frequency rather than the duration of the swing sessions was the more important element of inducing resistance. Daily sessions were highly effective in inducing adaptation; yet sessions as far apart as every ten weeks still showed a slight, gradual loss of susceptibility.

3) Adaptation was stimulus-specific in that dogs adapted to vertical motion became ill when exposed to horizontal motion, and vice versa.

4) Several drugs were tested as to possible interference with the adaptation. One of these was the barbiturate, V-12, which is highly successful in suppressing the vomiting associated with canine motion sickness. There was apparently <u>no</u> interference with the adaptation process; yet the animal was protected against motion sickness.

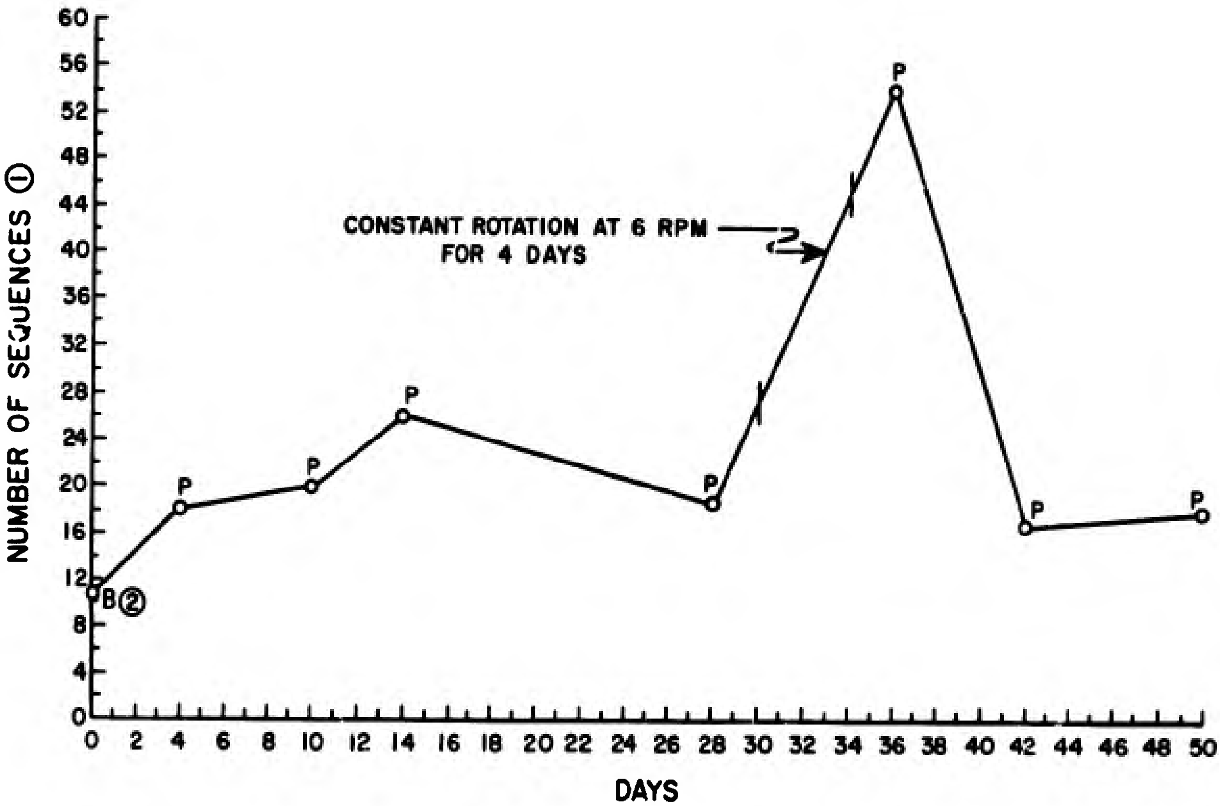
If human adaptation is similar remains to be seen. However, in recent drug studies where the Dial Test (12) is used to simultaneously assess the susceptibility to canal sickness and measure the effectiveness of the drug being tested, the placebo baseline when the Dial Test was given three times weekly was different from the same baseline when the Dial Test was given five times weekly (fig. 10). It appears there was a greater loss of susceptibility when the Dial Test was given five times weekly.



①A sequence consists of 5 head movements and 1 rest period

②Placebo baseline; mean susceptibility

Although it has been shown that the adaptation is rather stimulus-specific (35, 37, 38), by selecting several subjects for four-day runs at 6.0 rpm who had just participated in the above drug studies, several interesting interactions were noted (fig. 11). It was noted that the subjects had less difficulty at 6.0 rpm than would have been expected, implying that the Dial Test given once per day for five days per week had transferred some adaptation to the 6.0 rpm study. Even more striking is the transfer from the four-day run at 6.0 rpm to the later Dial Test determinations at angular velocities to 20 rpm. Note the return to the control baseline in about one week. Thus it seems that there is significant transfer between various angular velocities. This is also indicated in the ability to attain an angular velocity of 10.0 rpm with fewer symptoms when stepwise increases in angular velocity are employed, allowing subjects time to adapt at each level before the next is attempted (39).



①A sequence consists of 5 head movements and 1 rest period
② Placebo baseline; mean susceptibility

Figure 11

Little information is available on the effects of drugs on adaptation. However, the unusual resistance to canal sickness demonstrated by those subjects who have only partial bilateral vestibular loss (40) and a few individuals with unilateral loss (41) suggest interesting possibilities in terms of seeking temporary, reversible suppression of vestibular function.

There is also little information as to whether it is possible to adapt to a rotating environment and at the same time maintain the adaptation to the earth situation. The on-board experimenter (24) who participated in the loading and unloading of the SRR while it was halted three times daily did not experience the ataxia upon stopping which was so obvious in the subjects who had remained motionless during the stops and seemingly lost their adaptation to the earth environment. This important practical question remains to be carefully studied.

SUMMARY

To summarize, then, the above experiments:

1) Human adaptation to prolonged rotation is a manifold process composed of elements of different time courses.

2) Current experiments seem to have three major time periods:

    a) An early perrotation period characterized initially by ataxia and after a variable delay the nausea syndrome may appear. During this period the rate of adaptation seems to be greater in more alert and active subjects.

    b) A late perrotation period characterized by a fatigue syndrome; yet performance on various psychological tests may show no significant decrease in performance.

    c) A postrotation period characterized initially by ataxia but with a rapid readaptation to the earth environment.

3) There is sufficient individual variation in the adaptation to rotation to warrant the grouping of subjects into high, average and low levels of adaptation potential.

    a) Subjects with average or low adaptation potential will adapt to prolonged rotation at 1.0 rpm.

    b) Subjects with average potential will usually adapt to 3.0 rpm, yet may not adapt to 5.4 rpm. Subjects of high potential will experience little difficulty adapting to 5.4 rpm.

    c) Subjects with high potential will have significant difficulty adapting directly to 10.0 rpm.

4) There are important differences between the stimulus environment of the erect subject on the SRR and the astronaut moving in the plane of rotation of a rotating spacecraft. In spite of these differences, there is early experimental evidence that adaptation of the subject erect and in the plane of rotation is similar in many respects, at least on a ground-based rotating platform.

5) More information is needed concerning the adaptation process itself. In particular, an ability to transfer adaptation from one rotating environment to another would be useful to precondition susceptible personnel prior to launch.

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Calcium and Nitrogen Balance Studies During Gemini VII Flight

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CALCIUM AND NITROGEN BALANCE STUDIES DURING GEMINI VII FLIGHT

Leo Lutwak, Ph. D., M. D.

INTRODUCTION:

In considerations of the possible effects of long-term space flight on human physiology, the metabolic response of the musculoskeletal system appears as a major probable stress response. Many studies have been carried out in the past of the effects of simulated weightlessness in individuals at ground-level conditions. Obviously, such studies can only give indications of possible phenomena that might be observed under conditions of true weightlessness such as would be experienced in space flight.

Weightlessness has been approximated experimentally using conditions of complete hospital bedrest or of prolonged continuous water immersion. Although these situations are only approximations of the zero gravity state, considerable information has been gathered of the circulatory, cardiac, muscular and skeletal responses to relative lack of gravity stress.

The early study of Cuthbertson (1) of eight normal subjects and patients confined to bedrest for varying periods of time up to two weeks demonstrated that urinary calcium excretion increased and negative calcium balance resulted within this period of time. In 1945, Keys at Minnesota (2) reported carefully controlled bedrest studies in several subjects, but unfortunately no measurements of calcium balance or of calcium metabolism were carried out. The highly controlled studies by Dietrick, Whedon, and Shorr (3) of immobilization of four healthy young men demonstrated quite clearly that the conditions of immobilization by controlled bedrest, with the added restraint of body casts, led to noticeable increases in urinary calcium, significantly negative calcium balances, as well as parallel changes in nitrogen and phosphorus metabolism. Considerable individual variation was noted amongst the four subjects, but this did not detract from significant observations because of the careful control of other factors that might influence calcium excretion, such as dietary composition and total body activity. Identical diets were used during a pre-bedrest control phase as were used during the bedrest phases and during the post immobilization control phases.

With the advent of space flight, additional studies have been reported concerned with the effects of weightlessness on skeletal metabolism. Graveline, et al (4) reported, in their study of the effect of one week of continuous water immersion of one subject, that no increase was seen in urinary calcium excretion. On the other hand, Birkhead, et al (5), studying four subjects during 42 days of bedrest and 18 days of controlled activity preceding and following the bedrest phase, demonstrated that even when minimal activity such as that connected with eating, bathing, and excretory functions were permitted, sustained increases in urinary calcium excretion developed and persisted throughout the phases of immobilization. Contract studies supported by the National Aeronautics and Space Administration (NASA) carried out at the Texas Institute of Rehabilitation and Research (6) have shown similar phenomena, although of lesser magnitude and, in addition, demonstrated changes in bone density of the os calcis during bedrest.

Carefully controlled studies of calcium metabolism under varying conditions of physiology and pathology have demonstrated previously that significant changes in calcium excretion generally occur over long periods of time, and are not significant unless careful collections are carried out under controlled conditions for periods for at least two weeks (7, 8). Therefore, mineral balance studies were not attempted in the current Gemini program until the first long duration flight was scheduled, that of the Gemini VII mission. This flight, which was to last for fourteen days, allowed the design of appropriate protocols permitting, in addition to inflight observations, carefully controlled pre-flight and post-flight studies as well. An examination of musculoskeletal metabolism obviously involves more than simply measurement of dietary intakes, utilization and excretions of calcium and nitrogen. Muscle metabolism involves both nitrogen and phosphorus mechanisms. Bone physiology is dependent upon utilization, not only of calcium, but also of nitrogen and phosphorus, as well as of magnesium, sodium, and sulfur. Furthermore, the relative absorptions and excretions of these elements are under the influence of various endocrine systems as well as of dietary components such as fats, vitamins, sodium, and potassium. Thus, a carefully designed study of musculoskeletal metabolism requires the measurements of balances of calcium, nitrogen, phosphate, magnesium, sodium, potassium, sulphate among the obvious factors. In addition, there should be estimates of endocrine activity such as adrenocortical activity. Measurements of the excretion of adrenocortical hormones and of sodium and potassium were previously incorporated as part of the scope of the M-7 experiment to be carried out in conjunction with the Gemini space flights. Close cooperation and collaboration, therefore, between the present experimenters and those associated with the hormonal body fluid studies was planned as part of the protocol for this study.

GENERAL PLAN:

The experiment was designed to comprise four phases:

1. A dry run pre-flight phase involving volunteer subjects to test the various procedures to be utilized. Since this was designed primarily to test the laboratory techniques, the volunteers were to be selected from civilian personnel associated with the project and the phase was to be of relatively short duration.

2. Pre-flight control phase. This period of the study would involve the

two astronauts of the prime crew and the two astronauts of backup crew of the Gemini VII mission. This would last ten days, from T-12 to T-2, and would consist of completely controlled intake and collections as described below.

3. The inflight phase was to involve the two flying astronauts. This was to last throughout the entire inflight phase of 14 days.

4. Post-flight phase to last 4 days beginning immediately upon recovery of the flight craft and to involve the two astronauts who had participated in the mission.

Various experimental factors were to be controlled throughout the entire study. Optimal experimental conditions require the accurate control and measurement of diet, urine, feces, sweat, and activity, as well as of fluid intake. Each of these factors will be discussed in more detail.

1. Diet. The diet of all three phases, for optimal interpretation of metabolic data, should be as similar as possible. Since each man would serve as his own control for comparison of pre-, in-, and post-flight phases, inter-individual variation would be permissible but, attempts should be made to keep the dietary intake as comparable as possible among the three phases. To provide this degree of control, therefore, the pre-flight phase was to be carried out at the Manned Space Operations Building at Cape Kennedy. A diet, constant in composition, would be planned by a specially trained metabolic dietician and prepared under her supervision at the crew quarters, to be fed to the crew under supervised meal situations. No additional snacks would be permitted and every attempt would be made to ensure complete ingestion of the prepared menus. The inflight dietary intake would be easier to control since all of the food for the Gemini VII flight would be prepared beforehand according to previously arrived at protocols, and all food would be pre-packaged in the form of the usual Gemini flight food packs to be eaten in a prescribed sequence. Post-flight dietary control would be achieved by pre-packaging of the identical diet utilized during the pre-flight phase for use on board the recovery vessel for the first two days of the post-flight period and subsequent feeding at Cape Kennedy under the identical conditions used during the pre-flight phase.

2. Urine collections. Complete collections of urine are essential for calculations of metabolic balances. During the pre-flight and post-flight phases, collection facilities were to be established in the crew quarters and at various sites at Cape Kennedy where the crew would be undergoing training and preparation. Individual refrigerators and commodes were to be placed in the toilets in the crew quarters at the Flight Simulator Facility and at the blockhouse near the Gemini VII craft. Individual plastic containers with labels and marking devices were located adjacent to the collection sites and a team of aides were to make regular rounds of the sites to recover the containers and return them to the preparative laboratory to be established in the Medical Operations area.

Inflight urine collection was to be accomplished utilizing the previously designed urine transport system. Engineering constraints did not permit all urine voided to be collected. The system was to provide a means for measurement of total volume of each voiding by means of a tracer dilution technique and for preservation of aliquots of each sample. Provision was also made for labeling of each sample with the astronauts initials and mission time of voiding.

3. Stool collections. Pre-flight and post-flight stool collections were to be carried out using the toilet and refrigeration facilities provided at Cape Kennedy. Inflight stool collections were to be made with the Gemini defecation devices previously designed.

4. Sweat collections. It would not be feasible to carry out the complete sweat collections for the entire duration of all three phases. Therefore, during the pre-flight and post-flight phases, 24-hour sweat collections were to be scheduled. During these periods the subjects, after complete washing down of the entire skin surface, would don previously extracted flight underwear suits and would wear these for a continuous 24-hour period. At the end of this, another washing down would be carried out. The wash water and the suits were to be combined and the total fluid eventually concentrated into a form suitable for analysis. For the inflight phase, a total 14-day collection would be carried out with extraction of the inflight underwear removed immediately after recovery.

5. Activity. Because of the constraints of pre-flight training, it was not considered feasible nor desirable to control physical activity. Therefore, during the pre-flight and post-flight phases ad lib activity was to be expected, and this was to be considered to be an additional variable in the study. Inflight activity was to consist of that necessary for maneuvers, plus a fixed program of exercise which was to be arrived at by the astronauts and the staff of the Center Medical Operations.

6. Fluid intake. Fluid intake was to be ad libitum, but the quantities ingested were to be recorded. The majority of the fluids during the pre- and post-flight phase was to be obtained with the diet; calibrated cups were provided to each of the subjects for measurement of additional fluid intake in the course of the day. Inflight fluid intake was to be estimated from the water dispensing device on board the craft.

7. Specimen preservation and analyses. All pre-flight and post-flight specimens of urine, feces, sweat, and diet were to be assembled at a provisional laboratory established in the Medical Operations area. Pertinent measurements of volumes were to be carried out, aliquots of the urine samples were to be preserved by the addition of appropriate chemicals, frozen and shipped to the laboratories at Cornell University in Ithaca, New York for analyses. Aliquots of the same urine specimens were to be pre-

served with alternate chemicals, frozen and shipped to the laboratories associated with M-5 study. Stool specimens were to be frozen and shipped similarly to the Ithaca laboratories. Inflight specimens were to be recovered from the craft as soon as possible and shipped for analysis to the appropriate laboratory. The specific chemical determinations to be carried from each sample are listed in table I and are discussed below.

TABLE I

ANALYSES PERFORMED

ANALYSES	MATERIAL*	METHOD
Volume	U	a) Routine, pre- and post-flight b) T_2O dilution, inflight
Specific Gravity	U	a) Routine, pre- and post-flight b) Refractometry, inflight
pH	U	Routine, pre- and post-flight
Creatinine	U	Autoanalyzer colorimetry
Calcium	U,F,D,S	Autoanalyzer Atomic Absorption
Magnesium	U,F,D,S	Autoanalyzer Atomic Absorption
Sodium	U,F,D,S	Flame Photometry
Potassium	U,F,D,S	Flame Photometry
Phosphate	U,F,D	Autoanalyzer colorimetry
Sulfate	U,F,D	Atomic Absorption
Chloride	U,F,D,S	Coulometry
Nitrogen	U,F,D,S	Autoanalyzer
Fat	F,D	Wistreich Extraction

*U= Urine; F= Feces; D= Diet; S= Sweat

RESULTS:

The results of this study of the effects of space flight on musculoskeletal metabolism as measured in the course of the 14-day Gemini VII flight of December, 1965, are far from unqualifiedly successful. The data were obtained from studies involving only two subjects, and therefore suggest only extremely preliminary, tentative conclusions. There were many problems, both forseeable and unforseeable, associated with the conduct of this experiment leading to variations in the observations for each subject. In addition, as predictable, the two subjects responded quite differently from each other. Despite these inadequacies, however, we believe that the experiment was of value in that it represents the first effort to obtain information on possible metabolic changes in man during space flight. In addition, the experience obtained can lead to the better planning of subsequent studies to obtain more conclusive data.

A. Variations from initial protocol. Despite the preparation of an extremely rigid protocol for the M-7 experiment, it was apparent to the investigators that adherence to this protocol would not be completely possible in view of the factors which controlled the experimental environment under which this was carried out. The governing principle for all work in the space effort must, at present, be the practicable engineering feasibility of putting man into orbit and then getting as soon as possible to the moon. In the course of the Gemini flight series, scientific information of all kinds has been gathered, particularly in the areas of astronomy, radiation, and geography. The primary goal of all of these studies has been the acquisition of knowledge of practical significance to the conquest of space. Flights essentially for obtaining knowledge for its own sake are now in the planning stage. To date, consideration of the effect of space flight on the functional integrity of man from the medical and physiological points of view, has claimed limited attention except for evaluation of cardiovascular and otolith functions. Medical studies at present must be justified only in terms of what must be learned for astronauts' safety in flights of up to two weeks duration and for prediction of possible adverse influences on health and safety for flights of longer periods. Gemini VII was the eighth orbital flight, but only the first in which a specific effort was made to obtain physiologic data by complete collection of excreta in connection with planned controlled studies. Even in this flight, medically oriented studies were only a small part of an extensive list of operational and experimental activities required of the astronauts before, during, and after flight. For these reasons, it was impossible to carry out what would be considered an ideal experimental protocol, particularly from the point of view of mineral metabolism. Engineering, training, and flight restrictions forced many compromises in the acquisition of physiologic data.

1. Dietary control. It soon became apparent that a 10-day pre-flight control phase was not sufficient from the point of view of establishing constant dietary intake. It is well-recognized in ground based metabolic studies carried out under conditions of a hospital metabolic unit that variable periods of time of up to one week may be necessary to establish constancy of dietary intake acceptable to the subject as well as to the experimental protocol. Since only ten days were available for the entire pre-flight phase, such control was not completely possible. As can be seen from table II, considerable day to day variation occurred particularly in the first week of the study. It was necessary to add or remove items of food from the daily menus to insure palatability and acceptability of the menu. In addition, the mean intake of various nutrients was considerably in excess of that desirable from the point of view of a control study comparable to the projected inflight phase. Calcium intake was relatively the same as that projected for the inflight study, but dietary intakes of nitrogen, phosphorus, sulfate, sodium, and potassium were considerably in excess. The post-flight phase dietary control is quite comparable with the pre-flight phase since similar foods were used. As is apparent, the inflight intakes of all constituents except

TABLE II

ELEMENTAL COMPOSITION OF DIETS
(A) F.B.

Day	Ca (gm.)	Mg (gm.)	Na (meq.)	K (meq.)	PO_4 (gm.)	SO_4 (gm.)	N (gm.)
T-12	1.2873	.4340	258.8	114.4	2.5048	2.4202	25.481
T-11	1.3359	.4427	230.9	162.3	2.8645	2.7458	24.945
T-10	1.2558	.4391	177.6	143.9	3.1082	3.1083	28.094
T-9	1.3553	.4532	268.8	120.9	2.5189	2.3435	24.384
T-8	1.3483	.4522	263.5	169.1	2.9733	2.9491	27.452
T-7	1.2630	.4540	156.9	148.3	3.1292	3.1281	27.947
T-6	1.3354	.4438	232.7	116.7	2.4775	2.2876	22.314
T-5	1.3289	.4609	258.5	163.9	2.9258	2.9093	26.974
T-4	1.2840	.4549	174.6	146.9	3.1442	3.1497	28.248
T-3	1.3272	.4309	231.8	114.0	2.4415	2.2835	22.226
Mean	1.3121	.4466	226.4	140.0	2.8088	2.7325	25.807
s.d.	.0343	.0094	40.0	20.7	.2774	.3462	2.185
Inflight							
1	.8705	.2278	144.0	53.2	1.5372	.9533	18.275
2	1.1561	.1646	166.6	38.4	1.4247	.7311	13.046
3	.9702	.1386	137.4	20.9	1.3748	.6288	10.914
4	.7142	.2241	186.8	48.6	1.3263	.9472	15.495
5	1.2734	.2377	143.5	36.1	1.3212	.9215	15.625
6	1.3189	.2251	147.2	40.7	1.5416	1.0918	19.239
7	1.1651	.2436	88.9	22.7	1.2761	.8974	17.287
8	.8817	.1801	135.8	36.6	1.2150	.8876	17.526
9	.8279	.2373	121.7	35.8	1.1519	.9768	18.490
10	1.1039	.2222	125.7	36.9	1.4139	1.0937	17.502
11	.5555	.2013	199.4	42.4	1.0733	.9609	16.905
12	1.4700	.1773	128.2	39.4	1.5481	.7547	15.533
13	1.3267	.1917	180.2	40.1	1.6457	.9042	16.497
14	.9551	.1013	125.5	23.5	1.2209	.4886	8.958
Mean	1.0421	.1981	145.1	36.8	1.3622	.8741	15.807
s.d.	.2513	.0404	28.4	8.9	.1613	.1632	2.847
Post							
1	1.2372	.3564	244.9	128.8	2.5485	2.5354	22.044
2	1.3913	.5260	294.8	169.3	3.2455	3.0358	28.920
3	1.1735	.4266	169.1	126.5	2.6297	2.6050	21.869
4	1.4118	.4100	245.7	106.1	2.4686	2.3906	22.244
Mean	1.3035	.4298	238.6	132.7	2.7231	2.6417	23.769
s.d.	.1009	.0613	44.9	22.9	.3070	.2403	2.977

TABLE II Continued

ELEMENTAL COMPOSITION OF DIETS
(B) J L.

Day	Ca (gm.)	Mg (gm.)	Na (meq.)	K (meq.)	PO_4 (gm.)	SO_4 (gm.)	N (gm.)
T-12	1.2940	.4076	253.6	113.9	2.3958	2.2311	21.981
T-11	1.3780	.4078	218.5	149.8	2.5854	2.5898	21.693
T-10	1.2773	.4340	134.8	133.9	2.9256	2.9370	25.019
T-9	1.3260	.4318	225.0	116.0	2.2969	2.1408	22.978
T-8	1.3483	.3949	226.1	140.8	2.6477	2.7127	23.510
T-7	1.2534	.4506	144.8	139.3	2.8846	2.8685	24.867
T-6	1.3074	.4126	224.7	114.7	2.4019	2.2503	22.048
T-5	1.3554	.4073	214.4	143.6	2.6764	2.7177	23.590
T-4	1.2423	.4272	134.4	135.3	2.8557	2.8604	24.732
T-3	1.3029	.3983	223.1	111.1	2.3537	2.2536	21.977
Mean	1.3085	.4172	199.9	129.8	2.6024	2.5562	23.240
s.d.	.0419	.0169	41.8	13.7	.2223	.2916	1.237
Inflight							
1	.8705	.2278	144.0	53.2	1.5372	.9533	18.275
2	1.1561	.1646	166.6	38.4	1.4247	.7311	13.275
3	.9702	.1386	137.4	20.9	1.3748	.6288	10.914
4	.7142	.2241	186.8	48.6	1.3263	.9472	15.495
5	1.2734	.2377	143.5	36.1	1.3212	.9215	15.625
6	1.3189	.2251	147.2	40.7	1.5416	1.0918	19.239
7	1.1651	.2436	88.9	22.7	1.2761	.8974	17.287
8	.8817	.1801	135.8	36.6	1.2150	.8876	17.526
9	.8279	.2373	121.7	35.8	1.1519	.9768	18.490
10	1.1039	.2222	125.7	36.9	1.4139	1.0937	17.502
11	.5555	.2013	199.4	42.4	1.0733	.9609	16.905
12	.4700	.1773	128.2	39.4	1.5481	.7547	15.533
13	1.3267	.1917	180.2	40.1	1.6457	.9042	16.497
14	.9551	.1013	125.5	23.5	1.2209	.4886	8.958
Mean	1.0421	.1981	145.1	36.8	1.3622	.8741	15.807
s.d.	.2513	.0404	28.4	8.9	.1613	.1632	2.847
Post							
1	1.2537	.3379	184.1	124.8	2.4581	2.4355	19.841
2	1.3477	.4306	217.2	145.3	2.8991	2.7817	25.428
3	1.1250	.3932	130.5	128.2	2.6972	2.6879	24.091
4	1.4126	.4172	265.9	115.8	2.5067	2.4098	22.457
Mean	1.2835	.3947	199.4	128.5	2.6403	2.5787	22.954
s.d.	.1100	.0354	49.3	10.7	.1741	.1598	2.083

calcium were much lower than during the control phases. In addition, for reasons that remain obscure, it was impossible for the subjects to consume the inflight diet in the programmed sequence. As a result, there was considerable day to day variation in the intakes of all nutrients. The diets had been planned for constant daily composition, but since the three meals were eaten out of sequence in each 24-hour period, this constancy was not achieved.

2. Urine collections. No difficulties were encountered in obtaining reproducible accurate collections during the pre-flight and post-flight phases. The relative constancy of the 24-hour excretions of urinary creatinine during these aspects of the study are witness to this conclusion (table III). Inflight, however, various problems arose. Due to mechanical difficulties the inflight urine transport system did not function wholly effectively, and either variable quantities of urine were lost before the addition of the tritium tracer for estimation of total volume of voiding or inadequate mixing with tracer occurred. In addition, some of the storage bags for transport of the urine samples to the ground burst in the course of the flight or upon recovery, leading to further loss of urinary samples. Urinary creatinine excretions calculated on the basis of recovered samples were extremely variable and low (table IV). Such extreme differences as were noted between the pre-flight and the inflight date could not be accounted for on the basis of changes in renal function, and therefore must be attributed to either losses of urine prior to the addition of tritium or to undiscovered errors in the tritium dilution technique for calculation of volume. Therefore, with due acknowledg-

TABLE III

24-HOUR URINARY CREATININE EXCRETIONS

PRE-FLIGHT PHASE

Day	F.B. (Gm.)	J.L. (Gm.)	E.W. (Gm.)	M.C. (Gm.)
T-12	2.2782	1.7693	2.6570	2.2216
T-11	2.2490	1.8499	2.6332	2.1940
T-10	2.1899	2.0545	2.5772	2.3300
T-9	2.4357	2.2465	2.8481	2.4253
T-8	2.2773	2.1299	3.0074	2.7678
T-7	2.2995	2.1831	2.7599	2.3635
T-6	2.4166	2.4570	3.0574	2.6948
T-5	2.3623	2.2022	2.9920	2.1441
T-4	2.2525	2.1980	2.9212	2.2209
T-3	2.0890	2.4046	2.9567	2.3617
Mean	2.2850	2.1495	2.8410	2.3724
s.d.	.0980	.2047	.1642	0.1985

TABLE IV

INFLIGHT 24-HOUR URINARY CREATININE EXCRETIONS

Day	F.B.* (Gm.)	J.L.+ (Gm.)
1	1.6760	1.1980
2	1.4721	1.4744
3	1.3216	----
4	1.5834	1.6672
5	1.4232	2.1074
6	1.4949	1.7365
7	2.1146	1.7632
8	1.4196	2.0850
9	1.4415	1.8489
10	1.7532	2.0317
11	1.9849	1.5812
12	2.0556	1.6242
13	1.6650	1.2397
14	1.2022	1.8944
Mean	1.6148	1.7545
s.d.	0.2677	0.2479

* - Mean of pre-and post-flight: 2.3968
\+ - Mean of pre-and post-flight: 2.1963

ment of the probable error, it was decided to correct all inflight urinary excretion values on the basis of presumed "true" urinary creatinine excretion (table IV). This latter value was calculated as the mean of urinary creatinine excretion of the 10 pre-flight control days plus the 4 post-flight control days for each of the two astronauts studied in flight.

3. Fecal specimens. No difficulties were encountered in the collection of fecal samples either pre-flight, inflight, or post-flight. As part of the preservative technique for the inflight phase, a lipid soluble dye preservative mixture was added immediately after passage of the stool. This dye led to false values for the estimations of inflight excretion of stool total lipids.

4. Sweat collections. No apparent difficulties were noted in the collection and estimation of sweat losses during any of the phases studied.

DISCUSSION:

The principal goal of these studies has been to measure changes, if any, that may have been produced by the period of near-zero gravity in space in total body metabolism related to the musculoskeletal system. Changes in excretion of other body constituents are of interest insofar as they may demonstrate effects on the primary targets systems.

Calcium Metabolism: Since 99% of the body calcium is in the skeleton, changes in the economy of this element reflect skeletal changes. Immobilization by disease, or as an experimental situation, results in increased bone resorption (9) leading to hypercalciuria and eventual skeletal osteoporosis. In figure 1, urinary excretion of calcium is plotted against time for astronaut F. B. No significant change was seen in the first seven days of space flight, but a marked increase occurred starting at about the eighth day, and persisted during the four days of observation after flight. Since dietary intake of calcium was somewhat lower during flight than during the pre- and post-control phases, and since fecal excretion of calcium remain relatively unchanged, the net balance of calcium during flight (fig. 2) was significantly more negative for this phase.

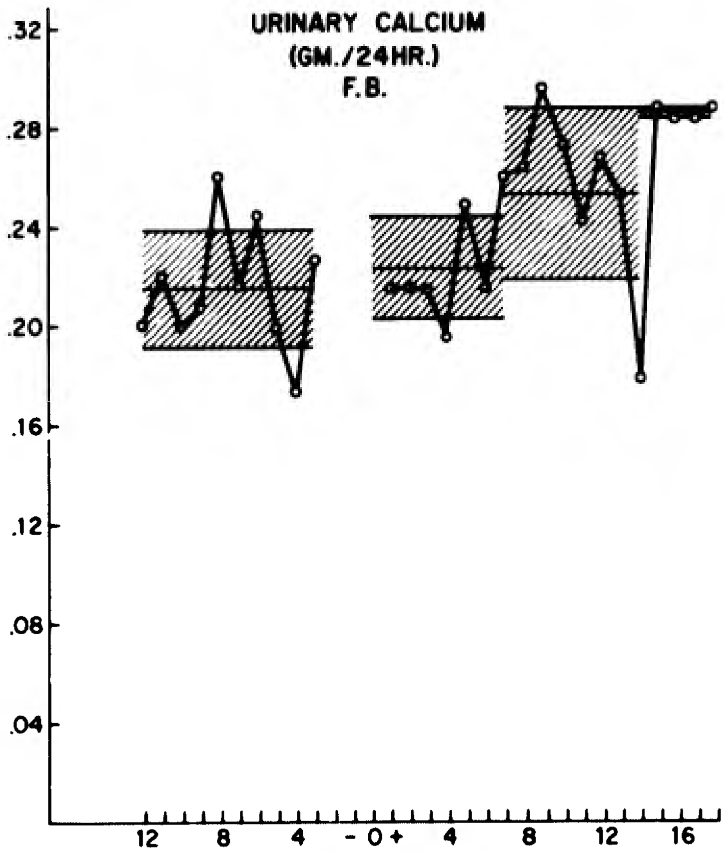


Figure 1

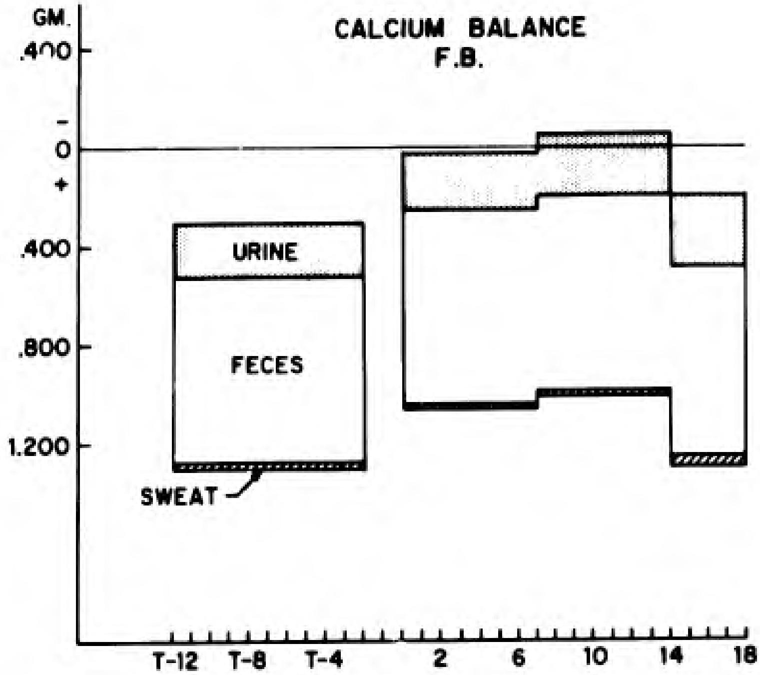


Figure 2

The data for astronaut J. L. are less striking. Urinary excretion of calcium (fig. 3), during control phases was much less than that seen with F. B.; the excretion in flight was not significantly greater than pre-flight; however, the excretion during the second week was greater than that during the first week of flight, and remained so during the four days after recovery.

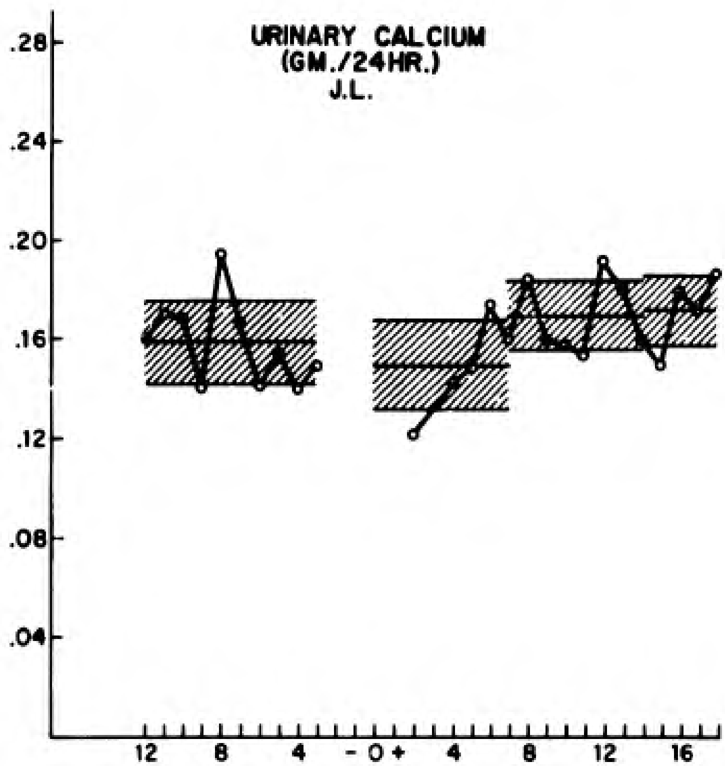


Figure 3

Since, in this individual, too, dietary intake of calcium inflight was less than during the control phases, and since, furthermore, fecal excretion increased during flight, there was significantly less positive balance of calcium during the weightless phase (figure 4).

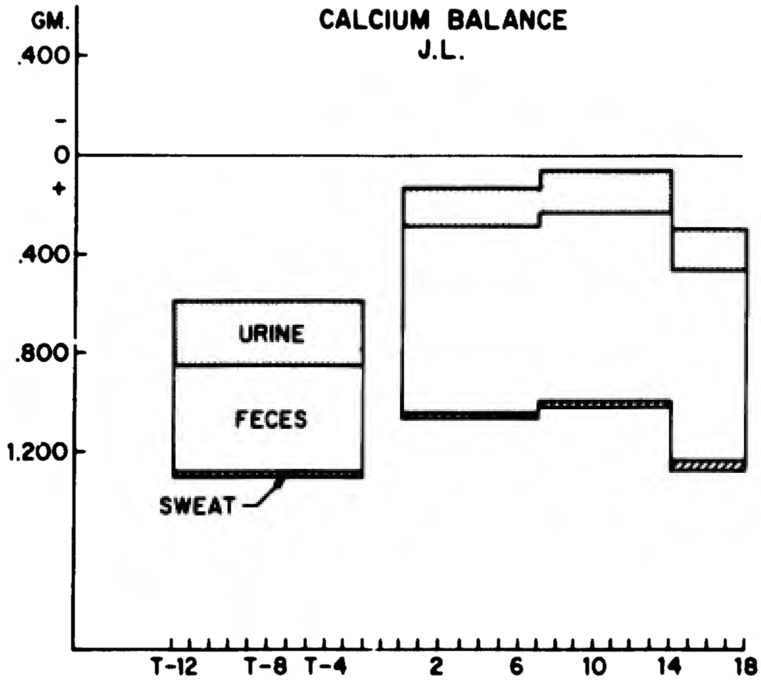


Figure 4

Of interest is that dermal losses of calcium, listed as "sweat", were low for both men in all phases and slightly higher during the relatively inactive post-flight recovery days.

Magnesium Metabolism: Approximately 5 to 40% of skeletal magnesium is available for turnover reactions, i.e., between 2 and 15 gms. (10). Urinary magnesium excretion is also a function of dietary intake, as well as of aldosterone production (11).

Urinary excretion of magnesium in astronaut F. B. is plotted in figure 5. No change occurred during the first week of space flight, but significantly increased amounts of magnesium were excreted in the second week, a pattern similar to that seen for calcium excretion. Starting inflight and persisting through the four days of recovery phase, urinary magnesium excretion fell dramatically. When the balance data are examined (fig. 6), the increased urinary excretion of magnesium during the inflight phase becomes of greater significance because this was seen in the presence of reduced dietary intakes. The positive balance during the post-flight period results from decreased urinary and fecal excretion both, while dietary intake was increased, suggesting repletion of previous losses.

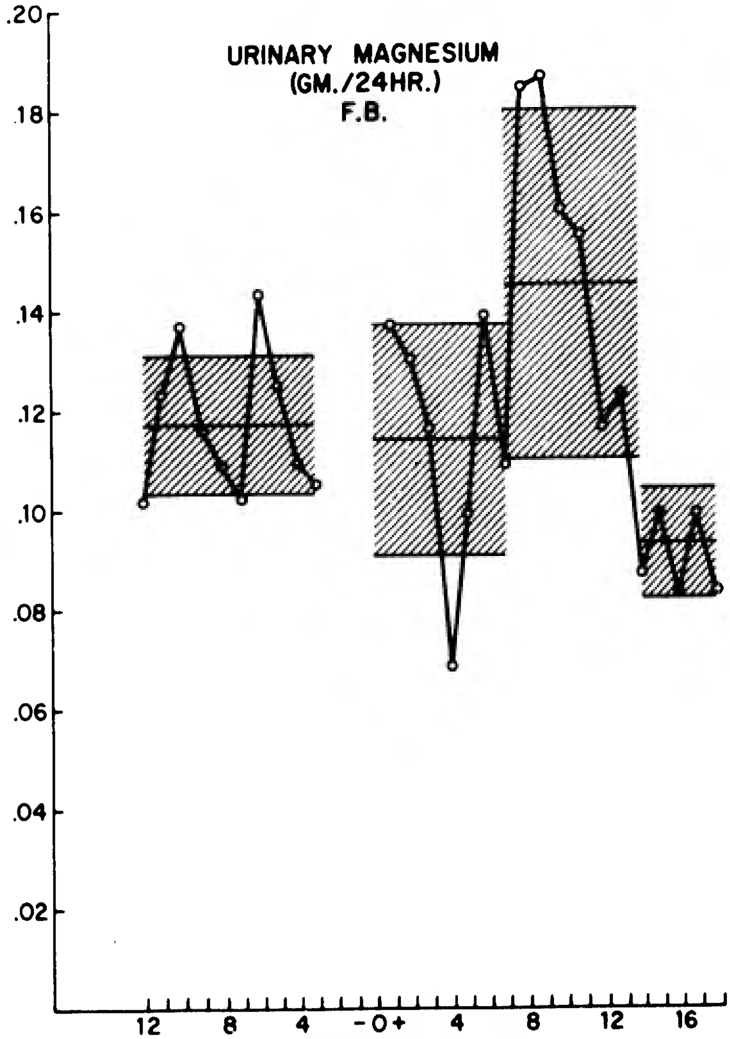


Figure 5

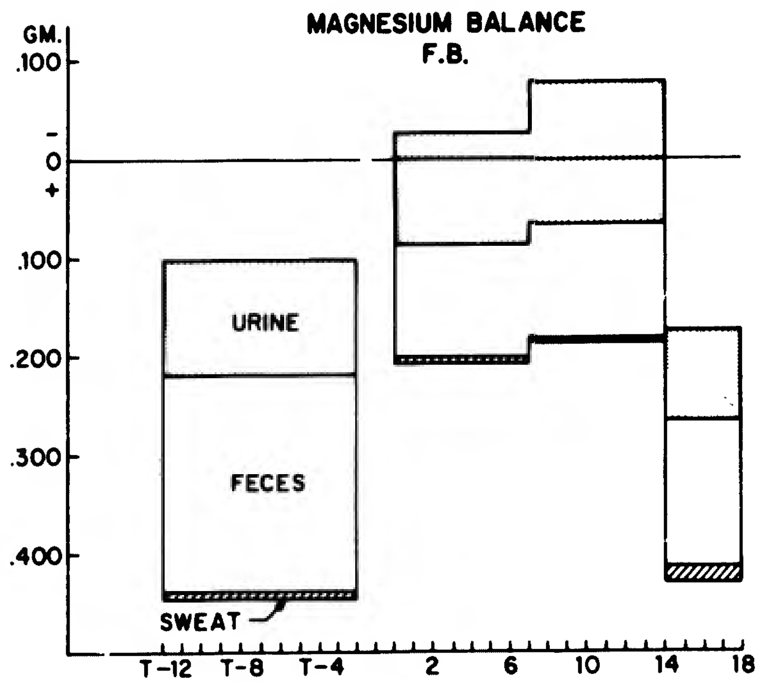


Figure 6

The data for astronaut J. L. (figs. 7 and 8), are qualitatively similar, but of lesser degree. The most significant change in magnesium metabolism demonstrated was that of post-flight retention.

Figure 7

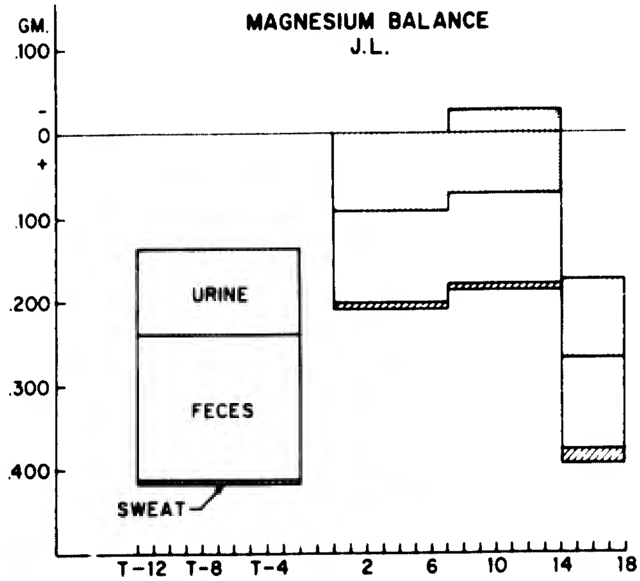
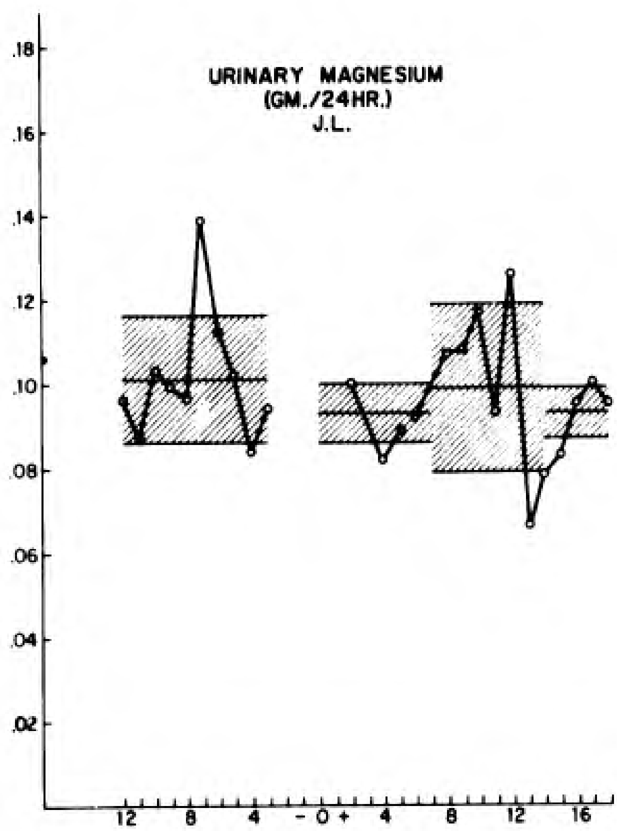


Figure 8



The data of dermal excretion demonstrated the relative insignificance of this route of loss in magnesium metabolism.

Phosphate Metabolism: Phosphate is present in the body as the principal anion in bone salt, as well as in protein and in soluble forms. Urinary excretion of phosphate is a function of dietary intake, bone salt turnover (45% of urinary calcium values), and of muscle metabolism (6.8% of urinary nitrogen excretion values) (12). In addition, carbohydrate metabolism may influence shifts of phosphate among body compartments.

The data obtained for astronaut F. B. (figs. 9 and 10), demonstrate an increase in urinary phosphate over the first nine days of space flight, occurring during the time when dietary phosphate was half that of the control values. Thereafter, despite relatively constant dietary intake, urinary excretion dropped to control values. Despite decreased fecal excretion, the balances became more negative during the flight, returning to the control levels after returning to ground level.

Similar results were obtained for astronaut J. L. (figs. 11 and 12).

Sulfate Metabolism: Urinary sulfate is derived primarily from protein catabolism (approximately 7% of urinary nitrogen) (12). Fecal sulfate is usually constant over a wide range of intake values.

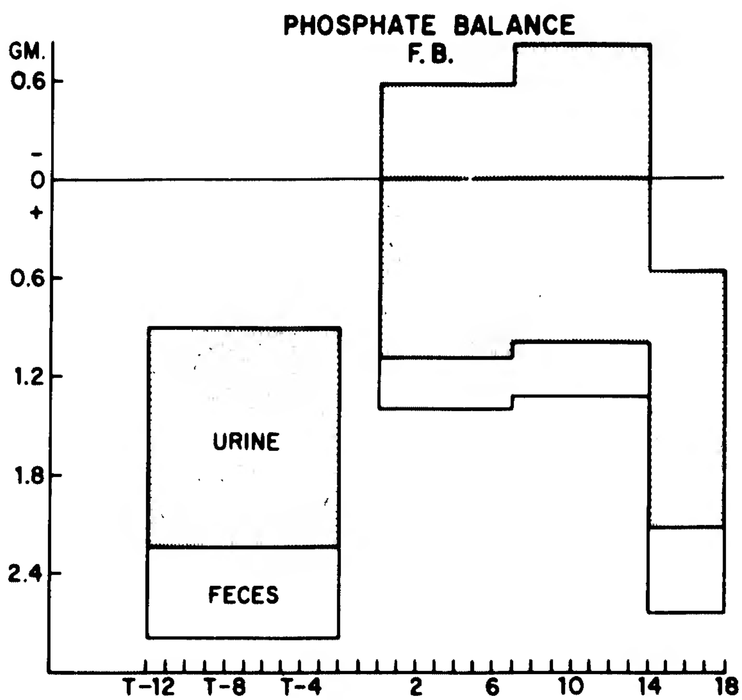


Figure 9

Figure 10

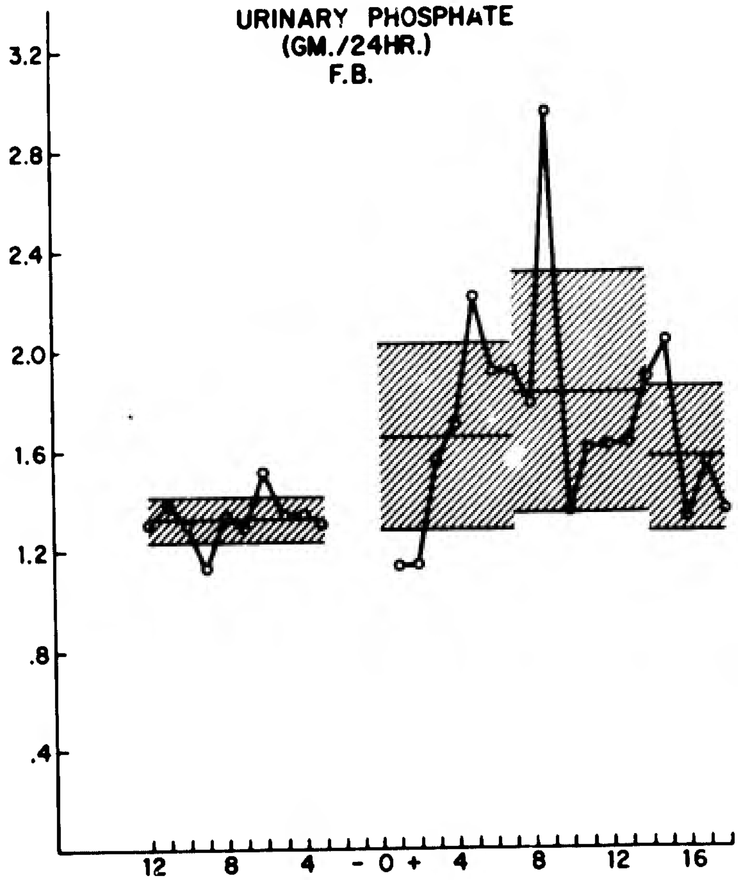
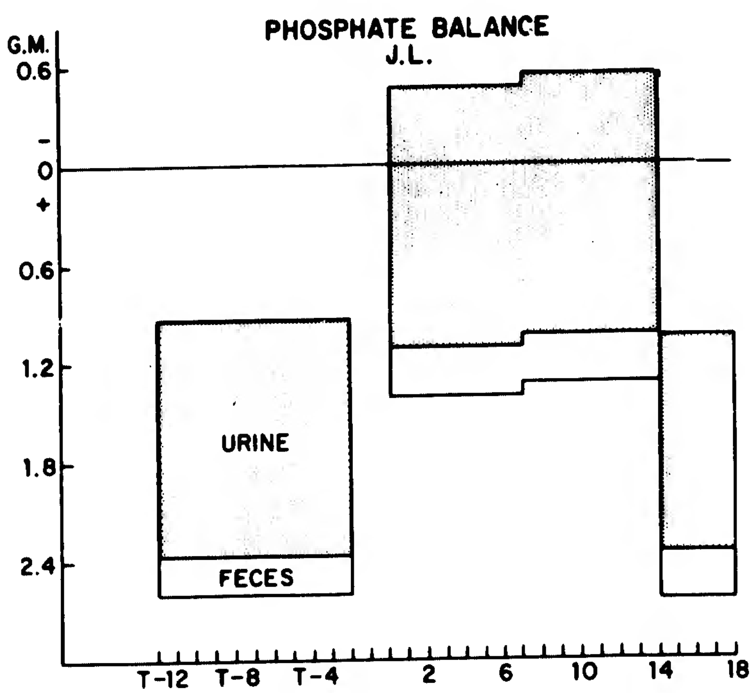


Figure 11



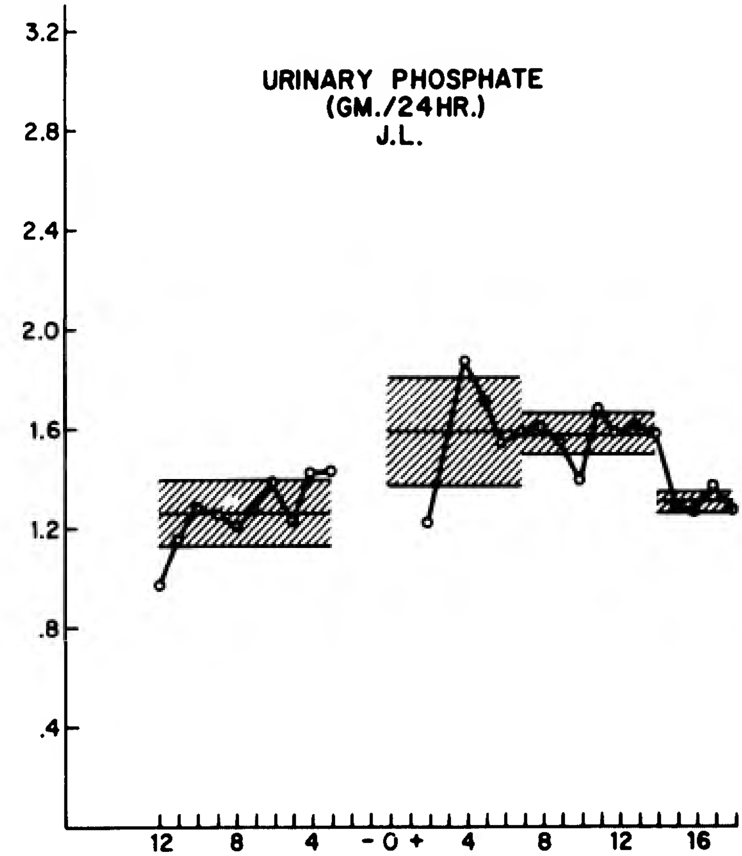


Figure 12

The sulfate excretion data for astronaut F. B. (figs. 13 and 14), show a slight fall in the urinary excretion during the space flight, and with a rise to slightly above control values during the post-flight period. Since the curtailment of dietary intake inflight was marked, these changes in excretion

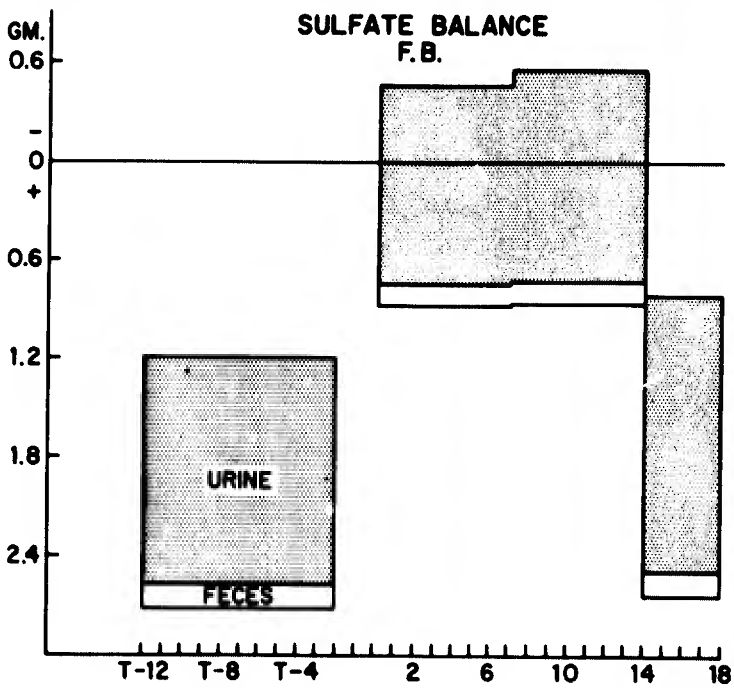


Figure 13

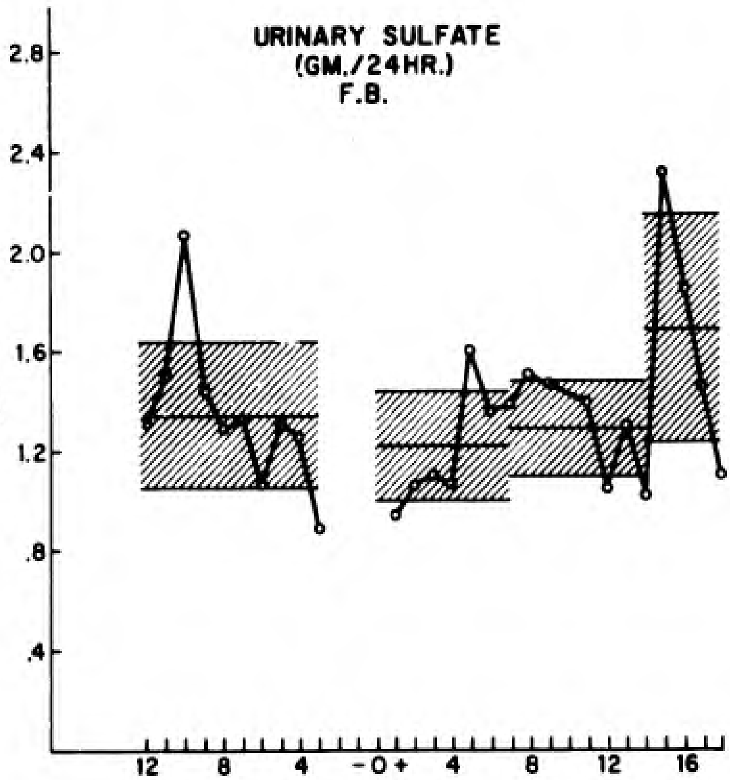


Figure 14

resulted in negative balance during flight, and returned to control balance levels post-flight.

Similar data were obtained for astronaut J. L. (figs. 15 and 16).

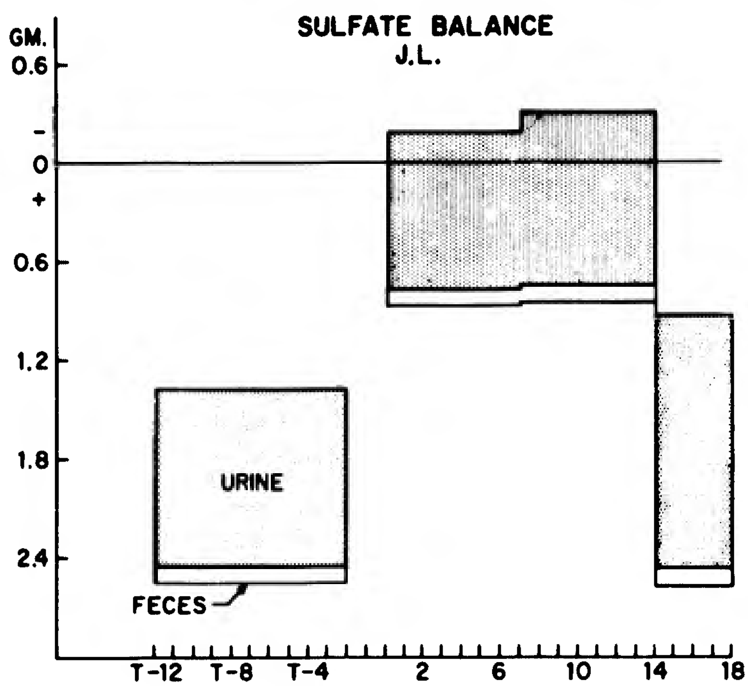


Figure 15

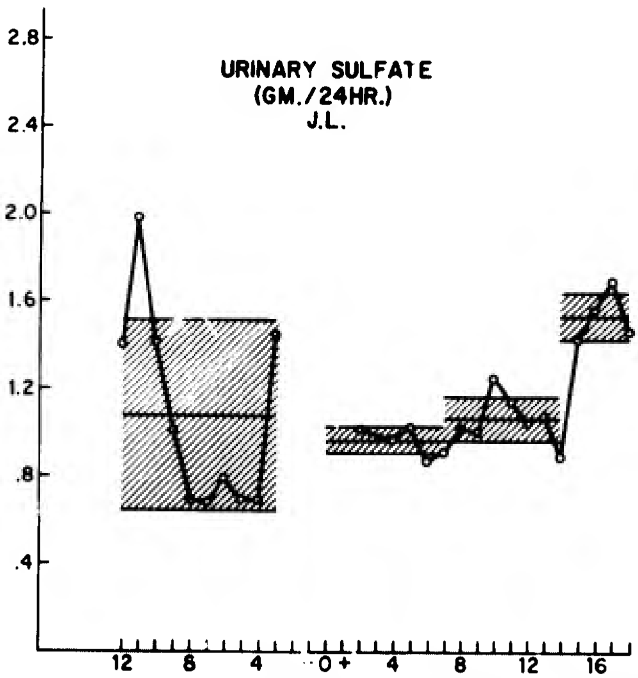


Figure 16

Nitrogen Metabolism: Fecal nitrogen is relatively constant over wide range of dietary intakes in any individual. Urinary nitrogen reflects dietary intake and protein metabolism.

In both astronauts F. B. and J. L (figs. 17 and 18), urinary nitrogen fell during flight and returned to pre-flight values during the post-flight phase.

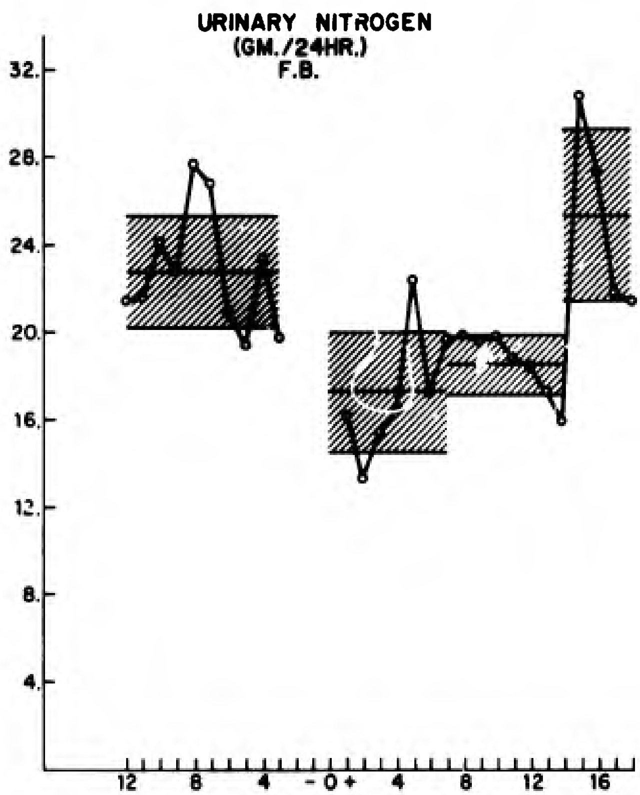


Figure 17

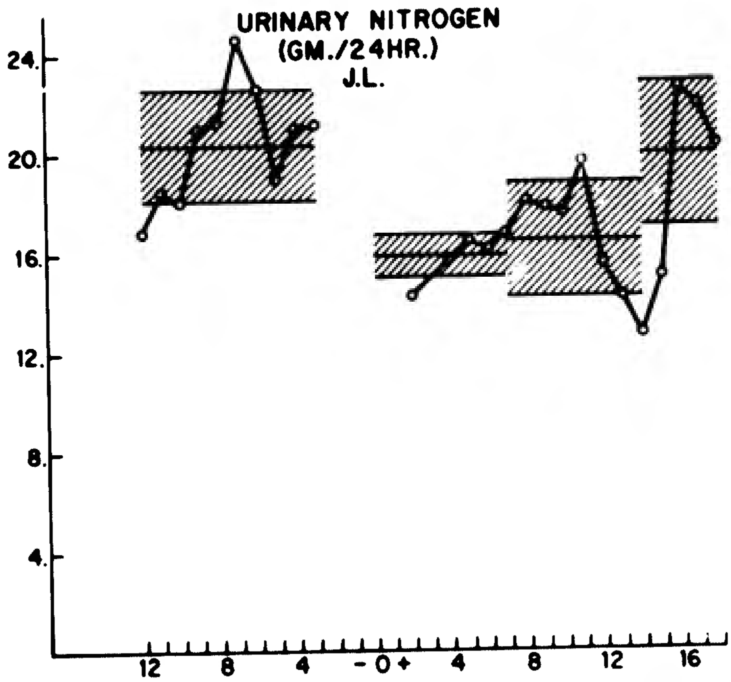


Figure 18

Dietary nitrogen was significantly less during the flight with the result that nitrogen balance became negative during this phase (figs. 19 and 20).

Sodium Metabolism: Urinary sodium is a function of dietary intake, of aldosterone activity, and of glucocorticoid secretion. Restriction of intake produces secondary hyperaldosteronisn with reduction of urinary sodium excretion. Fecal losses of sodium usually are small and relatively constant.

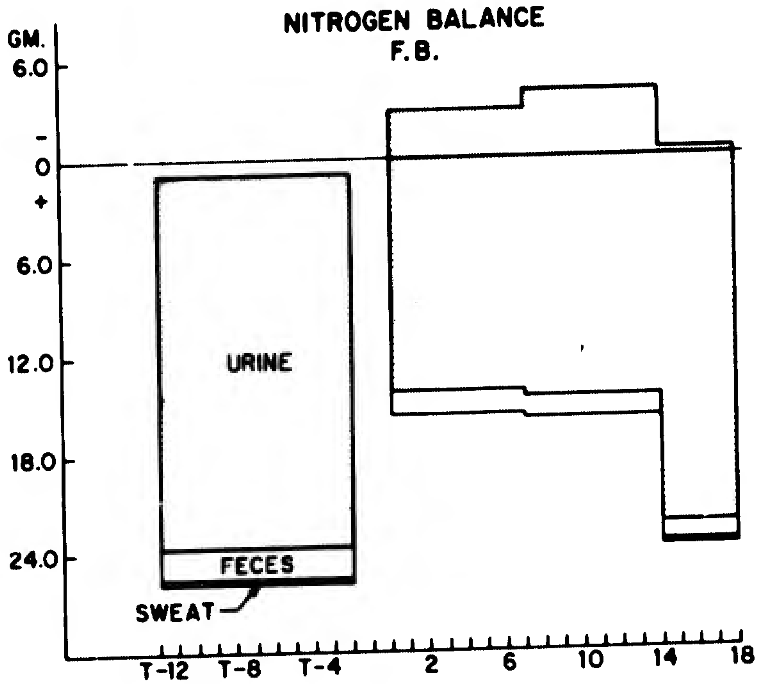


Figure 19

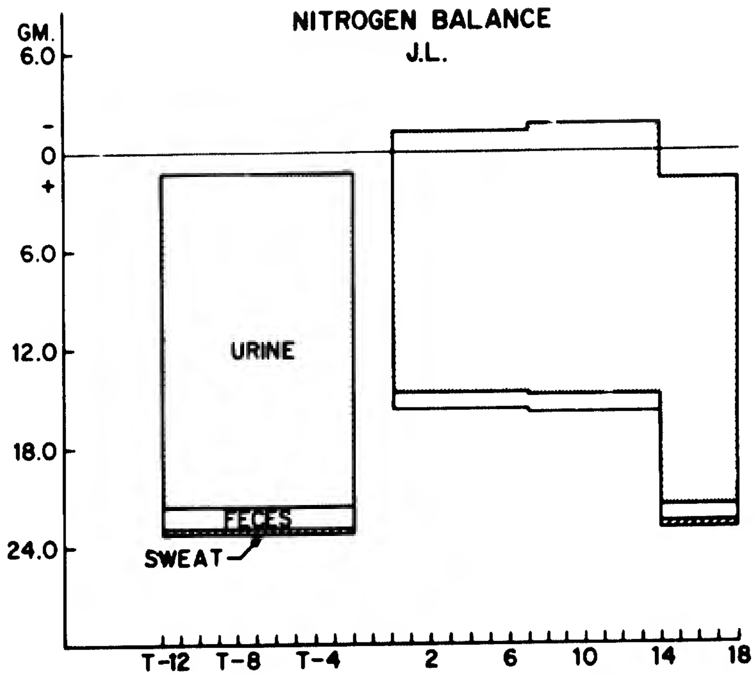


Figure 20

The two astronauts studied showed different patterns. In F. B. (figs. 21 and 22), despite the decrease in dietary sodium, there was an increased natriuresis during the first week of flight, return to control values during the second week, and significant retention in the early post-flight period.

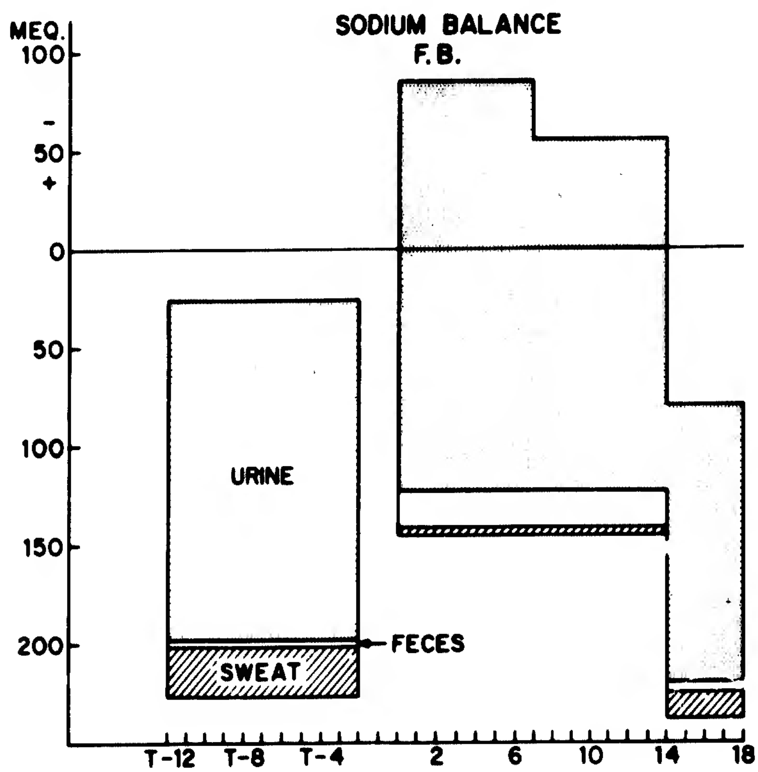


Figure 21

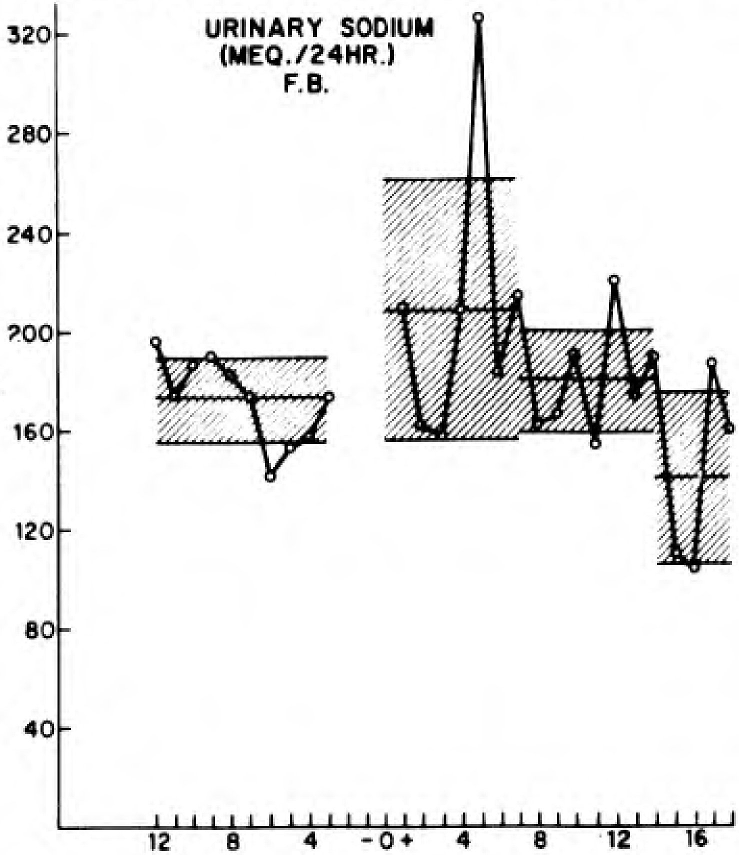


Figure 22

Conversely, J. L. (figs. 23 and 24), demonstrated no changes in sodium excretion during the first part of the space flight, a slight increase thereafter, and then marked retention post-flight.

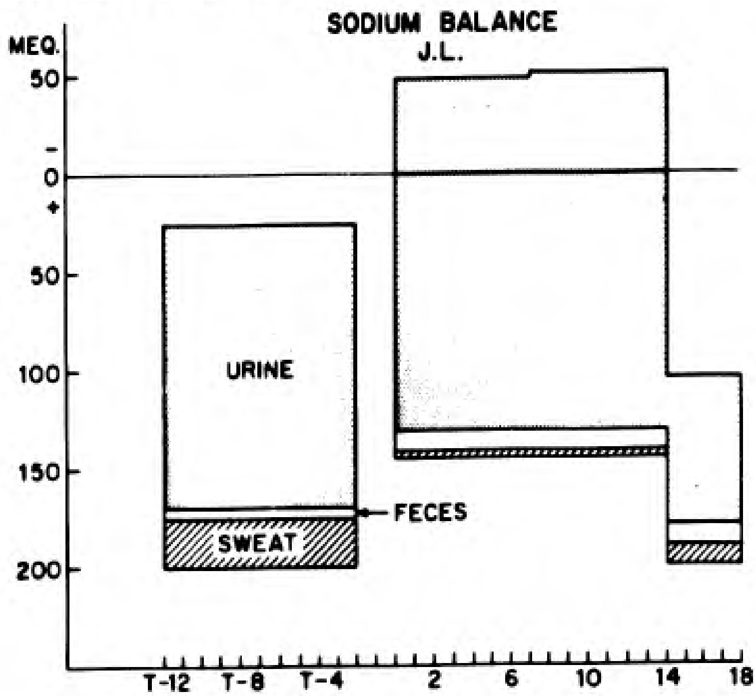


Figure 23

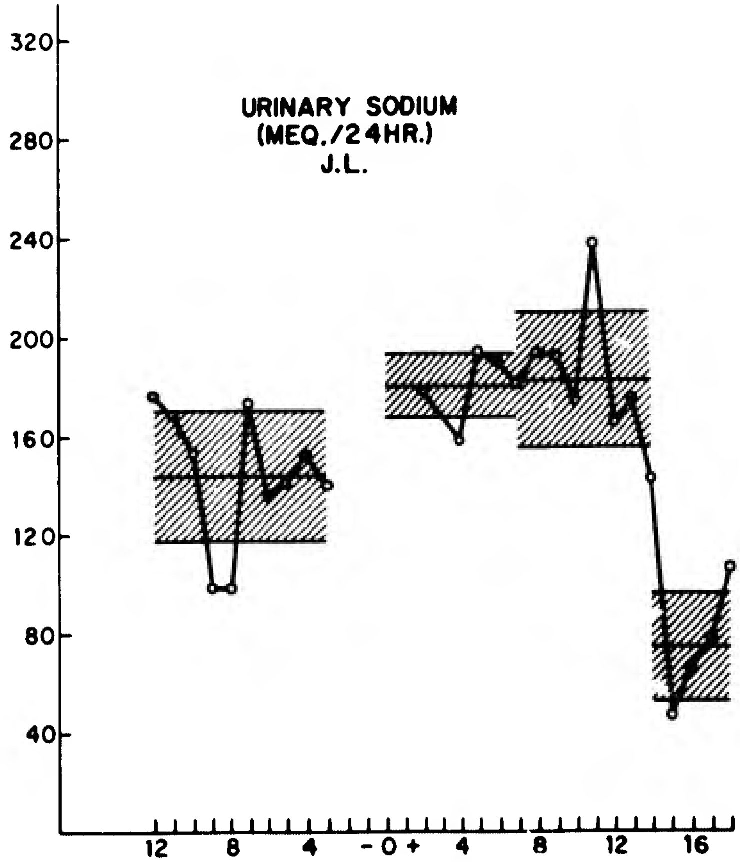


Figure 24

Correlation of these observations with measurements of urinary 11-hydroxycorticosteroids and aldosterone may shed some light on the mechanism. These observations must be taken into account in explanation of changes in urinary calcium since a correlationship between urinary calcium and urinary nitrogen has been demonstrated.

Potassium Metabolism: Urinary excretion of potassium reflects protein metabolism, aldosterone secretion, and glucocorticoid action. The variability in response seen with F. B. and J. L. may be due to variations in endocrine responses.

F. B. (figs. 25 and 26), showed an initial decrease in urinary potassium as a result of space flight in the presence of a marked decrease in dietary potassium. During the second week urinary potassium rose (which correlated with the simultaneous decrease in urinary sodium). Immediately post-flight potassium excretion fell to pre-flight values as the dietary intake was increased.

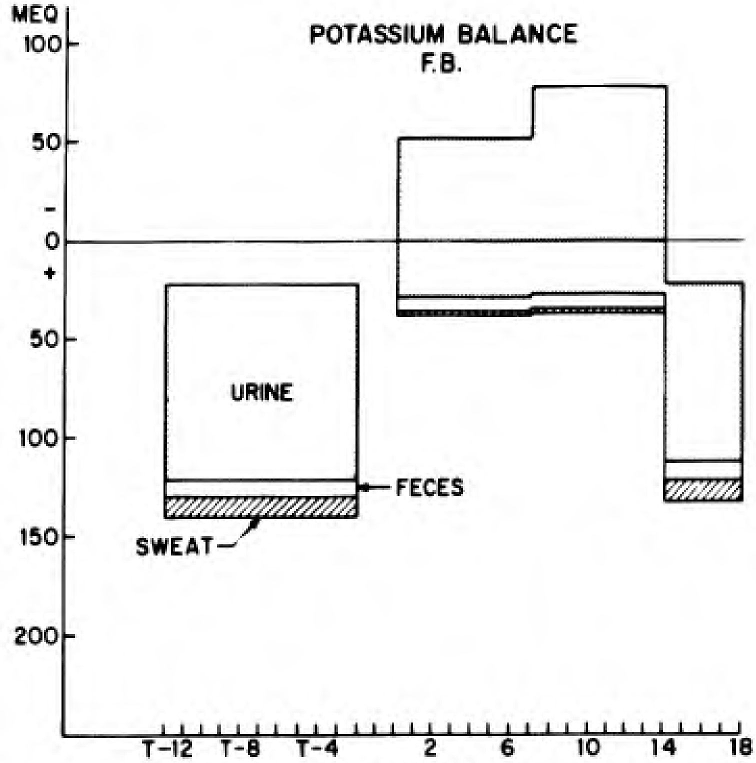


Figure 25

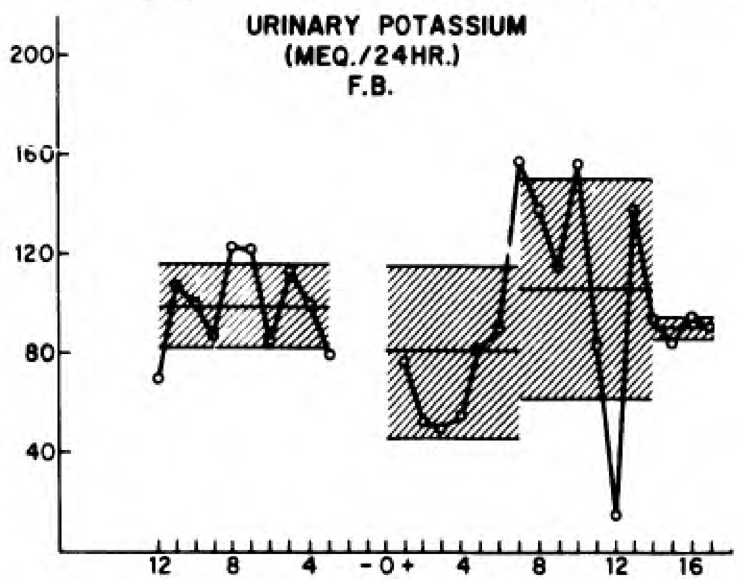


Figure 26

J. L. (figs. 27 and 28), showed only a slight fall in urinary potassium in the first week of flight despite the marked restriction in intake. During the second week the excretion fell further and then rose to pre-flight values during the recovery phase.

Chloride Metabolism: Chloride metabolism is controlled primarily by renal excretion, following, passively, the excretion of cations. Since sodium forms the largest proportion of renal cation, control of chloride depends chiefly on the control of sodium.

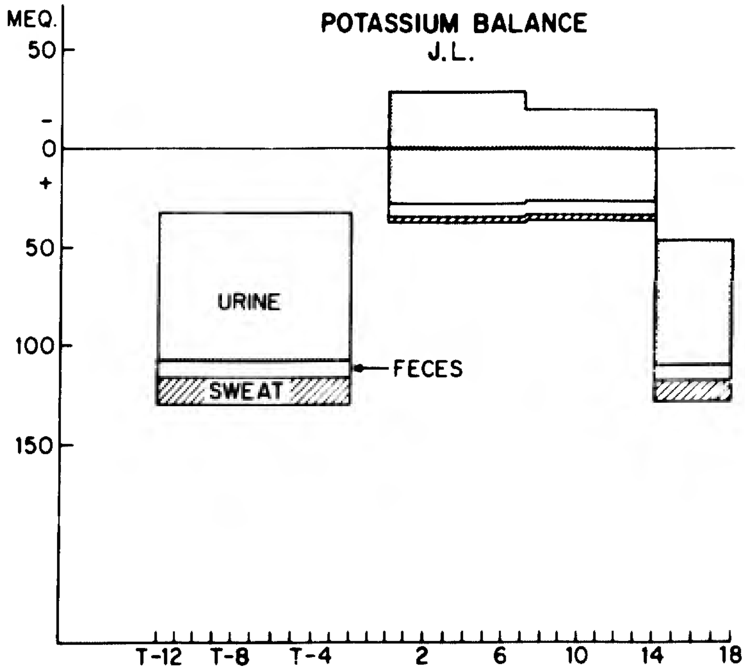


Figure 27

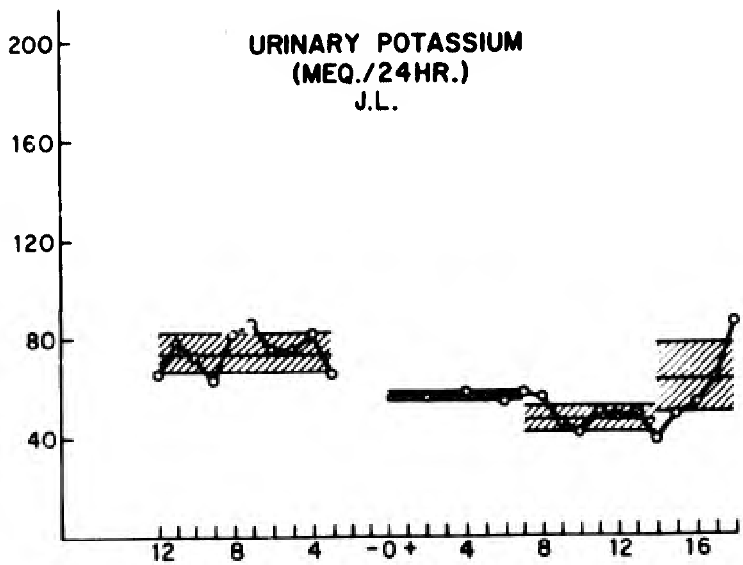


Figure 28

J. L. (fig. 29), showed a pattern of chloride excretion parallel to that of sodium excretion.

F. B., on the other hand, (fig. 30), excreted chloride in parallel with potassium. The reason for this discrepancy is not apparent.

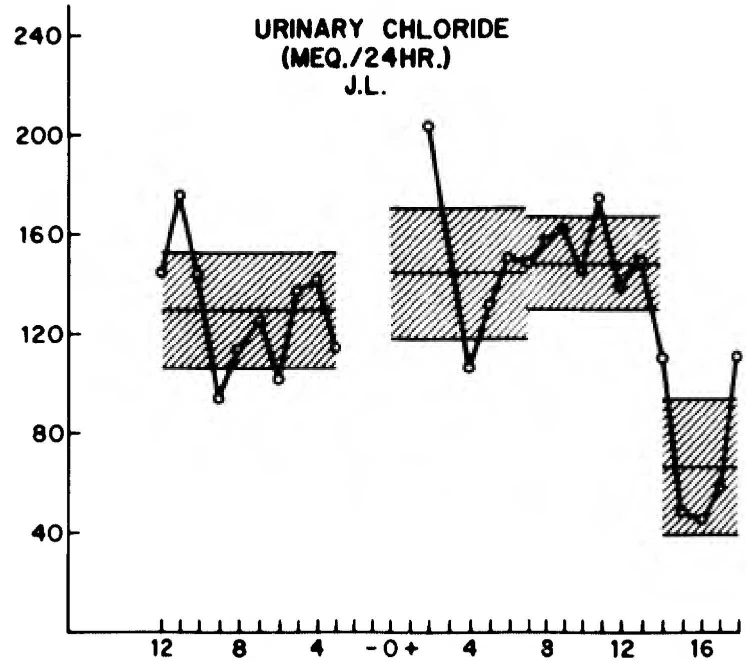


Figure 29

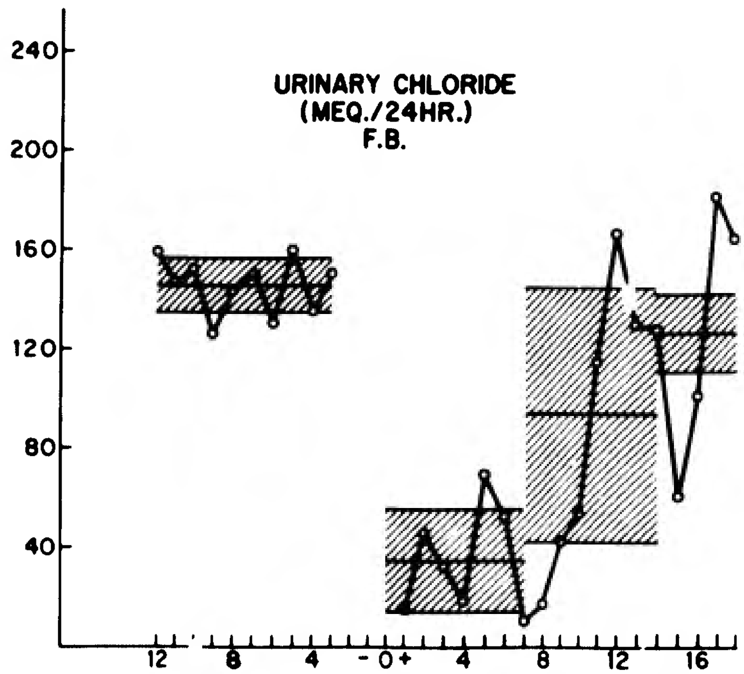


Figure 30

Balances of chloride were not calculated because of technical difficulties in measurement of dietary chloride.

Sweat Losses: Sweat was a significant route of loss only for sodium, potassium, and chloride in these studies. Sweat losses of calcium, magnesium, sulfate, phosphate, and nitrogen were low and insignificant in the calculations of balances.

SUMMARY AND CONCLUSIONS:

1. An attempt was made to perform complete metabolic balance studies on two astronauts during ten days pre-flight control phase, fourteen days of space flight, and four days of post-flight recovery phase, measuring intake and excretion of calcium, magnesium, phosphate, sulphate, nitrogen, sodium, potassium, and chloride.

2. Problems of engineering and experimental design prevented optimal performance during the inflight phase, resulting in variations in dietary control and losses of urine samples.

3. Considerable inter-individual variability was demonstrated, as would be expected, in all experimental parameters measured.

4. In one subject, significant increases in urinary calcium occurred during the second week of flight and persisted during the recovery phase.

5. Significant losses of phosphate were found inflight for both subjects with rapid recovery post-flight.

6. Little change in nitrogen metabolism was noted in either subject.

7. Patterns of excretion of sodium, potassium and chloride were different for each subject and were suggestive of changes in adrenal corticosteroid production.

8. Sweat losses of calcium, magnesium, sulfate, nitrogen, phosphate were insignificant during all three phases.

9. In order to arrive at generalizations concerning the effects of space flight on bone and muscle metabolism, more studies will have to be carried out in more subjects to account for individual variability, and under better control of dietary intake and collection of excreta.

ACKNOWLEDGMENTS

This discussion would be incomplete without the acknowledgment of the collaboration of Dr. G. Donald Whedon, Director of the National Institute of Arthritis and Metabolic Diseases, the co-principal investigator of this project and of Dr. Paul LaChance of the Manned Spacecraft Center, Houston, the in-house investigator. In addition, invaluable assistance was given by Miss Jeanne Reid of NIH, the dietician, who participated in the project, and by Dr. Keith Smith, formerly of NASA, who helped coordinate the many details.

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Hypodynamics: Cardiovascular Aspects

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HYPODYNAMICS: CARDIOVASCULAR ASPECTS

Colonel Timothy N. Caris, USAF, MC

The normal human heart and vascular system have tolerated and successfully withstood all of the stresses of orbital flight (up to fourteen days) and the associated prolonged exposure to zero gravitational forces ("weightlessness") except for one aspect. Following periods of "weightlessness," and upon re-exposure to normal gravity, varying degrees of transient orthostatic intolerance have been noted. Some of the pilots, both American and Soviet, have shown a tendency for fainting upon assuming the erect posture.

Until now, relatively few orbital flights have been made, and by necessity, only limited physiologic studies could be performed during these periods in order to evaluate this problem.

Fortunately, physiologic analogy to "weightlessness" can be obtained with subjects exposed to the recumbency and immobilization of prolonged bed rest or with total immersion of the body in water.

In all three situations--orbital flight, prolonged bed rest, or total body water immersion--similar changes in cardiovascular regulatory mechanisms develop that may well explain this orthostatic postural intolerance.

When man stands erectly, his large arteries and large veins are parallel to the normal gravitational field, and the weight of the columns of blood that fill them produces a significant hydrostatic pressure. Although blood leaves the heart and flows through the arterial system under a considerable "head of pressure," the propelling force is dampened considerably as blood flows through the myriads of smaller and smaller arterial subdivisions, through the huge beds of capillaries, and then finally into the veins.

For venous blood to return to the heart from the greater part of the body that lies below the level of this organ, the cardiovascular system must provide compensatory mechanisms to overcome the effects of hydrostatic pressure due to normal gravity. Such is the case, and the greatest part of the blood volume is returned back to the heart. If for any reason, the return of venous blood to the heart were to be inadequate, then cardiac output would similarly be diminished. As a consequence, there would be insufficient perfusion of the brain with blood with ensuing loss of consciousness or fainting.

As early as 1931, it was observed that when man assumed the erect posture here on earth under the influence of the normal 1G force of gravity and stood quietly for 40 minutes, there was a decrease of 15% in the total circulating blood plasma volume (1). Subsequent studies show that standing quietly for a period of time results in pooling of some of the plasma volume in the arterioles, capillaries, veins, and in the tissue spaces of the lower extremities (2, 3) because of the increased hydrostatic pressure. Man normally develops sufficient plasma volume, so that he can afford this degree of diminution of his circulating fluid with no untoward effects. The cardiovascular compensatory mechanisms mentioned earlier prevent progressively increasing pooling and insure a sufficient venous return and normal cardiac output.

If man is maintained in a recumbent position, the hydrostatic column of blood due to gravity shortens considerably. It changes in direction to one beginning with the anterior chest wall and continuing straight through to the back. The usual pooling of blood in the lower body noted with erect posture does not occur, and approximately 11% of the average blood volume is shifted from the lower extremities to the rest of the body, primarily into the vascular beds within the chest (4).

Under these circumstances, increasing amounts of both sodium and water are excreted through the kidneys until this shifted fluid volume is eliminated (5). The reason for this diuresis is not completely understood, but it appears that a volume receptor mechanism within the vascular system may be brought into play which decreases the secretion of aldosterone produced by the adrenal cortex (6). With a diminution of this hormone, the normal sodium reabsorption by the kidney is curtailed, and sodium with water is excreted. In addition, the increased circulating blood volume results in increased filling of the chambers of the heart. Such a situation stimulates still another response (Henry-Gauer reflex) which leads to increased water excretion by inhibiting the normal production of antidiuretic hormone by the pituitary gland (5, 7).

With total body immersion in water, the normal gravitational force influencing the body is opposed by the pressure of the immersion fluid outside the body. In this manner, "weightlessness" can be produced, and effects of hydrostatic pressures within the body virtually eliminated. It has been shown that immersion results in redistribution and excretion of body fluids very similar to those described with recumbency (8).

The limited amount of pertinent information available regarding man in orbital flight strongly suggests that similar body fluid responses occur under the zero-G environment as well (9).

It would seem logical to assume that the body fluid responses elicited by "weightlessness" are adaptive mechanisms to the new environment and of no consequence during space flight. When man returns to earth and is exposed again to normal gravitational forces, however, he no longer has the plasma volume to afford the usual quantity of fluid that pools in his lower body when he stands up. He has excreted that portion as excess during his adjustment to "weightlessness," He finds himself with an insufficient plasma volume to stand. There is a decreased volume returning to the heart; brain perfusion consequently may be compromised, and fainting may occur.

Such a simple explanation, however, is inadequate.

In studies using prolonged bed rest, there is no correlation between the amount of blood volume loss and the degree and incidence of intolerance to orthostasis among the subjects (10). When the hormone 9-alphafluorohydrocortisone is administered during prolonged bed rest so that sodium and water are retained despite "weightlessness," and plasma volumes are maintained as pre-bed rest levels, tolerance to subsequent orthostasis is not improved (11).

After prolonged bed rest, there is evidence to suggest that excessive pooling of blood occurs in the lower extremities when man assumes an upright position (12). Leg circumference during erect posture after periods of bed rest increases significantly, and purpuric hemorrhages in the skin of the feet and ankles are prevalent, suggesting increased fragility of the small capillaries. Perhaps under these conditions, the vessel walls are more permeable to plasma fluid and allow greater quantities to escape into the tissue spaces.

It would seem rational, then, that in addition to the loss of plasma volume that definitely occurs during weightlessness, we should concern ourselves with possible disturbances that may also occur in the compensatory mechanisms that normally protect and enable man to cope with the hydrostatic pressure produced by standing in his normal environment. These mechanisms prevent progressively increasing pooling in the lower body and insure a sufficient venous return and adequate cardiac output (2, 3, 13, 14). They include: 1) an increase in heart rate, 2) a pumping action of normal respiratory activity that tends to draw blood up the veins and into the heart, 3) external counter pressure applied on blood vessels by adjacent tissues, 4) active constriction of the diameters of vessels of the dependent vascular beds mediated through the liberation of norepinephrine, and 5) a pumping action by the leg muscles. The majority of the large veins of the lower extremities are situated in direct proximity to large muscle groups. The normal, at times imperceptible, contraction and relaxation of opposing muscle groups that occur continuously to maintain balance, even though man is standing still, provide a "milking-up" action, propelling blood up the veins toward the heart.

At our present level of understanding, it would appear that a zero-G environment produces a redistribution of body fluids, some loss of total plasma volume and, conceivably, a temporary impairment of the normal circulatory compensatory mechanisms that are needed to withstand the normal hydrostatic pressures of the gravitational forces here on earth. Muscular weakness and atrophy may well result from "weightlessness" (18, 19). There may be associated weakness, decreased tolerance for exercise and loss of support for leg veins (4). There may be a deconditioning of vasomotor tone with sluggish liberation of or poor response to norepinephrine (20, 21).

It would seem that this problem can be solved best by developing means to provide a physiologic analogy to gravity that may be used during exposure to zero-G environments.

Orthostatic intolerance after total body immersion can be prevented by simulating the hydrostatic pressure effects of gravity by inflating venous tourniquets repeatedly on all four extremities during immersion (15).

It seems logical that repetitive artificial pooling of blood in the lower extremities during periods of "weightlessness" may prevent the expected loss in plasma volume and stimulate activity of the normal circulatory compensatory mechanisms, conceivably preventing their deconditioning. To this end, a lower body negative pressure box has been developed at the School of Aerospace Medicine. Preliminary studies show that exposure to the lower half of the body to negative pressure for only two to three days following a period of prolonged bed rest results in plasma volume repletion (16) and complete tolerance to orthostasis (17).

Considerable investigation is being planned also to evaluate various exercise programs during "weightlessness" to determine their influence on the maintenance of orthostatic tolerance.

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Erthrokinetic Changes in Man Associated With Bed Rest

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ERYTHROKINETIC CHANGES IN MAN ASSOCIATED WITH BED REST

Captain Bernard S. Morse, USAF, MC

INTRODUCTION

The advent of manned orbital flight presents several physiological problems not heretofore relevant in normal steady-state bodily functions. With the use of ground-based environmental systems, such problems as cabin atmosphere and confinement have been investigated; however, the effects of prolonged zero gravity cannot be studied by means less difficult than orbital space flight. Data gathered from the Gemini missions already indicate alterations of cardiovascular dynamics and loss of blood volume. Similar changes have been noted in man during studies of water immersion and bed rest. In these situations the absence of major muscular effort and reduced workload upon the circulatory system simulate to some degree what would be expected during weightlessness. It has become generally accepted that immobilization imposed by simple bed rest serves as the best present model for predicting man's response to prolonged zero gravity. Taylor et al (1) in 1945 described a loss of blood and plasma volume and alterations in cardiovascular dynamics after 3 weeks of simple bed rest in normal healthy volunteers. Dietrick et al (2) in 1948 confirmed and extended these studies to include a loss of muscle mass, slight decrease in basal metabolic rate, and negative mineral balances (N, Ca and P). Miller et al (3) in a four week bed rest study observed, in addition to the loss of plasma volume, an appreciable decrease in the red cell mass. The red cell mass values were, however, obtained indirectly from radio-iodinated serum albumin plasma volumes and are subject to criticism because of an uncertain relationship between body and venous hematocrits when the steady state is perturbed. It is the purpose of this report to document the loss of red cell mass that occurs during bed rest with the use of a direct red cell label and to elucidate the erythrokinetic changes that lead to the loss of red cell mass.

MATERIALS AND METHODS

Bed Rest Subjects: Thirteen normal healthy male Air Force volunteer subjects were employed for the bed rest protocol. The first group was composed of five rated Air Force pilots, 28 to 33 years of age. The next two groups were composed of four subjects each, airmen basic volunteers, ages 18 to 22. All subjects were housed in an air-conditioned metabolic ward. The pilots were fed a 2800 calorie metabolic diet and the remaining groups were fed a general diet. Multivitamin supplementation, which included vitamin B_{12} and folic acid, was given daily.

The experimental protocol consisted of a 20-day adjustment period, 35 days of continuous absolute bed rest, and then a 20-day recovery period. During bed rest, the subjects were allowed to lean on one elbow for meals and were allowed to sit up only for bowel movements. Throughout adjustment and recovery periods they were encouraged to participate in occupational therapy, walks, and 5 Bx's.

Control Subjects: Eight normal healthy male Air Force volunteer subjects were used to control such variables as age, blood letting, seasonal changes, and stability of red cell and plasma volumes. This group consisted of airmen basic volunteers, ages 18 to 22, and enlisted Air Force personnel, ages 25 to 40, permanently stationed at Brooks Air Force Base.

Methods: All blood was obtained by venipuncture at 0730 in the fasting state. Standard laboratory procedures were employed for hemoglobin, microhematocrit, and serum bilirubin. Red cell counts were performed with a Coulter model B Counter and reticulocytes were estimated from peripheral blood smears supravitally stained with new methylene blue. Serum iron was measured by the automated method of Zak and Epstein (4), and autohemolysis was performed according to the method of Selwyn and Dacie (5). Saline washed Cr^{51} labeled autologous erythrocytes were employed for red cell mass determinations and red cell half-life estimates. The red cell mass determinations were performed in all subjects at the beginning of adjustment and bed rest periods and at the completion of bed rest and recovery periods. Nine of the 13 subjects had an additional red cell mass performed on the 24th day of bed rest. Red cell survival studies, complemented by red cell mass determinations and body surface counting of Cr^{51}, were limited to the group of rated pilots. Half survival values of Cr^{51} labeled erythrocytes were calculated from regression slopes fitted by the method of least squares. Plasma volumes were derived indirectly from the red cell mass using the corrected microhematocrit. All data have been graphed as the mean $\pm$ 1 standard error against the time axis. Probability values were derived with the analysis of variance technique, each subject serving as his own control.

RESULTS

There was an average loss of 183 ml of red cell mass at the end of 35 days of bed rest. In 12 subjects this decrease ranged from 68 ml to 328 ml of red cell mass (fig. 1). Only one of the 13 subjects showed no essential red cell mass change at the completion of bed rest. Regardless of the method of representation, the red cell mass plotted in ml of red cells (fig. 2), ml/kg (fig. 3), or ml/M^2 of body surface area, was significantly decreased ($p < 0.01$)* at the completion of bed rest. Red cell mass determinations in

*The term significant, throughout the remainder of the paper, refers to a p value of less than 0.01.

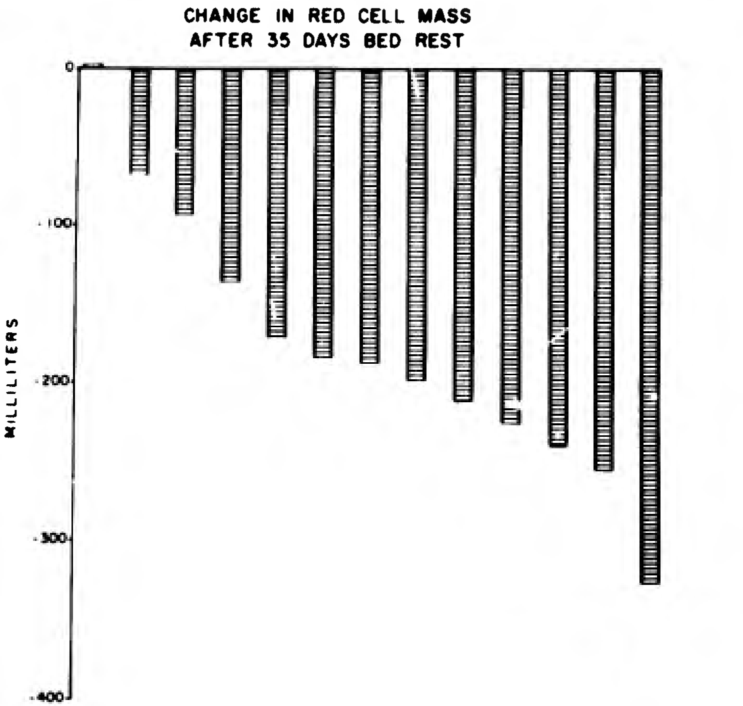

Figure 1. Change in red cell mass after 35 days of bed rest.

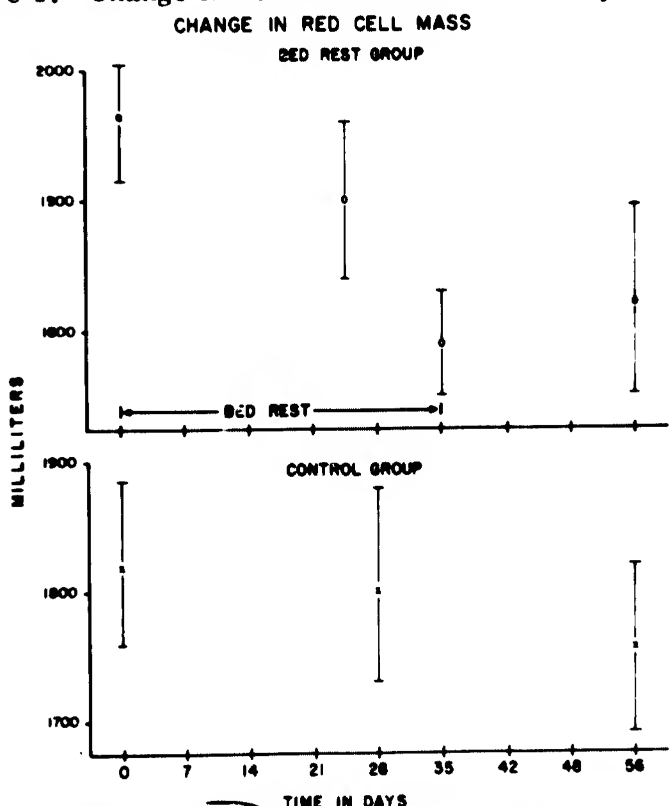

Figure 2. Red cell mass determinations (means ± 1 S. E.) at intervals throughout the study.

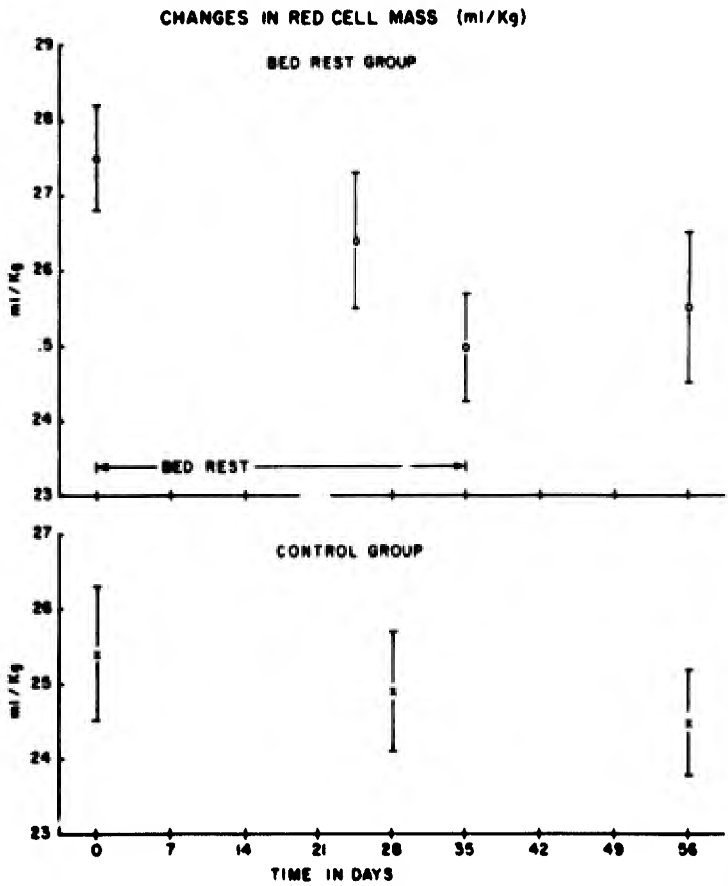

Figure 3. Red cell mass values plotted as a function of body weight in kg.

9 of the above 13 subjects performed on the 24th day of bed rest revealed a loss of 65 ml. Three weeks after the completion of bed rest, the red cell mass remained significantly below the pre-bed rest determinations.

Plasma volumes, although estimated indirectly from the red cell mass and corrected microhematocrit, showed a significant decrease of 200 ml during bed rest. Plasma volumes determined at the end of recovery, in contrast to the red cell mass, returned to values well above those obtained prior to bed rest (fig. 4). No significant alteration was noted in the plasma volume and red cell mass determinations performed on the control subjects.

Serial hematocrit values increased from 44 to 47% during the first two days of bed rest (fig. 5). Thereafter a near steady state was achieved and the hematocrit remained relatively stable, although decreasing slightly throughout the remainder of bed rest. There was a rapid decrease in hematocrit from 45 to 40% when ambulation was resumed. Hematocrit values then slowly increased over the next three weeks, but never quite returned to pre-bed rest values. Changes in hemoglobin concentration paralleled those of the hematocrit values and as a consequence the mean corpuscular hemoglobin concentration remained stable (fig. 5).

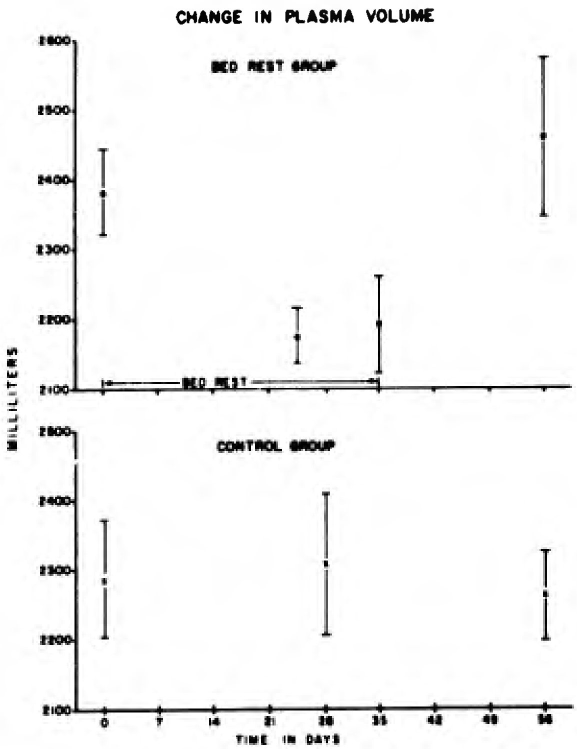

Figure 4. Plasma volume measurements at intervals throughout the study.

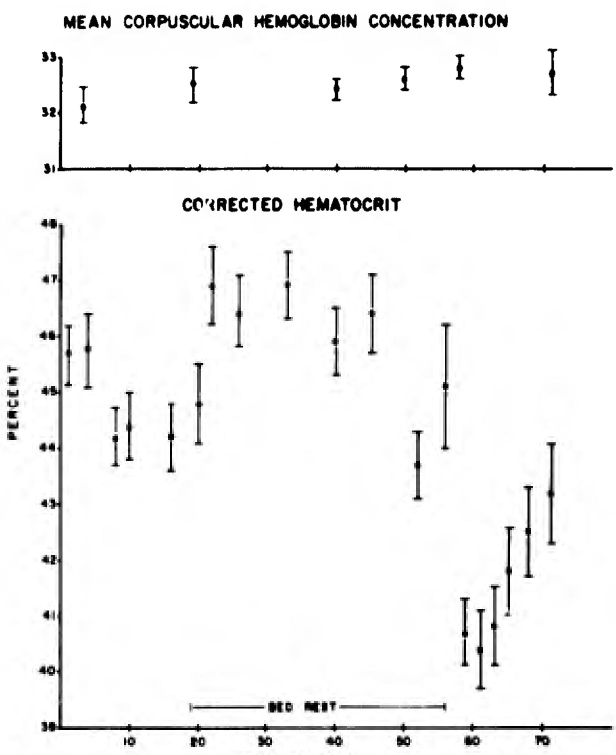

Figure 5.

Serial changes in corrected microhematocrit are shown in the lower portion of the graph and MCHC in the upper portion.

The data clearly indicate that a significant reduction in red cell mass occurs during bed rest, a reduction which must be explainable on the basis of one or more of the following mechanisms; blood loss, hemolysis, sequestration of red cells, and decreased erythropoiesis. Stool tests for occult blood were consistently negative. Serum bilirubin and red cell autohemolysis were unaltered during bed rest (fig. 6). Cr^{51} red cell half survivals started on the first and twenty-fourth days of bed rest, respectively, were comparable to the pre-bed rest values (table I). It should be noted, however, that a mild hemolytic process may be inferred from the data compiled after the completion of bed rest. For example, the Cr^{51} red cell half survival during this period of time was 20.7 days which differs significantly from pre-bed rest and bed rest values which ranged between 25 and 28 days. In addition, red cell autohemolysis increased to 2.8% during the recovery

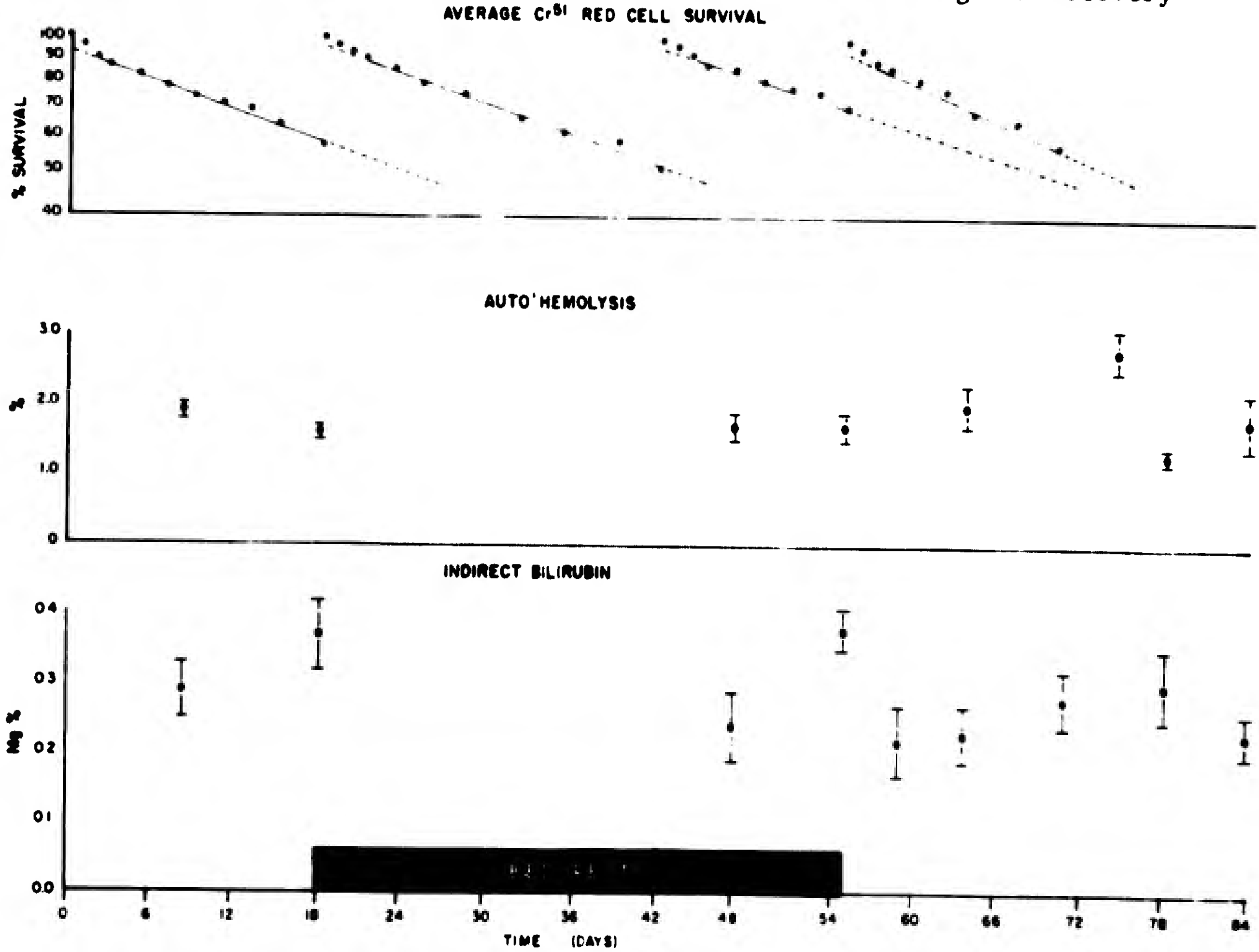

Figure 6. Serial changes of indirect serum bilirubin and rate of autohemolysis are illustrated in the lower portions. The upper portion of the graph illustrates average Cr^{51} red cell survival curves. Each curve has been extended by an interrupted line so that it bisects the half survival value.

TABLE I

Cr^{51} red cell half survival values. Period I corresponds to pre-bed rest control, periods II and III to the first and 24th day of bed rest, respectively, and period IV to recovery.

Cr^{51} RED CELL	T -1/2 (days)
CONTROL PERIOD	25.4 ± 1.1
BED REST I	26.7 ± 0.9
BED REST II	28.7 ± 0.8
AMBULATION	20.7 ± 0.7

period, a value substantially higher than those recorded prior to the completion of bed rest. Body surface counting for Cr^{51} appears to exclude splenic red cell sequestration (spleen/heart ratio remained below 0.5). Additional evidence against sequestration may be inferred from complete mixing of labeled cells in the circulation within 12 minutes when red cell mass determinations were performed.

Although ferrokinetics have not as yet been employed as a measure of the rate of red cell production in our studies, calculations have been attempted from reticulocyte counts. Figure 7 illustrates the serial changes in per cent reticulocytes occurring throughout the course of bed rest and reambulation. There is a slight drop in reticulocyte per cent during bed rest and a definite reticulocytosis (1.8%) in the recovery phase. Figure 8

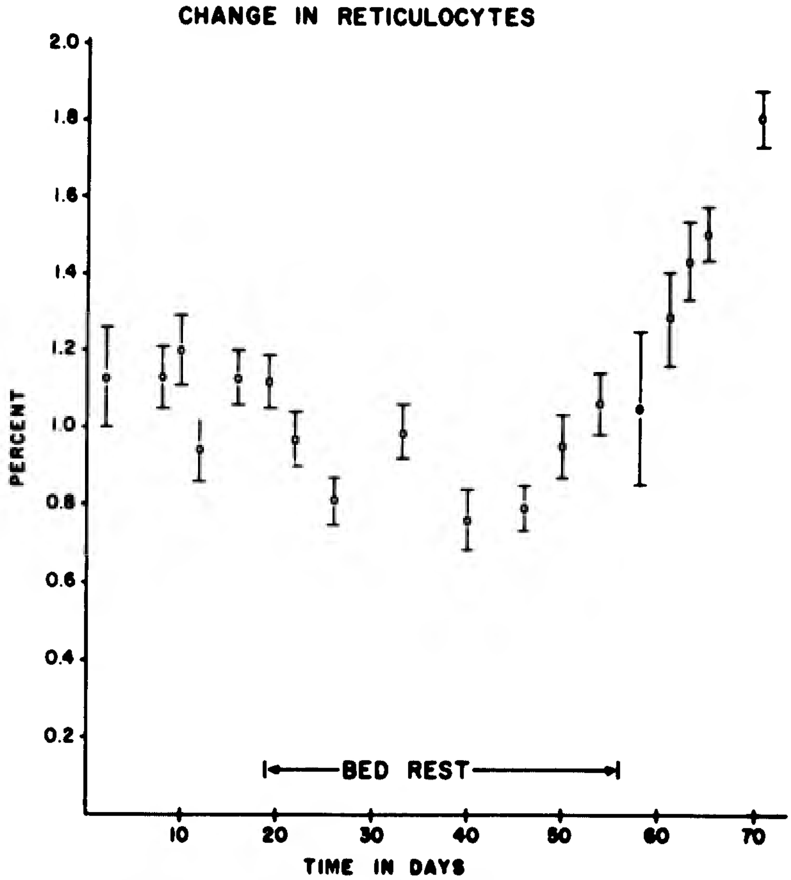

Figure 7. Serial changes in % reticulocytes estimated from peripheral blood smears.

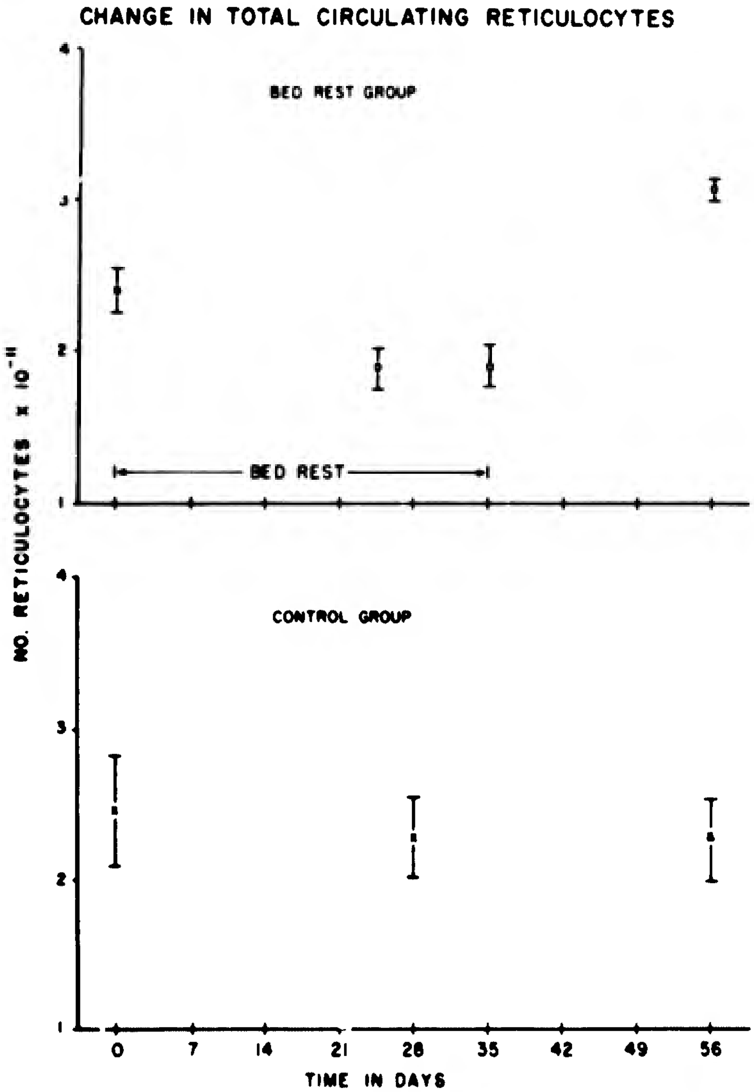

Figure 8. The upper portion of the graph illustrates values for total circulating reticulocytes in the bed rest group. Control values are indicated in the lower portion of the graph.

shows the changes in total numbers of circulating reticulocytes and a significant decrease is noted during bed rest; a pronounced reticulocytosis is observed at the end of the study. Reticulocytes decreased by approximately 20% during bed rest and only one of the thirteen subjects showed a slight increase at the end of bed rest. Total circulating reticulocytes in the control subjects showed no important deviation throughout the course of the experiment. Serum iron concentration as well as total serum iron (serum iron ug/ml x plasma vol ml) increased by 20% during bed rest and then declined abruptly during the recovery phase after bed rest (fig. 9). Serum iron binding capacity remained fairly constant throughout the experiment.

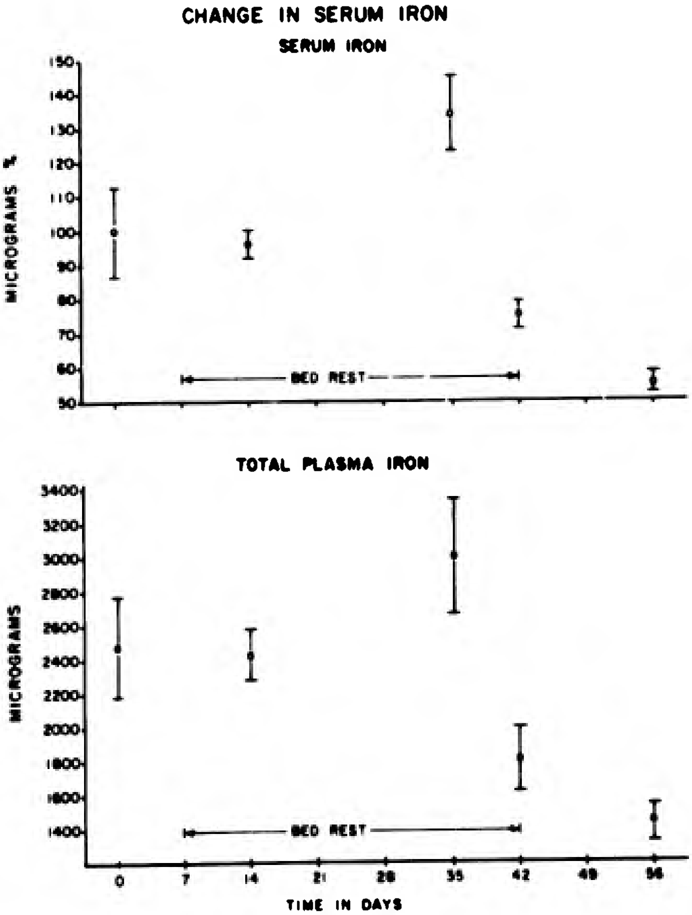

Figure 9. Serum iron determinations are illustrated in the upper graph. Total plasma iron was also calculated because of the changes observed in plasma volume and is illustrated in the lower graph.

DISCUSSION

The results reported herein agree with the previously described plasma volume changes that occur during bed rest (1-3). These workers used either T-1824 or radio-iodinated serum albumin for plasma volume measurements and indirectly derived the red cell mass. Both Taylor (1), Dietrick (2), and co-workers reported a decrease in red cell mass of 54 ml and 84 ml, respectively, after 3 weeks of bed rest. This loss is in agreement with our observed 65 ml decrease in 9 subjects after 24 days of bed rest; however, the values do not differ significantly from those obtained prior to bed rest. Miller et al (3) observed a more pronounced decrease in red cell mass amounting to 180 ml for 12 subjects after 4 weeks of bed rest, but the degree of statistical significance is questionable ($p < 0.05$). Erythrokinetic changes leading to the reduction in red cell mass were not investigated in these earlier studies, but an analogy was made to earlier work of Broun (6) that immobilization leads to a decreased rate of erythropoiesis in dogs.

Several possible mechanisms may be operative to explain the loss of red cell mass that occurred during bed rest. The consistently negative stool tests for occult blood would seem to indicate that blood loss did not occur. The spleen, a known site of red cell sequestration, did not show excessive accumulation of Cr^{51} counts by body surface scanning techniques. When Cr^{51} red cell mass determinations were performed, no essential difference in counts per minute per ml of blood was noted between the 12 and 25 minute sample, suggesting that the injected cells achieved complete mixing in the circulation during the first 12 minutes. In contrast, patients with splenomegaly, in whom a significant portion of their red cell mass is sequestered, may demonstrate decreasing red cell radioactivity levels for approximately 30 minutes following the injection of labeled cells owing to exchange with the sequestered compartment (7). No apparent hemolytic mechanism could be demonstrated during the course of bed rest as indicated by normal Cr^{51} red cell survival studies, the absence of substantial indirect bilirubinemia, and no alteration in autohemolysis.

On the other hand, there is considerable evidence to suggest that erythropoiesis decreases during bed rest. Reticulocyte percentages as well as total circulating reticulocytes decreased throughout the period of bed rest. This amounted to a 20% decrease in total circulating reticulocytes both at 24 and 35 days of bed rest and it may be inferred that a new steady state of erythropoiesis was achieved at 80% of the normal rate. The 20% increase in total serum iron near the completion of bed rest lends support to an impairment of erythropoiesis. Elevated serum iron concentrations are frequently in patients with hypoplastic anemias where iron turnover and the demand of iron for hemoglobin synthesis is decreased. During periods of accelerated erythropoiesis, the converse obtains, and serum iron concentrations are diminished. This condition is to be differentiated from iron deficiency where the serum iron binding capacity is increased and bone marrow iron stores are virtually absent.

The regulation of erythropoiesis has been extensively investigated in the past two decades. Although the endocrine system is known to influence red cell production (8), endocrine function during bed rest as measured by the serum concentration of butanol extractable iodide (9) and by the adrenal secretion of 17-hydroxycorticosteroids, cortisol and aldosterone (10), remains constant. Jacobson and his associates (11) have shown that erythropoiesis is influenced by erythropoietin, a humoral agent capable of differentiating the "stem" cell into an identifiable nucleated erythroid cell as well as affecting the rate of cytoplasmic maturation and hemoglobin synthesis within the nucleated erythroid cell (12). A recent report indicates that a renal enzyme, similar to renin, activates a plasma globulin to generate erythropoietin (13). The analogy to the renin-angiotensinogen system is even further strengthened since it is believed that the juxtaglomerular apparatus produces both renin and the renal erythropoietic enzyme (14).

The primary stimulus for the secretion and or activation of erythropoietin appears to be dependent upon the oxygen supply and demand of the tissues. Hypertransfusion of red cells, or for that matter hyperoxia, results in an increased oxygen supply to the tissues, which in turn shuts off erythropoietin formation and effects a cessation of erythropoiesis. Erythropoiesis is again reinitiated when the hemoglobin concentration or oxygen supply falls to levels normally maintained. Hypoxia or hemorrhage, in contrast, stimulates increased erythropoietin formation which in turn leads to an augmentation of the red cell mass. Dietrick et al (2) and Birkhead et al (9) have shown that the basal metabolic rate decreases slightly during bed rest, which implies a decreased tissue demand for oxygen. Since the hemoglobin concentration in our studies showed a relative increase during bed rest, it may appear to the body that tissue oxygen supply is increased in the face of a lowered tissue oxygen demand. Either situation or a combination thereof may be sufficient to alter the secretion or activation of erythropoietin. In order to test this hypothesis, urinary erythropoietin excretion during bed rest is currently being studied.

Upon resuming ambulation after the completion of bed rest several striking erythrokinetic changes became apparent. There was a rather abrupt decrease in hematocrit and hemoglobin concentrations in the peripheral blood which was probably due to augmentation of the plasma volume. The red cell indices (MCV and MCHC) remained constant, thus substantiating a lack of structural change in the red cell. A hemolytic mechanism may be inferred from the shortened Cr^{51} red cell survival during this period, the increased rate of red cell autohemolysis, and the failure to increase the red cell mass. It should be noted, however, that several factors unrelated to hemolysis can alter the slopes of Cr^{51} red cell survival curves, such as increased red cell production and red cell Cr^{51} elution. The rate of autohemolysis, well documented to the abnormal in patients with hemolytic anemias, became slightly elevated about two weeks after ambulation was reinstituted. The degree of autohemolysis was only slightly increased, a value well below the upper limits of normal for the method; however, it deviated significantly from both pre-bed rest and bed rest values. This test measures a hemolytic tendency in the test tube, which does not necessarily have to correlate with in vivo hemolysis. The value for the final red cell mass determination did not differ from that obtained at the completion of bed rest. An increased rate of erythropoiesis has been documented for this last period from the observed reticulocytosis. It becomes tempting to speculate that the lack of increase in red cell mass in the face of increased red cell production suggests a compensated hemolytic syndrome in which the rate of production balances the rate of hemolysis.

This relatively mild hemolytic process observed during the reambulatory period is reminiscent of Broun's (6) study in the early twenties in which he demonstrated overt hemolysis associated with physical activity after prolonged periods of immobilization in dogs. An analogy may also be made with the clinical syndrome of 'march hemoglobinuria'. Young males are predominantly affected and it has been shown that the hemolytic mechanism may be prevented by lining the soles of the shoes with a foam rubber instep (15). Apparently hemolysis results from the mechanical trauma to the red cells in the soles of the feet as the subject walks or runs. Chaplin and associates (16) have shown that physical exertion (e.g. running or playing basketball) results in an increase in the levels of plasma hemogolobin, a sine qua non of intravascular hemolysis. Mechanical traumatic hemolysis has also been observed in some patients in whom intracardiac prosthetic devices have been inserted. Studies of peripheral blood smears from these patients frequently show abnormal red cell morphology owing to fragmentation of the red cells by the prosthetic device. In addition, one such patient (17) demonstrated a diurnal variation in both the amount of hemoglobinuria and plasma heme pigment during rest and activity. The levels obtained during activity or daytime were substantially higher than those obtained during rest or nighttime. It is evident from the above considerations that physical activity may in some instances be related to red cell hemolysis. The velocity and turbulence of blood flow and consequent buffeting of red cells associated with physical activity may then determine the degree or rate of hemolysis. Such a mechanism may be operative throughout the period of ambulation following bed rest in our study. Although definitive proof and known provocative factors are lacking, it is tempting to speculate that the increased and perhaps turbulent blood flow through stiff joints, tender soles, and lax muscles may pose mechanical trauma to the red cells resulting in the observed hemolytic process.

SUMMARY

A significant reduction in red cell mass was observed at the completion of 35 days of bed rest. A decreased rate of erythropoiesis was documented by serial reticulo yte counts. Upon resuming ambulation at the completion of bed rest, there was an accelerated rate of erythropoiesis and evidence suggestive of a mild hemolytic process.

ACKNOWLEDGMENTS

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Hypodynamics: Metabolic Aspects

Major Malcolm C. Lancaster

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HYPODYNAMICS: METABOLIC ASPECTS

Major Malcolm C. Lancaster, USAF, MC

Exposure of man to the weightless state encountered in orbital flights has indicated that there are alterations in cardiovascular dynamics and loss of blood volume. The effect of prolonged weightless exposure on other physiologic parameters will have to await the findings of actual prolonged exposure to weightlessness in space, but simple bed rest has become generally accepted as a model for study since it appears to stimulate to some degree the expected effects of weightlessness. The effect of bed rest on some general aspects of metabolism, including breakdown product excretion, endocrine function, and muscle changes, will be discussed.

The effect of bed rest on metabolic balances appears to be a result of the change in level of activity which accompanies the recumbent posture rather than a primary result of the posture change itself, while certain other changes seen may be entirely posture-related. Bed rest also means living in a new environment and this has effects on body surface temperature, sweating and metabolism.

General Metabolism:

Caloric Requirements and Diet: Heat production or loss of a normal adult sedentary worker is about 3000 calories/24 hours. When a person is put to bed, this loss decreases to about 2000 calories, representing about a 30% reduction. If weight is to remain constant, a comparable decrease in caloric intake should accompany the assumption of bed rest.

The metabolic rate of an individual varies with the type and duration of activity and no comparison is possible between subjects at rest and those who are active. While Deitrick et al (5) found an average decrease of 7% in the basal metabolic rate of subjects when placed at bed rest, it is doubtful that the method for this determination has sufficient accuracy to allow this small change to be significant. Body weight changes are small if diet is adjusted to caloric needs. The initial recumbency diuresis which is seen may account for the loss of a pound or so but from that point, fluid balance is maintained. Studies in our laboratory as well as others (2, 5) have demonstrated a decrease in muscle group circumference suggesting a loss of muscle mass. It seems likely that the constancy of body weight is a result of an offsetting increase in adipose tissue, although attempts to measure total body fat to demonstrate this have been disappointing.

Nitrogen Metabolism:

Nitrogen and sulfur balance has long been used as a study of general protein metabolism. A normal man is in apparent positive nitrogen balance when active. At bed rest, the positive balance is maintained for about 4 days (fig. 1) and then quickly reversed and by about the sixth day a negative balance is assumed. A peak is reached by about the tenth day and there then follows a gradual decline to equal balance which is maintained for the remainder of the bed rest period. Return to activity produces the expected sudden large swing into positive balance. The total nitrogen loss in our studies has been about equal to those of Deitrick et al (5) despite the differences in approach, i.e., average cumulative balance of about 54 grams which represents about 1.7 kg of muscle.

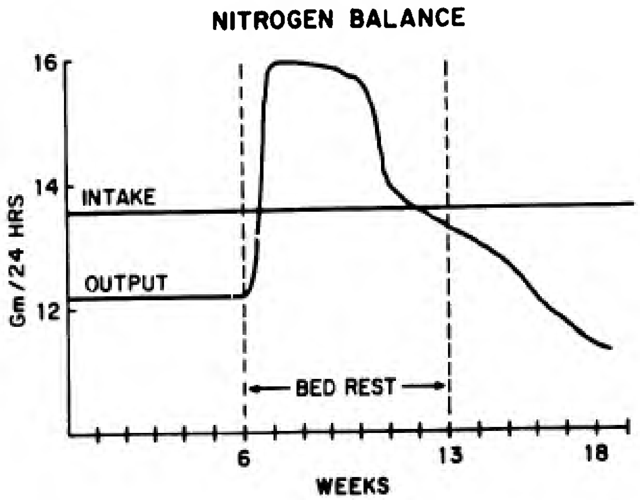


Figure 1

Sulfur and potassium excretion essentially parallels the nitrogen loss (fig. 2). The S/N ratio in muscle is 1:14 and in Deitrick's subjects the ratio was constant at 1.15.8, suggesting again that the losses come from protein breakdown.

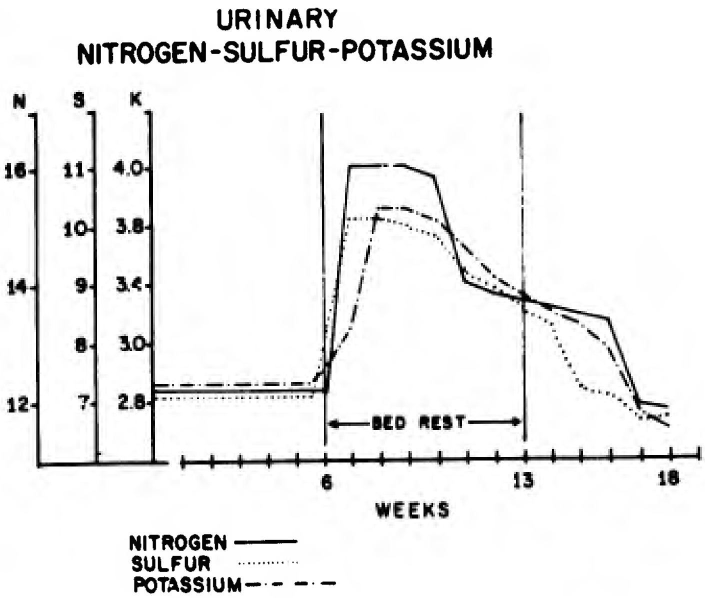


Figure 2

Sodium: There is little change in sodium excretion beyond the initial naturesis of assumption of bed rest (2). The diurnal variation persists (peak excretion between 1200 and 1800 hours) and there is a superimposed variation on a 2-5 day cyclic phase (1).

Calcium: During prolonged bed rest there is a progressive increase in calcium excretion in both urine and feces (fig. 3). Urinary calcium excretion reaches its peak at about the 6th week, having begun on about the 2d or 3d day. Subjects are in negative balance by the end of the first week. In Deitrick's study (fig. 3) the total loss in 7 weeks was as much as 23 grams. Birkhead (2) found similar high losses, as have we.

The precise mechanism of demineralization of bone during disuse is unsettled. Indeed we still do not understand normal bone formation and resorption. That muscle activity affects the shape of bone can hardly be denied when we look at the ridges formed in response to the mechanical stresses of muscle traction. In recent years it has been recognized that there is normal to excess bone formation during the time when demineralization of bone is occurring in disuse osteoporosis. Loss of mineral occurs as a result of degradation of matrix which is said to occur throughout the whole skeleton in disuse osteoporosis. The total loss of calcium represents only about 0.5% of the total body calcium in 4 weeks (8) and if indeed the loss is generalized there would be no concern for its structural effects. However, trabecular bone has a greater surface per unit weight and this would suggest the possibility of greater calcium loss from the trabecular bone which usually bears weight, i.e., long bones of legs, vertebrae and os calcis. Mack (9) has evaluated the radiodensity of the os calcis in bed rest. Her findings show a loss of density from the os calcis far exceeding that which would be predicted from the calcium excretion data. Further work is needed to clarify this question but it leaves one worrisome question when one contemplates prolonged inactivity and weightlessness.

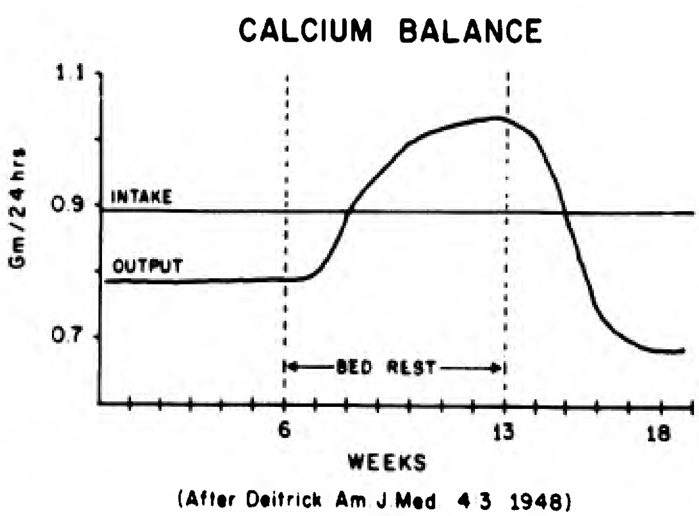
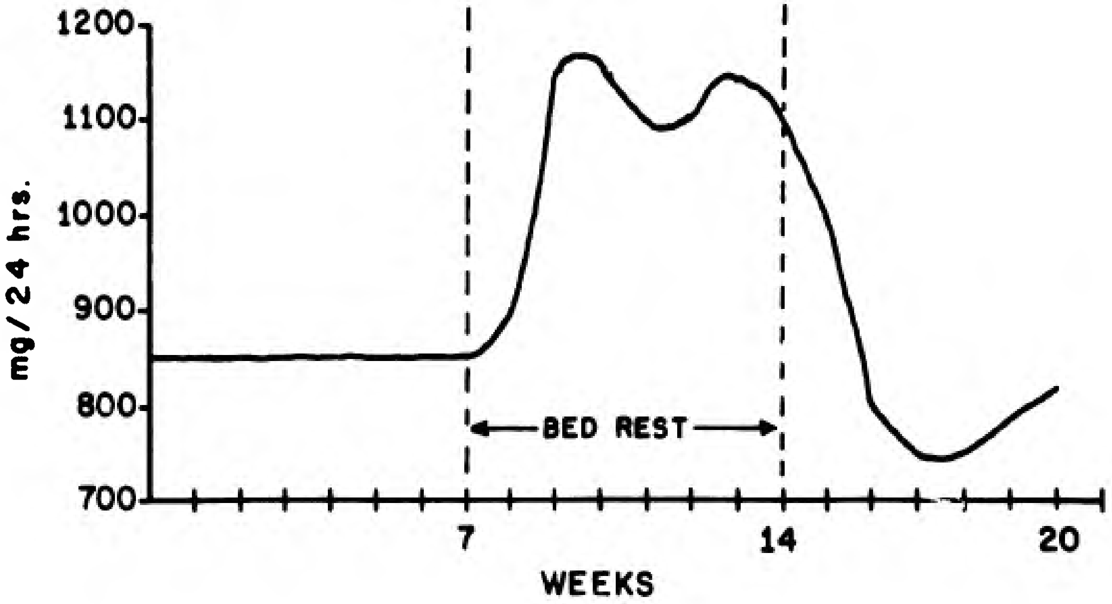


Figure 3

The potential of calcium precipitates forming in the urinary tract deserves consideration in view of the increased calcium excretion in the urine. "Recumbency Stones" are a well recognized hazard to hospitalized patients at prolonged rest in bed. It is unusual for a stone to develop in less than 2-3 weeks unless pre-existing urinary tract disease is present. Affecting the development of renal calculi are: (1) Concentration of calcium in the urine. (2) Concentration of citric acid in the urine. (3) Urinary pH. (4) Concentration of phosphate in urine. (5) Stasis. (6) Infection. Prolonged bed rest adds to the changes favoring calcium precipitation in all of these areas. Phosphorus excretion follows the same pattern as calcium but the increase is not great (fig. 4). During bed rest there is a slight rise in pH (fig. 5) and no change in citric acid excreted, all favoring calcium precipitation. These factors are also aggravated by the stasis that occurs owing to the calyces being below the renal pelvis in recumbency. Several clinical reports have emphasized the frequency of crystalluria (13) and stones (7) in patients during the early convalescent phase. To date we have seen no problems in our subjects in this regard but precaution might be reasonable in prolonged weightless exposures.

URINARY PHOSPHORUS



(After Deitrick Am.J.Med. 4:3 1948)

Figure 4

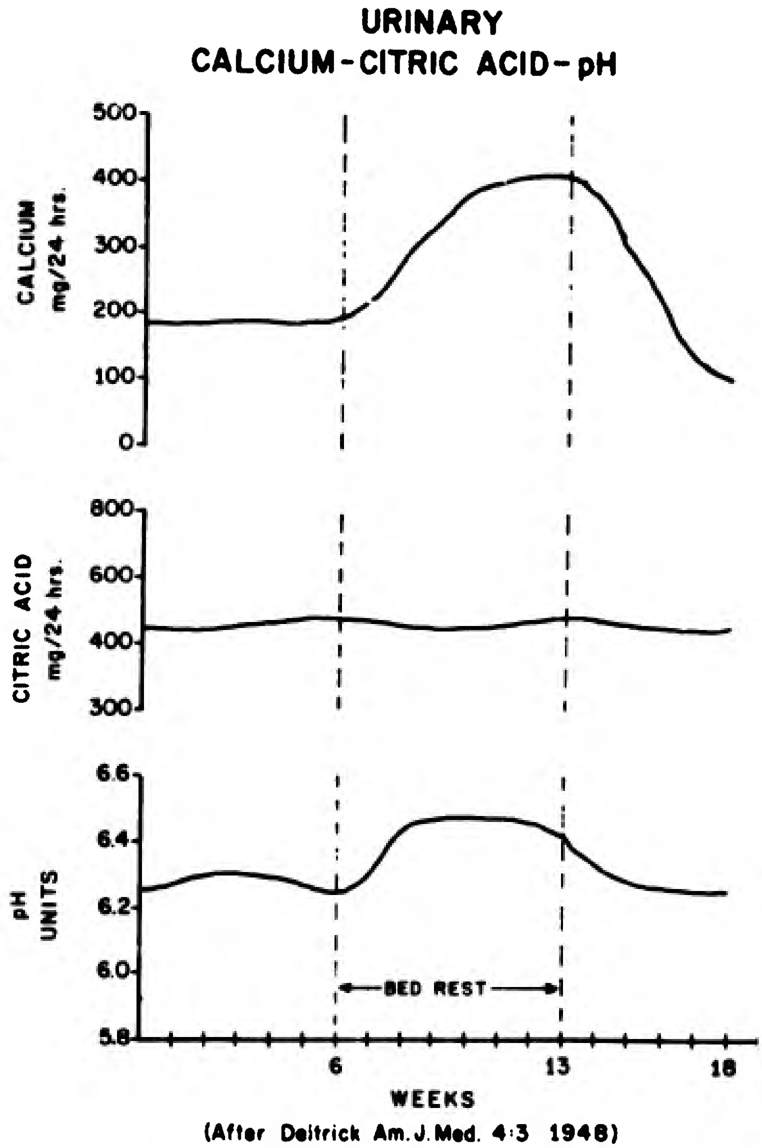


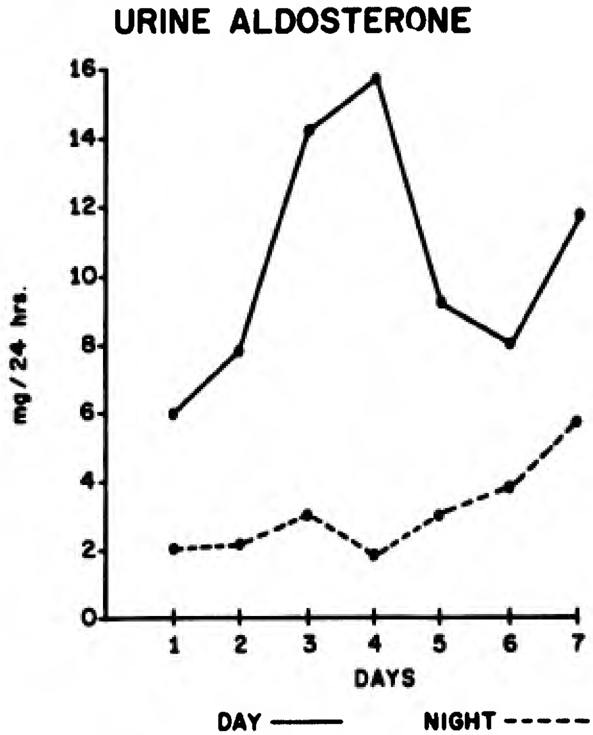
Figure 5

Endocrine Function:

Aldosterone: The secretion of aldosterone varies with posture and is not diurnal in the same sense that plasma corticoids are (figs. 6 and 7), (10). In subjects at bed rest this postural effect is eliminated and there is probably a near constant production varying with metabolic needs.

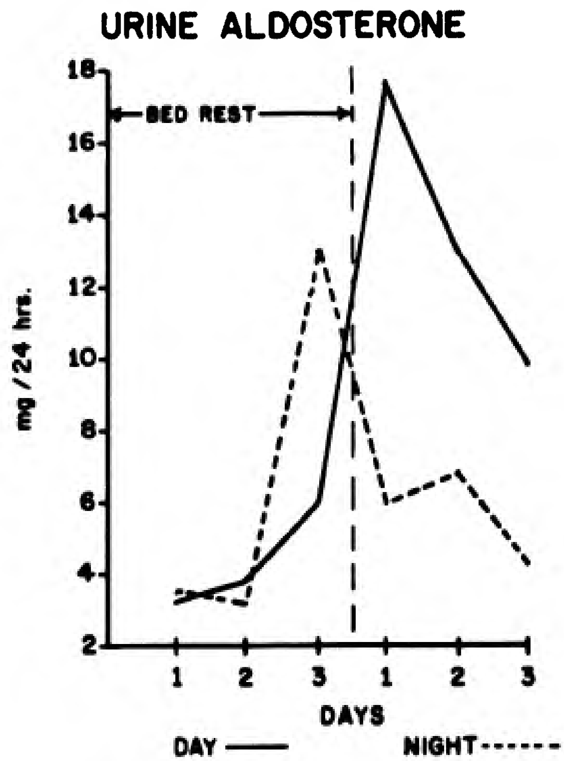
Other Adrenal Cortical Hormones: Neither the plasma levels of adrenal cortical hormones, the diurnal variations of these levels, nor the circadian rhythm of hormone production appears to appreciably change during prolonged bed rest (6).

Figure 6



(After Muller, Lancet 1:711 1958)

Figure 7



(After Muller, Lancet 1:711, 1958)

Skeletal Muscle: We have already mentioned that a loss of as much as 1.7 kg of muscle may be encountered in prolonged bed rest. It is general knowledge that unused muscles become weak and atrophic and although complete atrophy takes many months, the process begins in just a few days of bed rest. The muscles most affected are the muscles that resist gravity, i.e., the gastrocnemius-soleus, quadriceps femoris group, gluteus group and the erector spinae group. Deitrick's (5) patients had more extensive atrophy for the time in bed than ours, presumably owing to his use of immobilization in a plaster cast from the umbilicus down. He demonstrated up to 20.8% weakening of the gastrocnemius-soleus and 13.3% of the anterior tibials. He did not evaluate the quadriceps or buttocks group.

All of our patients have demonstrated joint discomforts, hobbling gait and some difficulty with equilibrium upon resumption of ambulation, symptoms which may be related to weakness of supporting muscles. Brannon et al (3) have reported that these symptoms are dramatically reduced if isometric exercises are performed during the period of bed rest. No other effects of exercise, even rather vigorous exercise, have been observed on the metabolic-chemical changes seen.

SUMMARY

In summary then, the metabolic changes associated with prolonged bed rest that appear to be significant at present are those that seem to be the result of the decrease in physical activity. The atrophy and weakness of muscles and the calcium loss appear to be from this effect. The potential deleterious effects of the calcium loss are weakening of trabecular bone structure and renal lithiasis.

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Vision in the Void

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VISION IN THE VOID

Hans-Georg Clamann, M. D.

The potential influences upon vision of astronauts during space flights are manifold. In the first place, there is the confinement into a comparatively narrow space, at least at the present state of spacecraft development. Visual targets are, most of the time, either very near (control panels), or at practically infinite distances (objects on Earth, planets, fixed stars). The environmental conditions can deviate considerably from the normal such as the pressure and the composition of the cabin atmosphere. These conditions have to be considered as far as they may have an influence upon vision.

The purpose of this lecture is to demonstrate that our visual system is neither capable of arriving at a so-called objective recording, nor of being uninfluenced by many psychological pitfalls. This latter condition can be demonstrated by many of the so-called optical illusions. After reexamination and review of some of the basic properties of our visual apparatus, one can then proceed to the relationship of such properties with the tasks with which the astronauts are faced, using their vision in space missions.

The human eye is always compared with a camera. It may be remembered that, like a camera, the eye has an optical, image-forming apparatus of which the lens adapts for changes in the distance of objects by changing its curvature (accommodation). Thus, the eye always tries to cast a sharp image upon the retina without changing the distance between the lens and the photosensitive layer (retina). Much as does the camera, the eye corrects for changes in light intensity by change in the size of the diaphragm (iris). Like a camera, the eye has the same type of optical deficiencies as any lens system: Chromatic aberration, astigmatism, and additional distortion as light rays come in at a very steep angle. The physical optical qualities of the refractive apparatus of the human eye are, indeed, so poor that von Helmholtz (1) said:

> "Now, it is not too much to say that if an optician wanted to sell me an instrument which had all these defects, I should think myself quite justified in blaming him for his carelessness in the strongest terms, and giving him back his instrument."

Helmholtz was, of course, aware of the marvelous function of the eye as a sensory organ and, therefore, he continued:

> "Of course, I shall not do this with my eyes, and shall be only too glad to keep them as long as I can - defects and all."

This statement in a very short form summarizes the fact that despite deficiencies in the quality of images cast upon the retina and the small size of the images, it is apparent that the function of our eye can easily compete with the function of the best cameras available with reference to quantity and quality of needed optical information.

In the eye, the retina corresponds to the photographic plate or film in the camera. In contrast to the photo-emulsion, however, the retina's light sensitivity is not the same over its entire surface. Of the two types of light-perceptive elements, rods and cones, the rods occupy the peripheral area and, as one approaches the central part of the fovea, the rods are increasingly replaced by the cones. While the cones are capable of sensing colors and bright light, the rods do not perceive colors, but are more sensitive and both elements can themselves adapt to a tremendous range of light intensity. Let us now consider the resolving power of the eye (2). The cones are arranged with only a few rods in the middle of the retina in the so-called central fovea of 1.5 mm diameter; the innermost part (0.55 mm diameter) contains only cones. This area is also free of any over-laying blood vessels. The cones form here a honey-comb pattern, each element of which has a diameter of about 1 1/2 microns (3).

Thus, the resolving power for an image based upon the size of the single photo-sensitive element is higher for the fovea of the retina compared with the photographic emulsion (size of grain for color films, 2.5 microns; for black and white film, 5 microns). To distinguish between two rays of light coming from two distinct points, according to the classic example, at least one cone between two cones has to be unilluminated. If one projects these rays in the simple way of geometric optics from the outside upon the retina, a minimum angle of vision of about 30 seconds of arc is obtained (fig. 1). Under normal environmental conditions, we are content to accept five minutes of an arc as distant enough for separation. Actually, our tests by the letters and numbers of an optician's test table are based upon this value. It is quite important to realize that this classic aspect is oversimplified. Very small rays of light do not produce a simple spot of light, but a diffraction pattern, i.e., the spot of light is surrounded by a number of light and dark rings. The spread (s) of this ring pattern depends on the wavelength of the incident light (λ), and the size of the opening (pupil) (a) in the following way:

$$s = \frac{\lambda}{a}$$

One sees that s increases with increasing λ and/or with decreasing a. Therefore, if two adjacent cones in the retina are struck by light rays, the diffraction pattern enables the cones to sense the two rays separately even without an intermediate cone. This aspect of the resolving power of the retina accounts for much higher sensitivity than originally accepted.

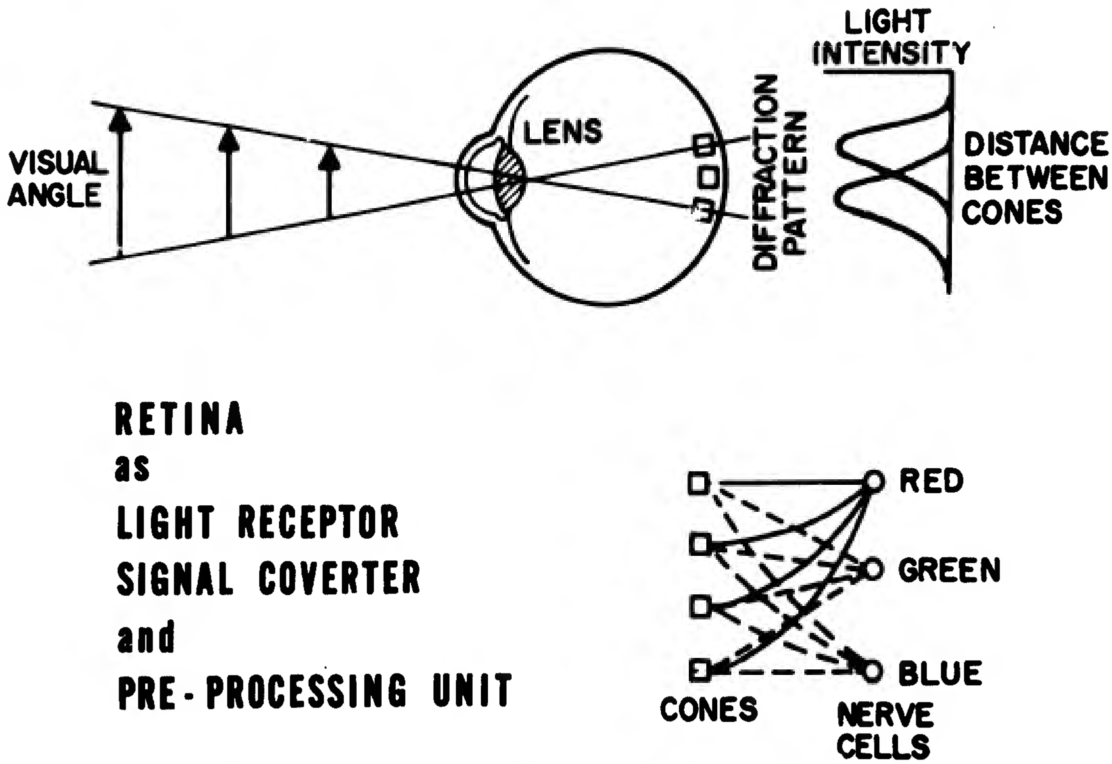


Figure 1. Schematic of the Human Eye. Two separate light rays strike upon the two cones in the retina's fovea, leaving one cone in between dark. This is a classic explanation for maximum visual acuity at a visual angle of about 26 seconds. Actually, very thin pencils of light cause a diffraction pattern of concentric rings (see text).

The picture at the right lower corner depicts the triple subdivision of cones, each connected to three nerve fibers (see text).

If one thinks about the size of an image within the retina, here is an example of the resolving power of the eye: A six-foot man (approximately two meters) at a distance of 50 feet (approximately 15 meters) forms an image of about two millimeters on the retina. Thinking of the optical deficiencies of the eye, the small size of this image, and yet our capability to distinguish details of the man we see, it becomes clear that other than optical means must exist for the eye to correct for the aforementioned optical deficiencies. One may also consider the fact that the size of the central cones (about 1 micron) falls within the magnitude of the wavelengths of light (the wavelength of light in the middle of the visible spectrum is .6 micron!).

A heated discussion arose as the astronauts and cosmonauts reported observing details on the Earth's surface from space vehicles. Some reported they saw houses and even railroad trains. These observations do not fit into the classic aspect of the resolution power of the eye. Of course, many physical factors have to be considered such as turbidity of the air and rapid changes of this turbidity which cause the so-called scintillation of the picture. Many papers have been written on this topic. I would like to mention only two: Ritter and Strughold (4), and Schmidt (5). The references in these papers also cite additional papers on the same topic. Next to the physical geometric optical approach, these authors mention such physiologic factors as the effect of contrast upon the resolving power of the eye. Here we touch upon something which also has been discussed in innumerable papers with many arguments pro and contra. We enter here a field which includes physiologic and psychologic aspects.

An experiment may demonstrate the influence of contrast upon visual acuity. Two vertical wires of .33 millimeters in diameter and 48 cm in length are mounted on a vertical board which is dull black in color. With the surrounding light intensity, the wires should be visible at least to a distance of 15 feet or better; but even with the most intense illumination, one cannot make the wires visible to the back of this auditorium. To enhance the brightness of the wires, there is a simple trick: Make the wires glow, which causes a higher illuminance than can any reflected light. The wires are heated now to a soft red glow. The audience can see them now down to the last row of seats and beyond.

Another example of the effect of contrast may be demonstrated by a case of the so-called simultaneous contrast (fig. 2). Slightly gray, circu-

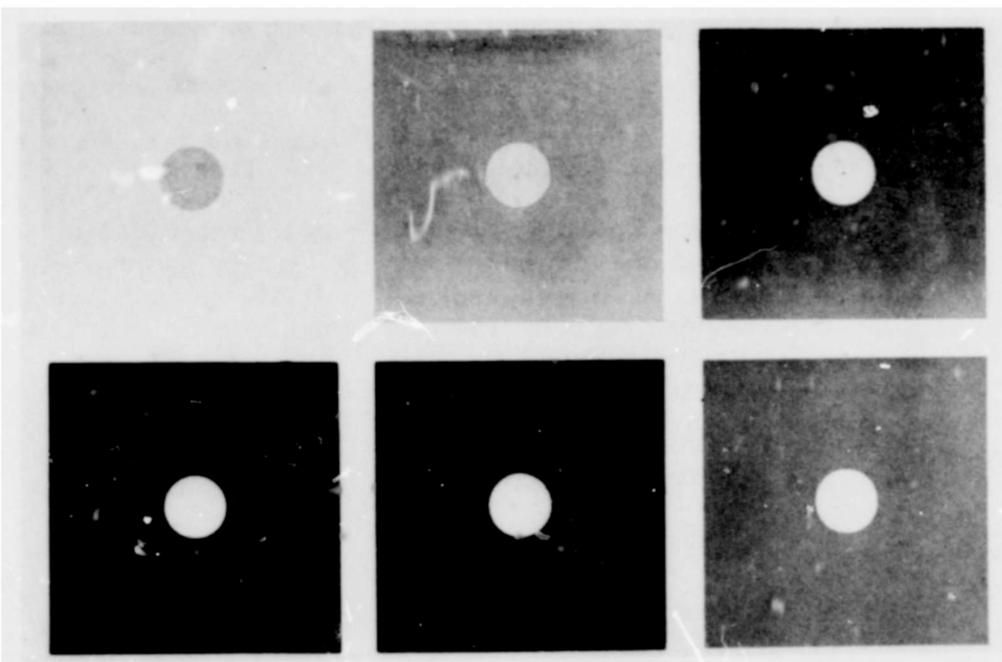


Figure 2. Simultaneous Contrast. The circular infields, actually all of the same luminance, seem to decrease in brightness as the surrounding squares decrease in darkness.

lar infields, all of the same luminance (in the original, but in this figure slightly different through processing), are surrounded by squares of varying gray shades of luminance. The influence upon the perceived brightness is clearly visible. This may be one of the mechanisms to enhance the sharpness of the image on the retina.

A few lantern slides may demonstrate other optical illusions. One which is not too widely known is Fraser's (6) spiral illusion (fig. 3). There seems to exist a line spiralling toward the center, and even simulating a certain depth toward the center. Actually, the "spiral" consists of concentric lines.

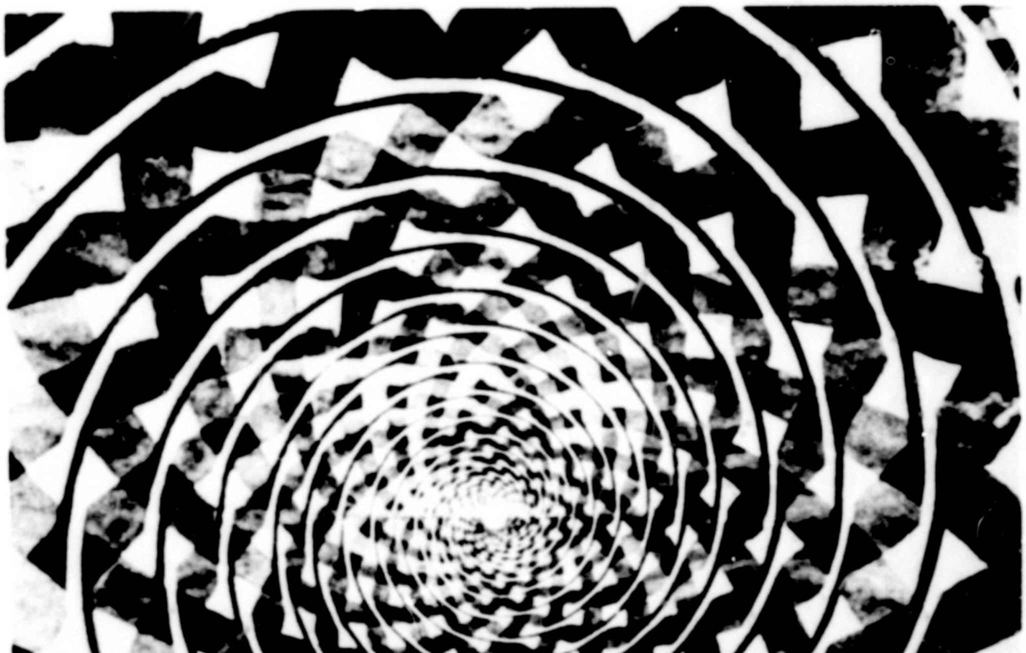


Figure 3. **Fraser's Spiral Illusion. This figure consists of a number of** concentric circles constructed of intertwining black and white lines on a background of a curved, radial pattern of gray bands. This arrangement causes a forceful illusion of a spiral arrangement.

An optical illusion which shows clearly the incapability of the eye to judge the length of vertical and horizontal lines when presented in the same picture (7) is the so-called "tall glass" illusion (fig. 4). The glass seems to be taller than the saucer is wide. Actually, the two measurements are identical.

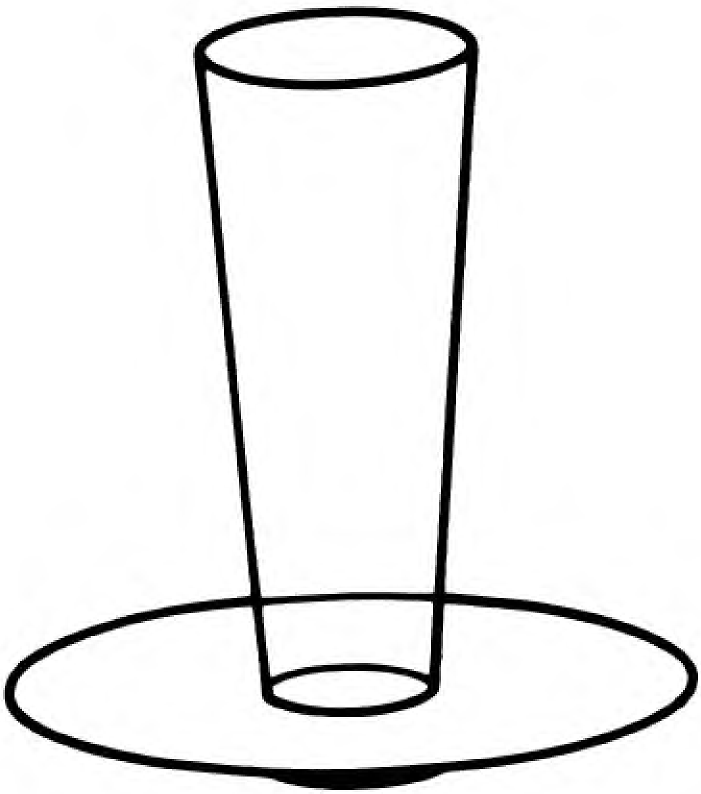


Figure 4.

This effect may participate in the judging of photographs such as the two views of a building (AMD Headquarters) at the same distance by photographic objectives, the focal lengths of which deviate considerably (figs. 5 and 6). Of course, the two pictures differ in size, but the main point here is the alteration between the dimensions of the building and the distance to it. The two trees on the left side seem to stand not only closer to the observer, but also closer to the building in figure 6 when compared with figure 7.

This situation may be important in the training of astronauts by means of optical observation systems of various focal length in combination with simulated bodies of the Moon or satellites. Without the indication of measurable distances by objective methods (optical or radar), the subjective estimate of a distance without the earthly clues may easily lead to misjudgment.

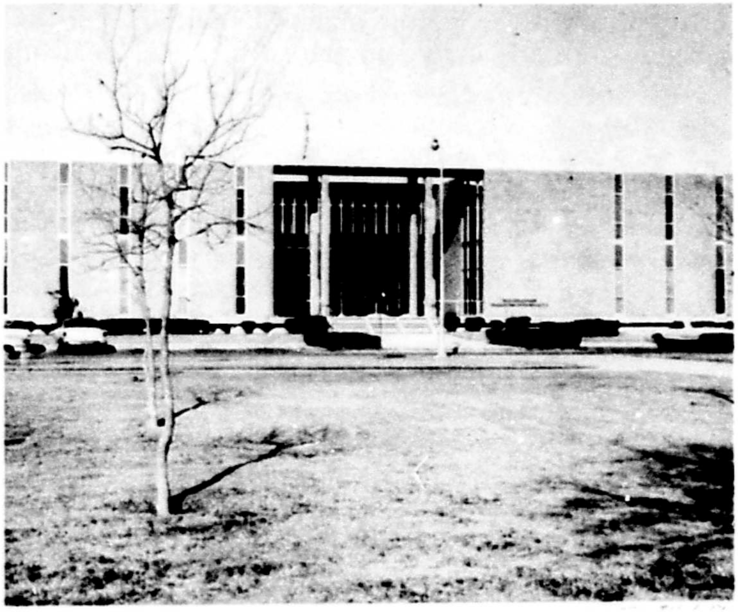


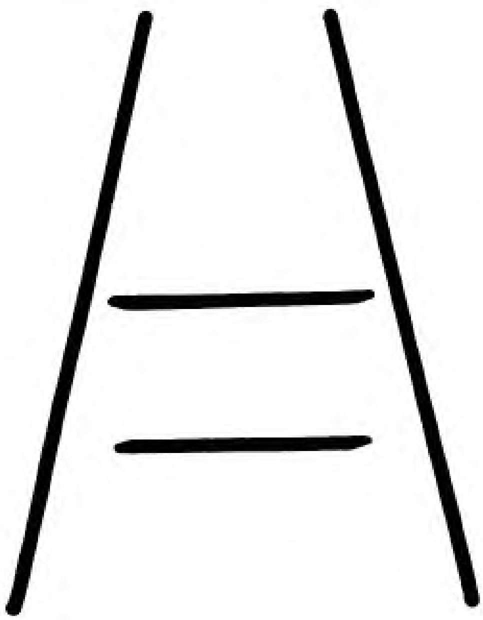
Figure 5. Figure 6. Two photographs were taken of the same building from the same distance. The first photograph (fig. 5) was taken with an objective having a shorter focal length (f = 90 mm) than was used in the second photograph (fig. 6) having a focal length of 135 mm. Both focal lengths, however, are considerably longer than the focal length of the human eye. (For normal young adults, varying in the average from 15.6 mm to 12.4 mm at the state of accommodation for near and far distance, respectively.) The ratio between the distance toward the building and the height and length of the building seems different in figure 5 and 6.

We may now consider an illusion which leads to tri-dimensional vision. Up to a certain distance (about 10 meters), our eyes are well-capable, by means of their stereoscopic function, to judge distances and the size of real objects at a given distance by the degree of convergence of the right and left eye ball (binocular parallax or stereopsis). Certainly, the size of the image on the retina is not decisive; otherwise, objects under the same angle of vision producing an image of the same size on the retina should be perceived as of equal size (8).

Since the last decades, we all are flooded with pictures in magazines, journals, and newspapers. Our eyes are so accustomed to two-dimensional pictures as a substitute for tri-dimensional reality, that our memory bank in the visual cortex does not revolt at the substitution.

The next illusion (fig. 7), the "Ponzo" figure, which may or may not be accepted as a fragmentary railroad track with two ties, leads us to the impression that the upper horizontal line is wider than the lower one because we accept this figure simply as depicting a "railroad track".

The capability of man to judge the size of certain objects at a distance, independent of the size of the image on the retina, has been a puzzle for a



The Ponzo Figure

Figure 7. The "Ponzo" Figure. This illusion suggests a fragmentary railroad track with two ties. The upper tie looks wider than the lower tie. Actually, they are of equal width.

long time. Numerous papers have been published on the subject of exposing observers to objects of various sizes, at various distances, and of various luminance (9-11). These and other authors found in these investigations that auxiliary "clues" (i.e., reflection from a wall, etc.) are used in judging the size of an object compared with a test object at a distance. Of course, change in accommodation and convergence in the perception of the size (12) are present when the object lies within a distance of 10 meters or less; but what if the distance is so great that these mechanisms do not lead to a feasible clue? The psychologists have coined a word, "size constancy", for the fact that we are able to arrive at a judgment of size, independent of the distance of the object. It has been found (13) that perceived distance, as measured by judgment of distance, does not correspond to the variation in distance demanded by changes in perceived size. This challenge may stem from a misunderstanding of the meaning of "distance" in this context. Stimuli that accommodate changes in distance may register upon the brain and automatically affect size perception without conscious recognition of this effect upon the observer. Pertinent literature in this direction can be found under reference 13. The most feasible test to exclude all of the real clues would be in substituting the tri-dimensional reality with two-dimensional simulation. This was done by Liedemit and Reuter (11). Following their idea of a landscape with a strongly emphasized tri-dimensional aspect, we see in such a landscape (fig. 8) a square sign

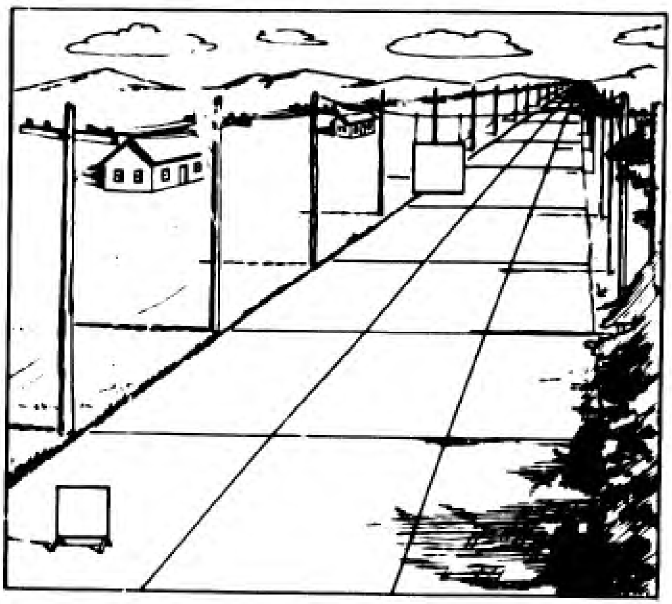


Figure 8. The "Size Constancy" Paradox. This picture suggests strongly the tri-dimensional aspect of a road leading into the distance. To show two squares, one near and one farther, one would have to draw the farthest one smaller. The observer would then feel the squares were of equal size (size constancy). In this illusion, the more distant square is actually of the same size as the nearer one. Therefore, it causes the illusion of being larger with reference to the simulated, tri-dimensional landscape.

in the foreground on the ground, and another square sign at a distance elevated between two poles across the road. Most observers will agree that the more distant square is perceived as being larger than the one in the foreground. No other clues than a two-dimensional illusion of a tri-dimensional situation are offered. This shows clearly that the memory bank in the visual cortex, or somewhere else within the visual pathway, supplies information and that it is not necessary to go to real experiments in which real clues cannot be excluded.

Visual illusions do occur to an even greater degree in color vision. I shall not compare here theories of color vision since such discussion would go beyond the frame of this paper. I would like, however, to mention the book of Hartridge (2) who discusses, among various theories of color vision, the one from Wright. He suggests a triple subdivision of cones in such a way that each cone responds to all wavelengths, but is connected to three nerve fibers one for the sensation of red, one for green, one for blue (see fig. 1, picture in the right lower corner). This would ascribe to the cones the role of a pre-processing apparatus rather than that of an all-processing sensor.

An experiment will demonstrate a simultaneous contrast of colors. The slide (fig. 9) demonstrates the arrangement in this experiment. Two white

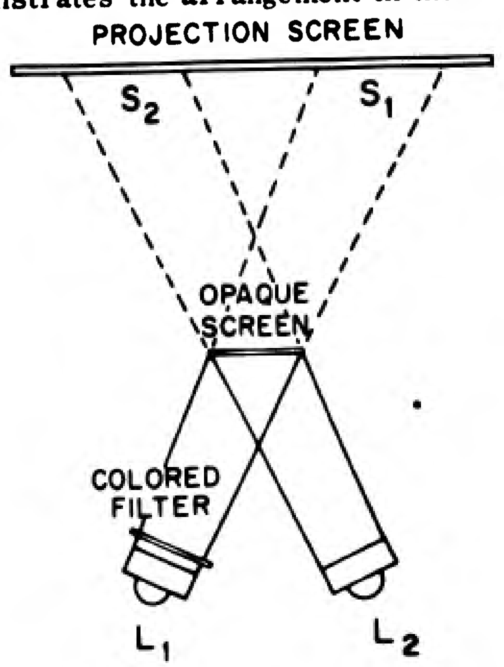


Figure 9. Colored Shadows. Two kleig lights, L_1 and L_2, cast their two over-crossing light beams upon an opaque screen. This screen will cast a double shadow, S_1 and S_2, upon a projection screen. Inserting a colored filter into the pathway of one light beam L_1, the corresponding shadow S_1 will appear in a color complementary to that of the filter.

kleig lights direct their beams against an opaque disc. Since both beams of light cross each other, two shadowy images of the disc appear on the projector screen. They appear to be dark images on a white background. Adding a red filter into one of the beams, the projector screen will appear to be light red. The shadow cast by the unaffected beam appears to be dark red, while the other shadow exhibits a vivid blue-green, the complementary color of red. Since physically there is no green emanating from this shadow, it is a purely subjective sensation or, in other words, our eye is capable of creating the sensation of color even when there is no color. Generally, such colored shadows are always represented as pairs of contrasting colors.

If the eye is offered a more sophisticated scene, then the illusion will be carried farther and we may see even more than one color, again with only one really presented. Such an experiment (fig. 10) has been demonstrated some years ago by Edwin H. Land (14), the inventor of the polaroid Land camera. As in his setup, a picture was taken of an arrangement of objects of various colors and shapes, such as colored tables, colored pencils and an ink bottle, with a camera carrying an ordinary black and white photographic plate. Before taking the picture, a red filter was inserted

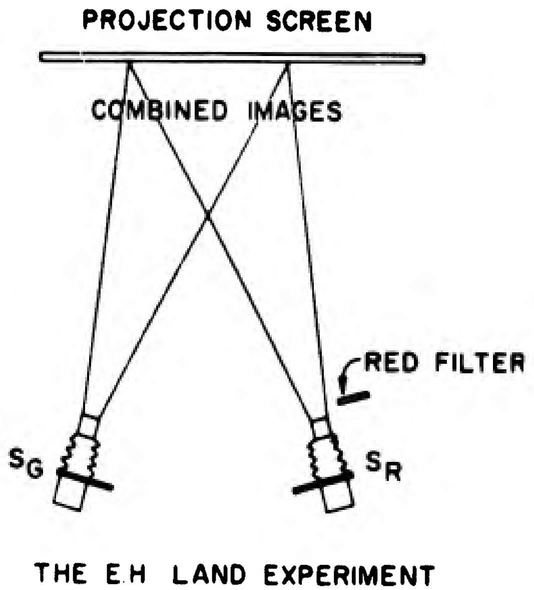


Figure 10. The E. H. Land Experiment. Two identical projectors project two identical lantern slides upon a screen so that the images form one picture. The lantern slides were obtained by two identical cameras taking a picture from the same arrangement of colored objects. The photographic plates are black and white, but one camera was equipped with a red filter, the other camera with a green filter. If either of the projectors holding these slides, S_G and S_R, are covered with a corresponding green or red filter, the picture on the screen will show all, if faint, colors of the colored objects.

before the lens. This filter, of course, did nothing but alter the shades in the black and white plate according to its spectral transparency (fig. 11, lower part). Then another picture was taken with the same arrangement, but this time using a green filter (fig. 11, upper part). Again, a black and white picture resulted, the shades this time altered according to the spectral transparency of the green filter. After processing each of the lantern slides, they were put in a separate projector with exactly the same optical qualities. Projecting these two lantern slides on the same area of the screen, they overlap and form a single black and white picture.

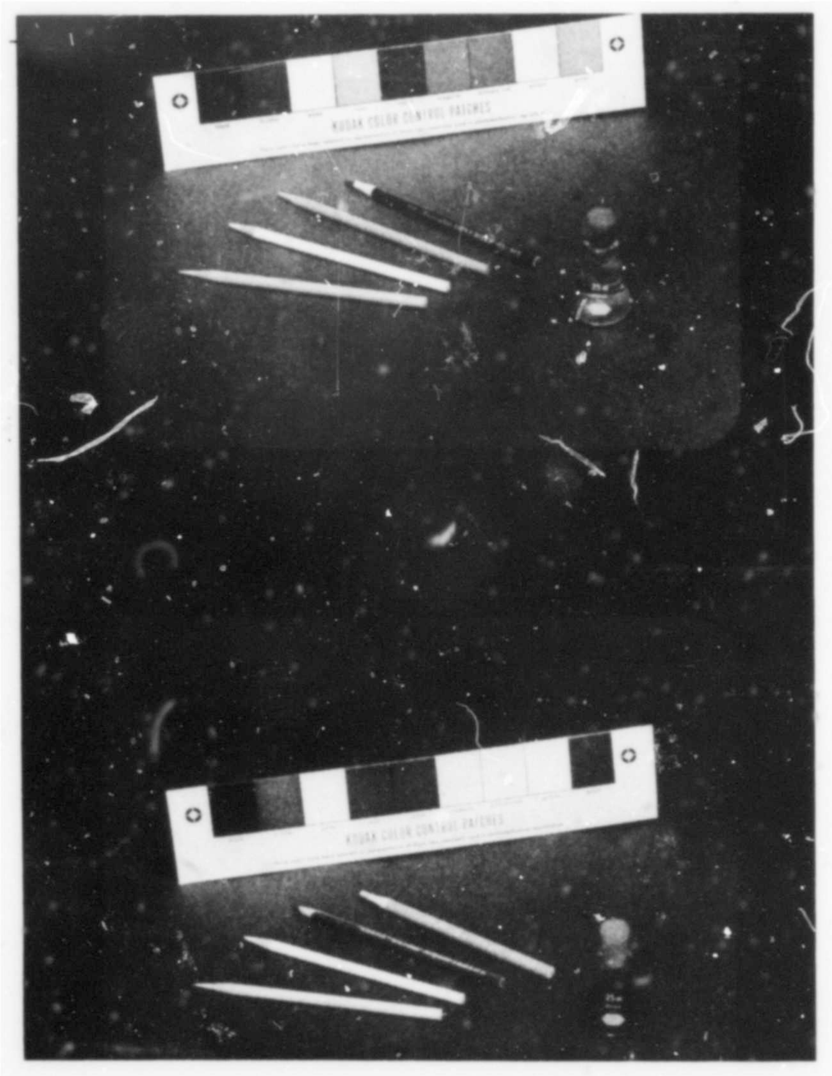


Figure 11. The actual photograph used in the Land Experiment. The upper picture was taken with a green filter; the lower with a red one.

Inserting a red filter before that projector which holds the lantern slide taken with a red filter, one would expect to see a reddish image, or maybe again some simultaneous contrast of green. But, we see a picture which retains some hues of yellow, brown, blue and some other tones. This experiment shows to what degree our eye is capable of adding imaginative colors to one real color. Dr. Land did embark on an extended hypothesis of color vision with which I would not totally agree, but he did mention the effect of simultaneous contrast at least as part of an explanation, and so do I.

Applied to vision in space, it is wise to use caution in observing targets on the Earth or other spacecraft, especially when looking upon the surface of the Earth with its rich bluish and greenish hues. Against such a background, simultaneous contrast may deceive the eyes of the astronauts.

I. Schmidt (15), in an oral presentation in London, England in 1959, advanced the hypothesis that the reddish and greenish colors on the planet Mars could be explained by simultaneous contrast.

Before going back to the celestial aspect. I should like to mention another illusion, that is the "buckled tank" illusion (fig. 12). Two pictures of a tank, side by side, differ in such a manner that the pictures are reversed with reference to left and right, and up and down. The indentations on the tank appear either as holes and buckles, or as rivets and dents. Turning the picture over, the appearance of the indentations is reversed. While this phenomenon certainly has to do with the direction of light, it is not enough to explain it fully. In looking at this picture, one may compare it with the Moon's landscape. Fortunately, we do know enough about the Moon not to confuse the craters with the hills. Maybe in approaching Mars, we will encounter such problems when observing with the eyes.

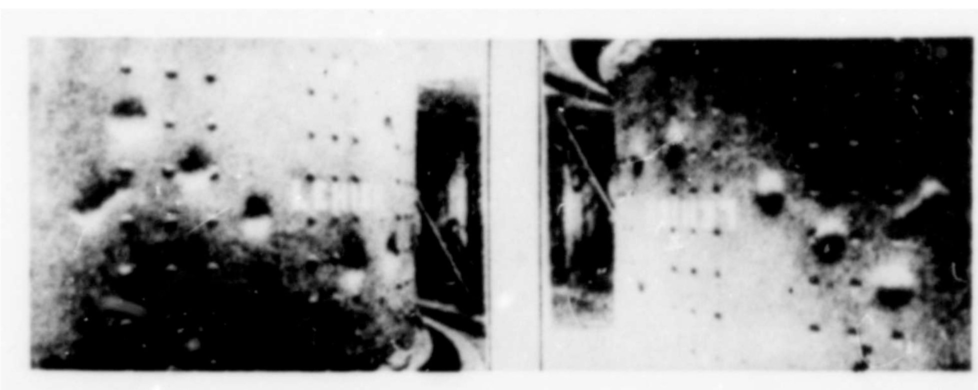


Figure 12. The "Buckled Tank" Illusion. Two pictures of a tank were taken: One picture being reversed with reference to the left and right, and up and down. The indentations of the tank appear either as holes and buckles, or as rivets and dents. Turning the picture over, the appearance of the indentations is reversed.

Now we will return to the celestial aspect. A topic very often discussed and investigated in the so-called Moon illusion, that is, the Moon appears larger on the horizon than at the zenith. Numerous investigations concerning the Moon illusion have been carried out (13, 16). After the most recent investigations, it is very probable that the Moon illusion is coupled with an illusion in the appearance of the sky. By simple experiments of pointing at the sky and trying to bisect the quartersphere, it becomes apparent that we do not perceive the sky as a hemisphere, but as a flattened cupola (fig. 13). This hypothesis can be corroborated by other observations. The condensation trail of a jet plane flying at a very high altitude on a clear day across the sky near or through the zenith leaves definitely the appearance of a flattened arc. In the Olympic Games in Berlin in 1936, about two dozen search lights were arranged around the arena at night, forming a tent-like cone over the arena. The beams were perceived as definite curves: Instead of a cone, one could see an ovoid-like figure. This aspect is corroborated by such publications as the one by von Allesch (17, quoted after 11), and Lueneburg (18). Both papers deal with a non-Euclidian aspect of the space surrounding us. Lueneburg gave it a thorough mathematical treatment possibly leading to better understanding of our vision. At least one author, Evans (19), besides this author is convinced of the correctness of Lueneburg's hypothesis.

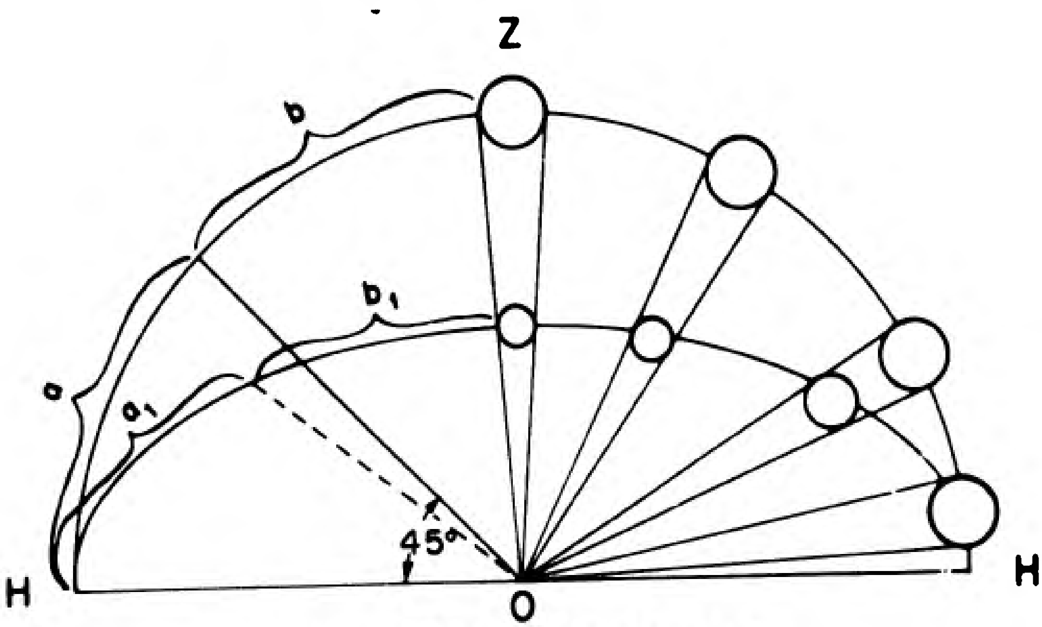


Figure 13. The Moon Illusion. The Moon Illusion (the Moon appears larger over the horizon (II) than at the zenith (Z)) in relation to the apparent shape cf the sky. When asked to bisect the actual arc of the celestial sphere into halves a and b, the Observer (L) will actually bisect the lower perceived arc into parts a_1 and b_1, indicating a flattened sky.

Summarizing the presented facts, one may recognize strong evidence the possibility that the centers upward from the retina in the visual pathway toward the visual cortex have not merely a transmitting, coordinating, and reflex-controlling function, but can be seen as parts of a computer mechanism, all participating in producing a "mental visual image" from the "physical image". A scheme of this kind is offered in (fig. 14). We still confuse our visual picture too much with a reality. This situation can hardly be better expressed than it has been done by Helmholtz: "We do not see the stars in the sky, but into the sky."

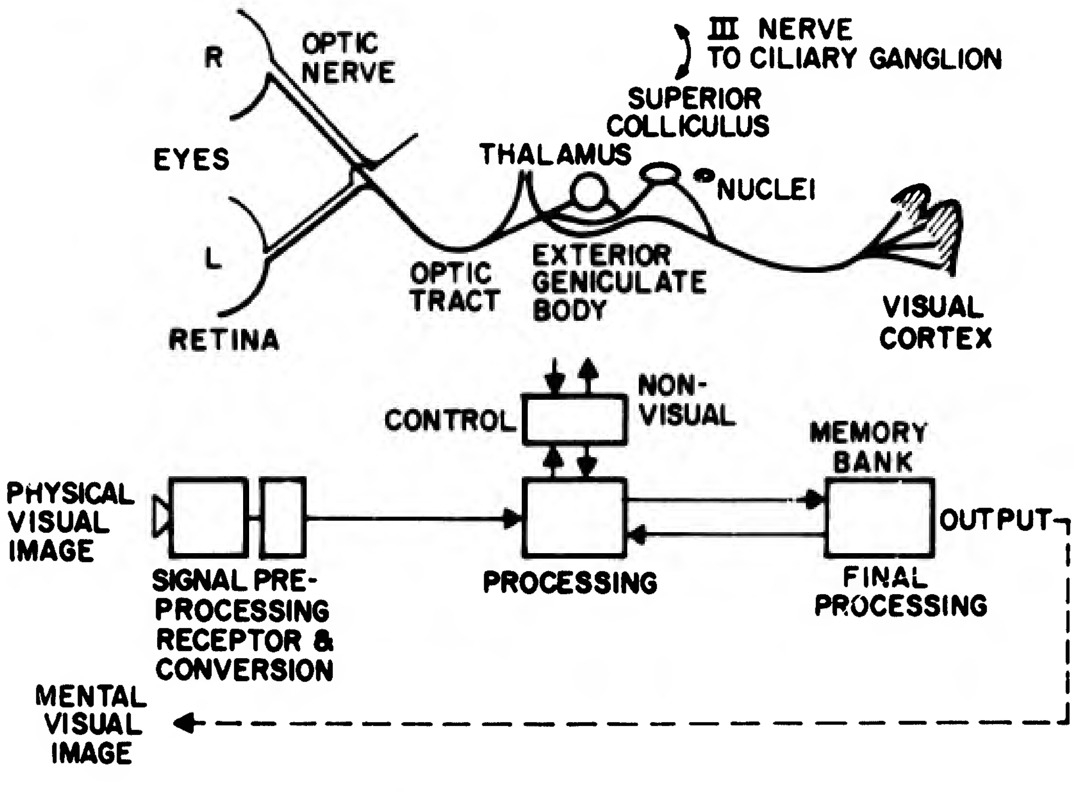
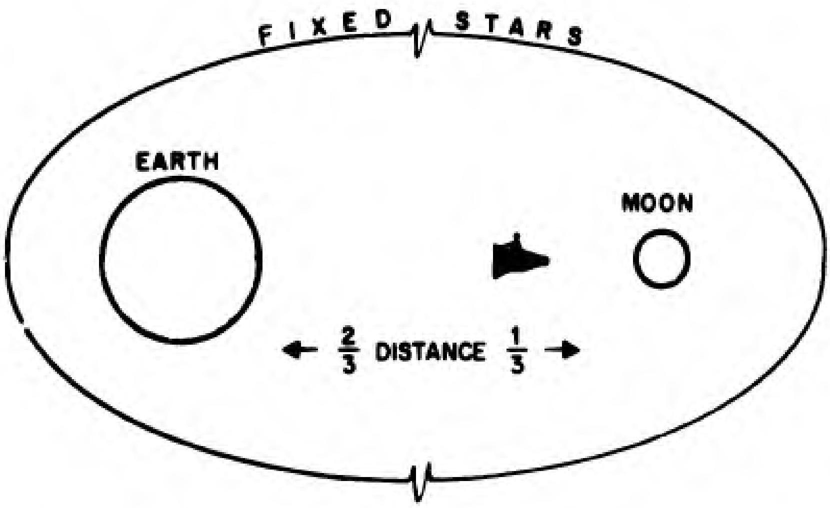


Figure 14. The Visual Pathway and its anatomic-physiologic components compare to computer model.

Finally, the author would like to offer a hypothesis. Based upon the previously mentioned Moon illusion, it seems that the shape of the sky depends upon reference points closer to the observer. Thus, an astronaut on his way to the Moon, capable of getting out of his spaceship (a window would obstruct his view too much), would see the sky wrapped around the Earth and the Moon, forming an ellipsoid-like cavity (fig. 15). Depending upon the distance from the Earth and/or Moon, this ellipsoid may take various shapes, depending on whatever celestial body (Moon or Earth) is closer to him.



HYPOTHETICAL SKY - CONFIGURATION ON TRAVEL TO THE MOON

Figure 15. The "Ellipsoid Sky" Hypothesis. Based upon the previously mentioned illusion, an astronaut traveling from the Earth to the Moon, having reached a distance of one-third of the total distance to the Moon, the Moon and Earth would appear of equal size. The hypothesis is brought forward that the astronaut, supposing he is outside of the vehicle, would see the sky studded with fixed stars wrapped around him in an ellipsoid fashion (see text).

The greatness of such experience would only be complementary to the most courageous, most far-reaching, most brilliant excursion man has ever taken since the beginning of his existence: His trip to the Moon, and his landing on the surface of the Moon.

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Application of Aerospace Medical Developments in Clinical Medicine

Brigadier General Thomas H. Crouch

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APPLICATION OF AEROSPACE MEDICAL DEVELOPMENTS IN CLINICAL MEDICINE

Brigadier General Thomas H. Crouch, USAF, MC

As a result of the recent extraordinary advances in technology, medicine has been faced with great new obligations that have demanded a fresh approach and untrammelled thinking to keep pace with the times. This explosion of knowledge in all areas of scientific research has provided many beneficial overlaps, and medicine has adapted ideas, techniques and much of the hardware of the aerospace age to its own needs. The purpose of this presentation is to relate how much of the space-age advancements have been applied to clinical medicine.

Today, an estimated quarter of a million Americans are walking around with silicone parts in their bodies. Among them are the 20,000 or more people with artificial heart valves. Titanium, developed as a space-age requirement, is an alloy component of the newer artificial valves. At least 80,000 people are living with hidden "brain drains" made of non-reactive dacron, teflon and silastic, which were inserted in order to prevent further development of hydrocephalus. The replacement of diseased aortas and other major vessels by these space-age plastics and silicone parts is a commonplace surgical procedure.

Thousands of people have the reassurance that their hearts will continue to beat rhythmically by the use of electronic pacemakers, which were made possible by the development of reliable mercury cell batteries and the miniaturization of solid state circuitry. Investigations of fuel cells and sources of energy associated with the space program have led to considerable current medical research in which they are used for pacing the heart and for powering artificial hearts.

The techniques of radiotelemetry developed for the biomedical monitoring of space flight have been adopted for monitoring the critically ill, the postoperative patient, and people with heart disease. The triggering of electronic warning devices, indicating need for prompt medical intervention, has saved many lives.

Studies of pulmonary function and respiration in aerospace medicine laboratories have made available for clinical usage the positive pressure respirators. Studies of oxygen toxicity have eliminated the reason for many so-called interstitial pneumonias previously found in patients who had been placed on controlled respiration with 100% oxygen for prolonged periods.

Aerospace low pressure chamber studies have resulted in the application of hyperbaric conditions to clinical usage. This condition, which permits a more complete saturation of the circulating red cell mass, has been used in surgery for such congenital cardiac defects as tetralogy of Fallot, transposition of the great vessels, pulmonary atresia, and pre-ductal or post-ductal coarctation. One unique use is in the harvesting of kidneys from cadavers for homotransplantation. Hyperbaric pressure seems to provide a higher percentage of success than ambient pressure. Hyperbaric oxygenation also permits easier conversion of ventricular fibrillation to a sinus rhythm. Its use in the "bends" and compression sickness of scuba divers is well known.

The development of Fiber-Optic lighting has increased the reliability of endoscopic procedures dramatically.

Laser beams are still largely experimental, but they have been used in relieving obstruction by bronchial and esophageal lesions. They give promise of new hope to people suffering from cancer. Malignancies have been destroyed successfully by exposure to a single-pulse, high-energy beam. Cutaneous melanomas, portwine angiomas, basal cell carcinomas, and small angiosarcomas have been attacked by the same method.

A new surgical technique uses the energy of the laser beam to interconnect blood vessels. However, the major clinical application is in eye surgery, where the ophthalmologist can focus, aim and fire the laser beam at a detached retina to obtain a rapid, painless and efficient repair.

Thermography depends upon the supersensitive detection of small fractions of a degree difference in heat. Thermograms have been taken to determine the presence of abscesses under casts, for inflamed areas are warmer than the surrounding skin. Where blood flow is decreased or cut off by vascular lesions or congenital obstructions, the sites can be localized. Certain malignant lesions are warm in contrast to surrounding tissues, whereas cysts and other benign abnormalities are cooler. Therefore, thermography becomes another extremely sensitive diagnostic tool in the detection and evaluation of disease.

An outgrowth of insulation studies in the aerospace industry is a plastic polymer gel of the same density as human fat at body temperature. This property makes the material an ideal padding for bedridden patients because it creates no pressure points and it prevents decubiti.

Bioelectric stimulation and control systems are a direct application of aerospace technology to the human body. Such a system has been used in an upper limb prosthesis that motivates a voluntary pinch mechanism in an artificial hand. Basically, the myo-electric impulses of voluntary muscles are transmitted through electrodes to an amplifier powered by a space-age battery. The output of the amplifiers goes to a motor in the base of the artificial arm that controls the pinch mechanism.

Myo-electric devices also translate the signals from a normally innervated muscle into a current for the stimulation of a paralyzed muscle through a potentiometer. Thus, motion of those parts would mirror the motion pattern of the normal muscle moving the potentiometer. This permits a grading in the strength of the contracture and better control than the mere "ON - OFF" stimulation of such muscle groups.

Another direct application of aerospace hardware is the use of Northrop cable for an upper extremity prosthesis. Used originally as throttle cable on aircraft, it is also called Bowden cable or linear pull cable, and gives the wearer more strength and better control of his artificial arm.

Most of you are familiar with the now commonplace use of Velcro closure tape. It, too, was designed originally for space suits, but now it has many and varied adherent, fastening and closure applications in clinics and hospitals, e.g., tourniquets, blood pressure cuffs, emergency splints, cervical collars, and braces.

Even methods and procedures have been borrowed from the aerospace industry, and they have had an influence on medicine. NASA and the Department of Defense devised a weapons systems approach that was designed to make hundreds of separate projects converge to serve a single purpose. The success of this convergence technique has been repeated and refined in Air Force Systems Command in the computerized management of projects of vast scope and complexity.

Now, as adopted by medicine, it represents the step-by-step planning of the most highly coordinated total-war effort ever mounted against specific diseases. The first project, "The Special Virus Leukemia Program of the National Cancer Institute", has made such impressive strides that similar program analysis and flow chart planning have been applied to cancer chemotherapy and will be applied to breast cancer.

The basic ingredient of the programs is the division of research into major areas with a manager in charge of each. These managers work under a single coordinator, the Program Manager. All of these scientists work in close collaboration with one another as well as with scientists both outside of the program and outside of the country. Therefore, any concept or finding anywhere in the world can be made known instantly anywhere else that it might be useful. In the past, years were lost after someone had completed research before the results were published and circulated.

Another method of expediting research has been to support duplicate efforts, a tactic that on the surface appears wasteful. Why have two men or two laboratories do the same work? In the normal course of research, a man or a team in one laboratory might work months or years to achieve a result and eventually publish a technical paper or present the data at a scientific meeting. However, nothing is ever accepted in science until someone else repeats the experiments and confirms the results. Therefore, if the data look exciting, someone else sets out to do exactly that; and months or years later, if the results are similar, the original work is considered confirmed. By assigning two men in two laboratories to a problem simultaneously, each confirms the work of the other (meanwhile exchanging data for their mutual benefit), and the extra months and years are saved.

The advantages of such programmed research are:

1. Delay is eliminated, for each step is completed in time for the next step to be taken, rather than waiting for random completion of the underlying research to provide a basis for advancement.

2. Multiplication of effort is prevented, because the central "Project Manager" coordinates the research.

3. Personnel can be used more effectively, because the central agency will be aware whenever a certain portion is "bogged down" and can divert more workers, funds and equipment into that area.

This type of research approach, as used in the development of weapons systems, where each contractor is responsible for the development of subunits that are to be incorporated into the entire system according to schedule, appears to be paying off.

Now I wish to discuss one phase in the application of data retrieval and computer techniques that promises to revolutionize hospital information systems.

The practice of medicine is largely a process of information collection, manipulation, retrieval and communication. The success of medical ventures is influenced more by the information processing skills of the participants than by any other single factor. Recognizing this, several companies have devised advanced concepts in medical application of computerized operation that virtually eliminates manual manipulation and retrieval of information. This acknowledges that the physician is both the source and user of most medical information, and the system is carefully adjusted to his needs. He is in direct contact with it, and not isolated from it by intermediaries. The grouping and storage of information are in a logical sequence that parallels the information structure instilled in the operator's memory by training and practice. For example, the elements of various types of medical orders -- general care, medications, and laboratory tests -- are stored in the computer. Using a photosensitive device called a "light pen", the physician "writes" a prescription by selecting the elements of the prescription in a pre-established sequence. I will demonstrate the instant retrieval of information on patients and how further recording of orders and information can be accomplished. I will portray the display of information that is stored in the computer.

After identifying himself to the computer, probably by a card similar to a charge plate:

```
PLEASE PLACE

IDENTIFICATION CARD

IN

OPERATORS SLOT
```

The physician is presented with a list of his current hospitalized patients. From this list he decides, for instance, to check on "Margaret Dean."

```
DR. JAMES MATHIESON

YOUR PATIENTS ON THIS DIVISION ARE:

CULBERTSON, DANIEL A. 56

DEAN, MARGARET L. 58

GUTMANN, JOHN B. 61

MANION, GEORGE W. 66

VERNON, SAMUEL M. 44

PLEASE SELECT ONE OF ABOVE, OR
OTHER PATIENT
```

With his patient identified, he selects from the records available on "Margaret Dean" the Medical Orders.

```
DEAN, MARGARET L. 58

          PLEASE SELECT TASK:

                    CHART REVIEW

                    PROGRESS NOTE

                    MEDICAL ORDERS

                    HISTORY & PHYSICAL

                    PROCEDURE NOTE

                    CONSULTATION NOTE
```

Immediately portrayed on the screen is a resume of all of the orders that he has written about "Margaret Dean" to date, but he may decide on more tests and therapy.

```
BED REST, BRP

VITAL SIGNS Q4H

TEMP., Q8H

WEIGHT QOD

DIET LO NA GM 2

DIGOXIN 0.25MG PO BID ---

PHENOBARB 30 MG PO Q8H ---

SECONAL 100 MG PO QOD QHS

HYDROCHLOROTHIAZIDE 50MG PO QOD IN AM

                                   ADV MED ORD
```

He decides that his patient needs more laboratory work.

MEDICAL ORDERS
GENERAL CARE
DIET
LAB
X-RAY
TREATMENT
MEDICATIONS
. . .

From the available laboratory sections, he selects chemistry.

LAB
CLINICAL MICROSCOPY
CHEMISTRY
BACTERIOLOGY
SPECIAL
PATHOLOGY
. . .

From the chemistry list, he selects Na, K, Cl, and CO_2 tests.

LAB CHEMISTRY		
FBS	NA	TOT SER PROT
2HRPCS	K	ALB/GLOB
BUN	CL	BIL DIR/INDR
	CO2	CEPH FLOC
CA	PH	THYM TURB
PHOS		
ALK PHOS	SGOT	PROTH TIME
ACID PHOS	SGPT	PBI
	LDH	
		ADV LAB ADV MED ORD

The upper part of the screen shows that he has chosen correctly a sodium, potassium, chlorine, and carbon dioxide evaluation. Now he selects the portrayal of advanced laboratory procedures under "Special."

NA, K, CL, CO2	
	CLINICAL MICROSCOPY
	CHEMISTRY
	BACTERIOLOGY
	SPECIAL
	PATHOLOGY
	. . .

From the list of special procedures, an EKG is ordered and the general medical orders section is called up again.

```
LAB SPECIAL

              EKG

              MASTERS

              EEG

              BMR

              RAI

              PULM FUNCT

              . . .

                              ADV LAB
                              ADV MED ORD
```

X-ray is chosen.

```
EKG

              GENERAL CARE

              DIET

              LAB

              X-RAY

              TREATMENT

              MEDICATIONS

              . . .
```

An x-ray of the chest and a barium swallow are decided upon, and additional orders are indicated.

X-RAY		
	PLAIN:	CONTRAST:
	CHEST	BA SWAL
	SKEL	UPPER GI
	ABD FLAT	GALL BLADDER
	ABD OBST	SM BWL
	SINUS	IV PYEL
	. . .	BA ENEMA
		. . .
		ADV MED ORD

Medication is the next order of business.

X-RAY CHEST, BA SWAL	
	GENERAL CARE
	DIET
	LAB
	X-RAY
	TREATMENT
	MEDICATIONS
	. . .

A diuretic is selected.

MEDICATIONS

ANALGESIC	BRONCHODIL	SEDATIVE
ANTACID	CARDIOTONIC	STEROID
ANTIBIOTIC	DIURETIC	STIMULANT
ANTICOAG	LAXATIVE	SULFA
ANTICONV	. .	. . .
ANTIDIAB		
ANTIHIST		
ANTISEPT		
. . .		
		ADV MED ORD

He selects spironolactone as his drug of choice.

DIURETIC

ACETAZOLAMID	NAQUA	THIOMERIN
ALDACTONE-A	NATURETIN	UREVERT
AMINPHYLLIN	POLYTHIAZIDE	. . .
CHLOROTHIAZD	RENESE	
CHLORTHALION	SPIRONOLACTON	
DIAMOX	. . .	
DIURIL		
. . .		

His order is for 25 mg.

SPIRONOLACTONE		
DOSE		
MILLIGRAMS		
1.0	25.0	100
2.5	30.0	125
5.0	40.0	150
7.5	50.0	200
10.0	60.0	250
15.0	75.0	300
20.0	80.0	...

He decides that the route of administration should be by mouth.

SPIRONOLACTONE 25MG		
ROUTE:		
PO	IM	SUBQ
PR	IV	TOP
. . .		

He decides that it should be given three times a day.

SPIRONOLACTONE 25MG PO		
FREQUENCY:		
Q5M	Q1H	QOD
Q10M	Q2H	BID
Q15M	Q3H	TID
Q30M	Q4H	QID
. . .	Q6H	Q2D
	Q8H	Q3D
	Q12H	QWK
	Q24H	Q2WK

With the order completed and verified, no other modification is needed.

SPIRONOLACTONE 25MG PO TID		
FREQUENCY MODIFIERS:		
	NO MOD	EVEN HR
	STAT	AC
	ONCE ONLY	PC
	PRN	BKFST
	QHS	LUNCH
	IN AM	DINNER
	IN PM	SUPPER
	. . .	ODD HR
		ADV MED ORD

This depicts other drug categories that could be visualized in detail if additional medications were to be prescribed. Believing that he has written enough, he wants to review what he has done.

```
SPIRONOLACTONE 25MG PO TID ---

ANALGESIC      BRONCHODIL     SEDATIVE
ANTACID        CARDIOTONIC    STEROID
ANTIBIOTIC     DIURETIC       STIMULANT
ANTICOAG       LAXATIVE       SULFA
ANTICONV       . . .          . . .
ANTIDIAB
ANTIHIST
ANTISEPT
. . .
                              ADV MED ORD
```

This depicts all of the new procedures and medications that he has ordered on Margaret Dean, and it is presented for verification, or revision if needed.

```
MED ORDERS DEAN, MARGARET L. 58

      NEW ORDERS:
      LAB NA, K, CL, CO2
      LAB EKG
      X-RAY CHEST, BA SWAL
      MED SPIRONOLACTONE 25 MG PO TID ---

                              VERIFY
                              REVISE
```

Now he is ready to select another patient on his service.

```
ORDERS ENTERED FOR DEAN, MARGARET L. 58

      YOUR PATIENTS ON THIS DIVISION ARE:

            CULBERTSON, DANIEL A. 56

            DEAN, MARGARET L. 58

            GUTMANN, JOHN B. 61

            MANION, GEORGE W. 66

            VERNON, SAMUEL M. 44

      PLEASE SELECT ONE OF ABOVE, OR
            OTHER PATIENT
```

A similar information structure and series of displays may be used by hospital administrative personnel. These could include displays for ordering supplies, entering and retrieving information on the status of facilities, supplies, personnel, financial activities, and many other subjects.

The potential benefits to the physician will fall into two principal categories: a more efficient use of his time and a continuing education. The former will result because the system will facilitate his routine entries, i.e., orders, progress notes, procedure notes, consultations, history, and physical examinations. His orders will be accomplished more quickly and accurately. What is far more important, they will be complete, immediately accessible, and legible.

The physician's knowledge of medicine will be reinforced continually and broadened by the structured information displays, because their use represents a form of programmed instruction through passive recognition. Like the check list used by the pilot, the information display will obviate errors and omissions for the physician. In addition, he will have instant access to a wealth of general medical information, e.g., poison control data, drug reaction data, diagnostic aids, and therapeutic guides.

Not only will the system make the physician more efficient, but it will reduce routine paperwork, eliminate typing pools, and facilitate charting that will be uniform, absolutely up to date, and legible. The procedure and medication orders will be displayed electronically to the ward, laboratory, pharmacy, or pertinent clinic immediately and recorded at the same time. The potential will mean sizable savings in time, personnel and money. Much of the drudgery now associated with the recording, processing and retrieval of medical information will be eliminated.

My presentation this morning has touched upon only the highlights of what space-age knowledge and technology have done and can contribute to the advancement of clinical medicine. It is my opinion that this is merely the beginning, and that the application of Aerospace Medical Developments in Clinical Medicine will continue to enhance both the knowledge and efficiency of the physician.

Cardiac Responses to Acceleration Stress:
I. Instrumentation and Technics

Captain H. Fred Stegall

Captain Stegall is a Research Medical Officer in the Biodynamics Branch, USAF School of Aerospace Medicine. He received his B. S. degree in chemistry from St. Edward's University in Austin, Texas, in 1956; his M. A. in physiology and M. D. degrees were awarded by the University of Texas Medical Branch, Galveston, Texas, in 1959 and 1961, respectively. He interned in the University Hospital, Seattle, Washington, and subsequently was postdoctoral fellow and research instructor in physiology and biophysics at the University of Washington. He received his commission in the U. S. Air Force in 1965. He has written a number of publications on cardiovascular physiology and ultrasonic bioinstrumentation, and is a member of the IEEE Group on Engineering in Medicine and Biology, American Association for the Advancement of Science, Alpha Omega Alpha, and Sigma Xi.

CARDIAC RESPONSES TO ACCELERATION STRESS:

I. INSTRUMENTATION AND TECHNICS

Captain H. F. Stegall, USAF, MC

The experimental skills needed to define the responses of the cardiovascular system to acceleration stress are no different from those needed to define responses to other stresses like exercise, hypoxia, or disease. In each case we must identify the pertinent stress placed on the system, the functional limitations imposed by this stress, the reflex responses elicited by it, and how the stimulus-response relationship may be modified. Pertinent variables describing each must be identified and then measured with an accuracy appropriate to the demands of the experiment.

The first illustration (fig. 1) outlines the general approach necessary to logical experimental design. This is certainly a significant limitation to function in a pilot pulling from up a dive--the cerebral hypoxia and unconsciousness which result when he pulls too many "G's." By outlining in sequence the factors which can cause cerebral hypoxia, we can identify those which may be significant by proceeding down this logical tree. Currently available information suggests that the most profitable line of inquiry lies along those boxes heavily outlined; development of a large pressure head between heart and brain which is not overcome by a rise in aortic

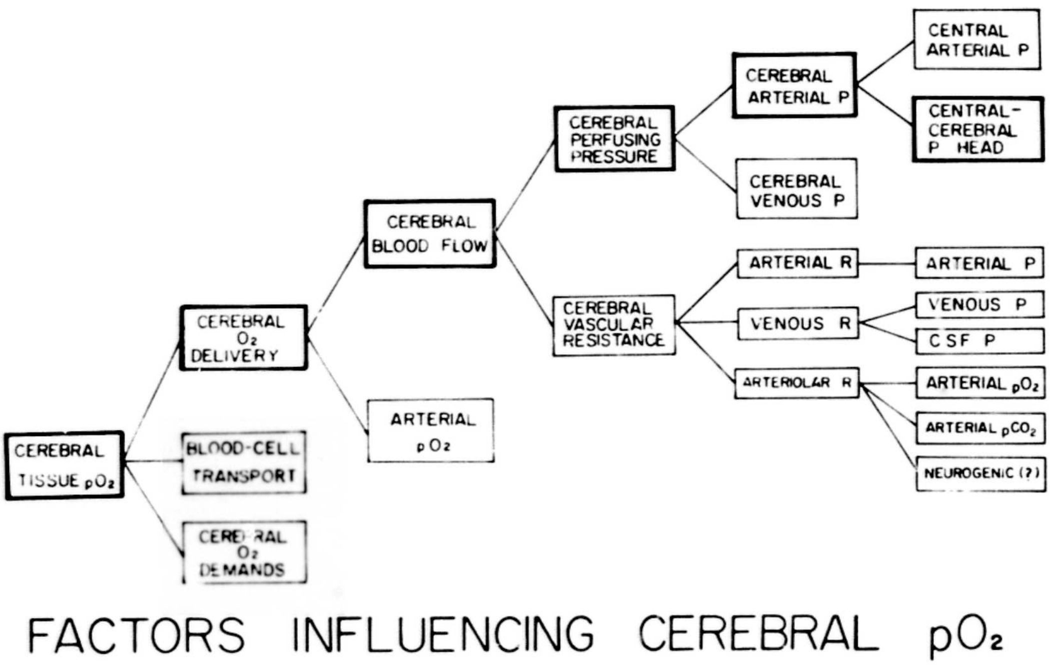


Figure 1

pressure appears to be responsible for cerebral ischemia and unconsciousness. This in turn indicates that methods for elevating aortic root pressure or decreasing the cardiocerebral pressure head might be expected to increase G-tolerance, and such is indeed the case. Lindberg and others (1) have demonstrated that G-suits appreciably increase peripheral resistance and raise aortic pressure, and of course assuming the semisupine position also increases tolerance by several-fold.

We are still unable to state what levels of cerebral arterial pressure and flow are the minimum necessary to sustain consciousness, or whether some reflexly induced vasodilation within the brain may help sustain flow in the face of declining perfusion pressure. We are reasonably certain that, given time to act, vasoconstriction in less vital organs increases the total peripheral resistance and helps maintain arterial blood pressure despite a declining cardiac output.

The complexity of the interacting control systems responsible for cardiovascular regulation, and the multiple elements involved in total cardiovascular reserve, force us to attempt to visualize the response of the system to this particular stress much as others have visualized responses to other stresses. We must measure pressure, flow, vascular resistance, and O_2 content at appropriate sites in unanesthetized (since) autonomic reflex activity is so often disturbed by anesthetic agents) animals or man in order to explore these mechanisms, and thus we conclude that fundamental studies in cardiovascular physiology are necessary to fulfill our mission of aiding men to survive in the adverse environments that military needs may demand of them. How severe may these be? In an aircraft traveling 1200 mph, a 360° turn of diameter 8 miles will expose the pilot to $+5G_z$ for over 75 seconds. One Apollo re-entry profile proposed for man demands $+20G_x$ exposure for about 60 seconds. These are well beyond usual limits, and protective devices are obviously necessary to preserve functional capacity.

Many of the techniques I will describe this morning are of relatively recent introduction, and we cannot describe results obtained by their use as yet. One of our major efforts here is simply to stay abreast of the rapidly expanding field of bioinstrumentation, for as we shall see, almost all of our instruments and techniques have limited application. However, since many are new and potentially of wide use and interest to other environmental physiologists, we have elected to spend some of our time describing them.

TECHNICS

If the limitations of man to acceleration stress are cardiovascular, we must determine pressure, flow, and resistance at appropriate sites. Techniques which can give as reasonably quantitative measurements of these three variables are thus potentially useful to us, and we will explore some of these.

Before proceeding further, we must recognize and identify certain restraints placed on our instrumentation by the unique environment in which it is to be used, i.e., high radial acceleration. First, devices must not be very heavy nor significantly restrict the normal physiological function under examination; this means we cannot, for example, use electromagnetic flow probes in animal studies since the increased weight of the probe under acceleration might seriously compromise flow through the vessel it surrounds. A second limitation reflects the nature of the environments we use; centrifuges tend to be electrically noisy, vibration-prone machines, separated from the investigator and his recording apparatus by relatively long distances over which signals must be sent through slip rings or by telemetry. Devices which are sensitive to noise or which need constant attention are simply impractical under these circumstances.

Pressure

The first group of instruments to be described are those capable of measuring pressures. Most of us have used the strain-gage manometer and intravascular catheter for this purpose, since it allows continuous, direct measurements with a minimum of manipulation. However, it is still necessary to place the catheter in the selected location and this may be a serious disadvantage for it is well known that arterial wall stimulation alone may cause a profound autonomic reaction (2). Moreover, such systems tend to "ring," or oscillate at their natural frequency (fig. 2), and may record deceptively high pulse pressures unless care is taken in their preparation. Small air bubbles seriously degrade performance, and one's technique must be repeatedly checked to be certain the recorded pressures accurately reflect intravascular pressures.

Pressure heads developed between the transducer mounting and the site selected as a reference level (usually the aortic root or right atrioventricular junction) may be insignificant at 1G, but amount to many millimeters of mercury during acceleration. The errors introduced in this way may be compounded by the fact that the reference site itself often moves with respect to its surroundings as accelerative forces are applied. If pressure is to be measured at the reference site itself, catheter-tip or implanted manometers may be employed as one solution to these problems. In recent years a number of devices of varying quality and size have become available for this purpose, and it seems probable that sufficiently small, sensitive, and stable catheter-tip manometers will be available soon at reasonable cost. Pressure transducers small enough to be implanted surgically in the ventricle or larger vessels of a medium-sized dog can be obtained from commercial sources (fig. 3).

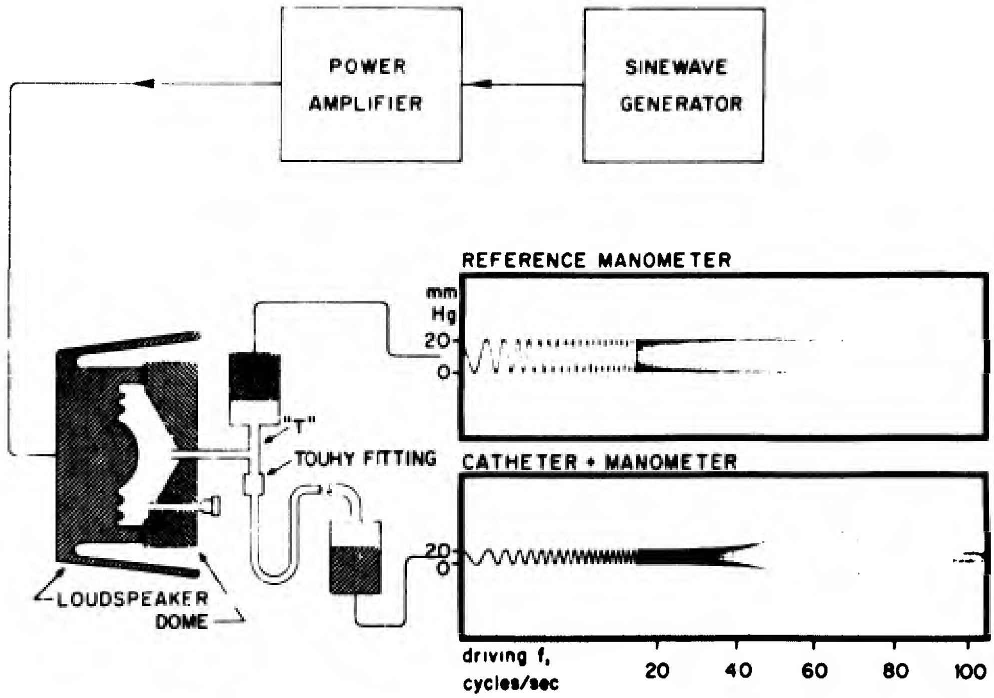


Figure 2

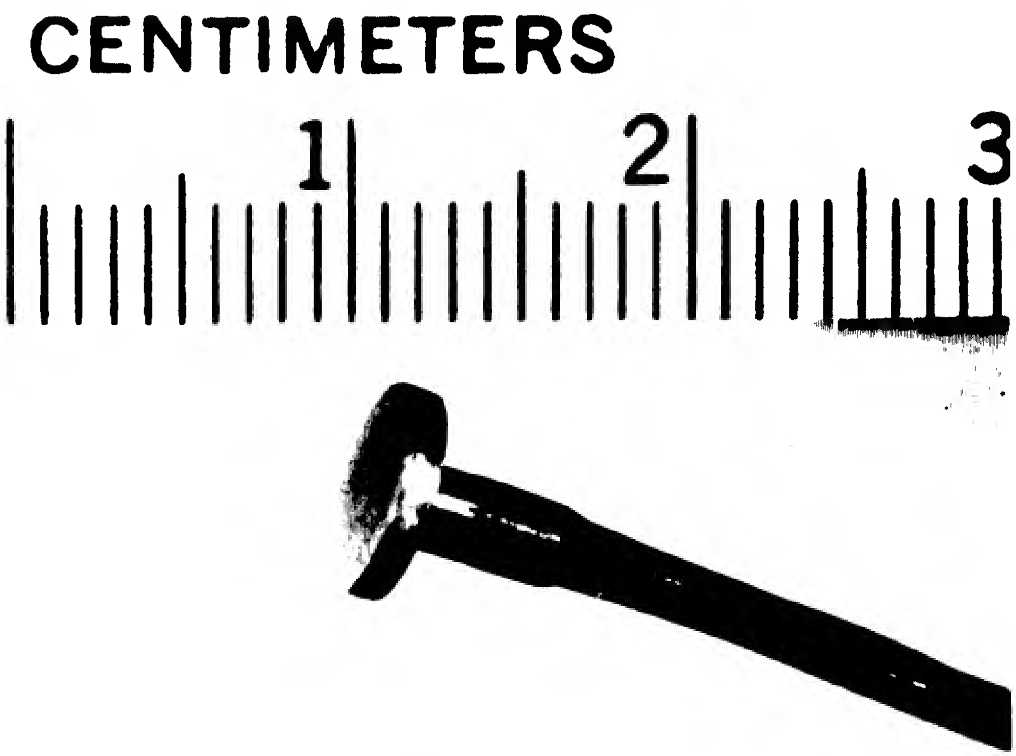
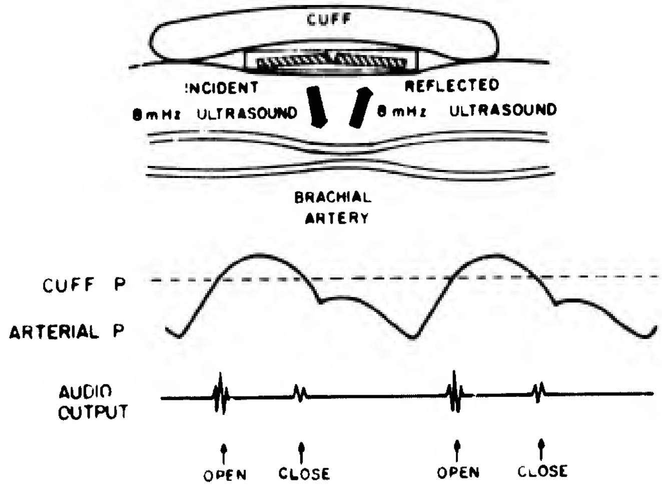


Figure 3

The only nonpenetrating way of reliably estimating arterial blood pressure remains the clinical sphygmomanometer. For many stress studies we can substitute a small microphone for the stethoscope usually used and obtain sufficiently clear Korotkoff sounds for measurement. One relatively recent improvement consists of substituting for the microphone a Doppler-shifted ultrasound detector (fig. 4) which actually senses movement of the arterial wall rather than the sounds produced by such movement (3). The detector is relatively simple, consisting of two piezoelectric crystals: one is driven near its resonant frequency by a power oscillator to generate 8 mHz ultrasound, and the other serves to detect ultrasound coming back through the skin. Sound reflected from non-moving structures has the same frequency as emitted sound, and is ignored by the detector; sound reflected from moving structures is shifted slightly in the frequency by the Doppler effect, and the beat frequency between the two may be amplified to drive a loudspeaker. The audible sound obtained in this manner is of higher energy and frequency than Korotkoff sounds, and thus the technique seems particularly well suited for measurements where high ambient noise masks the Korotkoff sound. Its principal disadvantage is the discontinuous nature of any sphygmomanometric approach; since an inflation-deflation cycle cannot occupy much less than thirty seconds, it is suitable for relatively steady-state measurements.

DETERMINATION OF BLOOD PRESSURE
BY WALL MOTION SENSOR

Figure 4



Volume and Linear Dimension

Cardiac and vascular volumes are, generally, difficult to measure. Since the cardiometer--essentially a plethysmograph for the ventricles--was devised over 60 years ago, little progress has been made in measuring ventricular volume in a continuous fashion. However, a number of strain or distance gages have been developed more recently which can be used to record some linear dimension change and give us some idea about changes in heart or vessel size. One of these--and perhaps the most compact and least massive--which has recently been simplified and miniaturized here at USAFSAM is the sonomicrometer (fig. 5), or sonic dimension gage. This device converts the transit time of an ultrasonic burst into a DC voltage proportional to the distance between two chronically implanted transducers. When these are sutured to the outside (fig. 6) or inside of the left ventricle, continuous records of external or internal ventricular diameter may be obtained, and in the latter case the relation between diameter and volume appears to be simple enough to permit conversion between the two with a systematic error of less than 10%. Even without absolute calibration, such

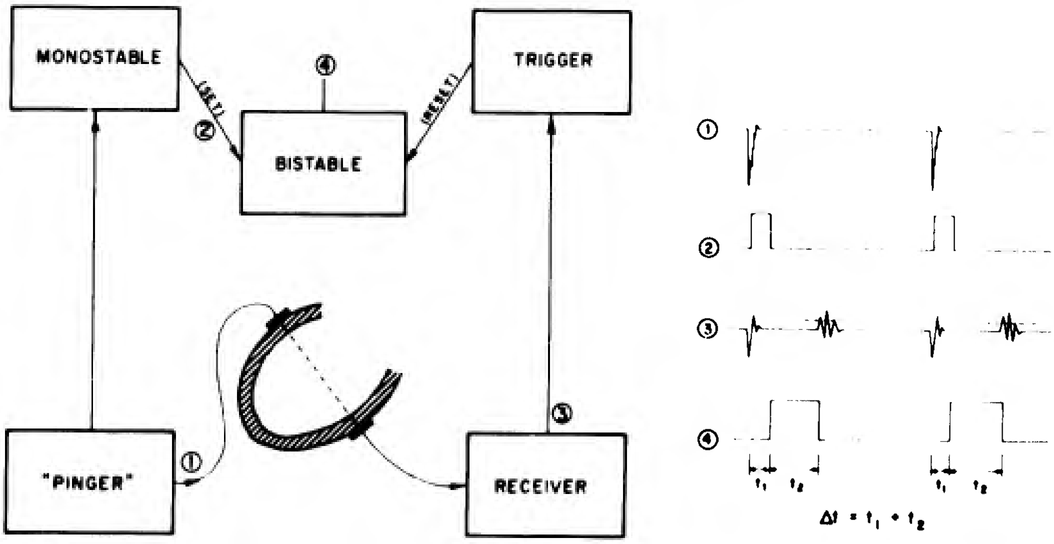


Figure 5

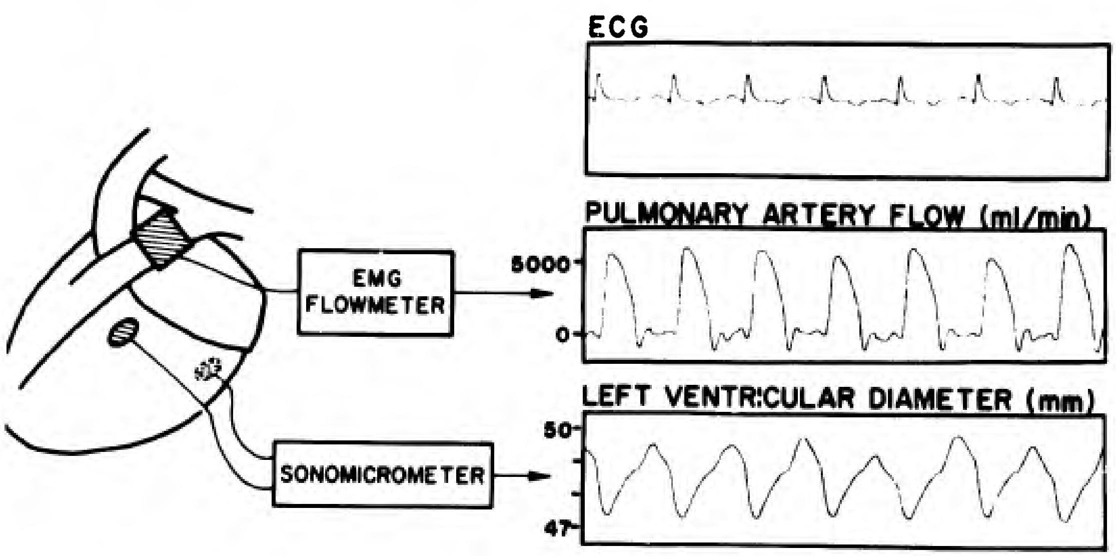


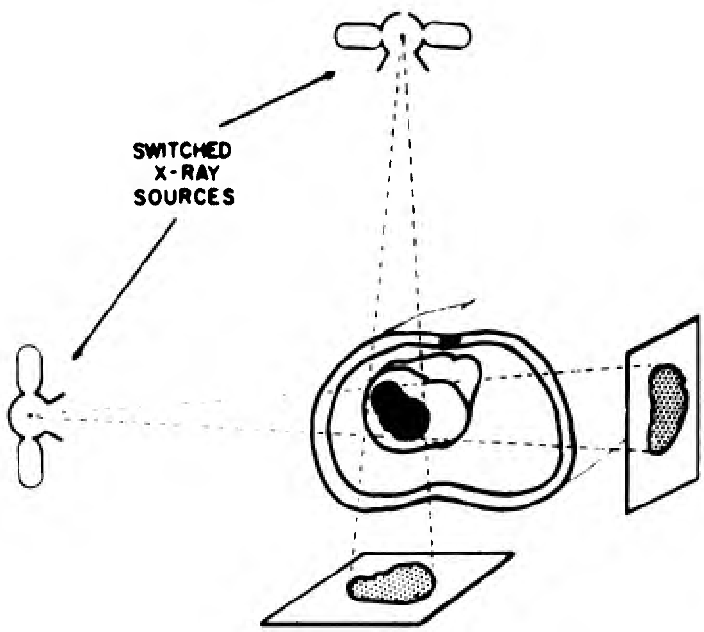
Figure 6

devices can reveal whether the heart size changes in response to acceleration or other stress, and can do so with a minimum of interference with normal function. Transducers may be also mounted across larger arteries or veins to determine changes in their size.

Several other strain gages have also been used, though in general they suffer from the necessity of being individually calibrated in place to yield reliable measurements. Bonded and unbonded resistance-wire gages, mercury-in-rubber (Whitney) gages, semiconductor gages, variable-inductance and variable-transformer types, and impedance changes (4) have all been used by cardiovascular physiologists with varying degrees of success. One particularly promising approach has been described by Pieper (5) in which a set of cantilevered "feelers" extends from a catheter tip to measure left ventricular dimensions; since it is threaded down the aorta, no penetration of the chest or pericardium is necessary and thus the interaction between myocardium and surrounding structures is preserved. Small cephalad-caudad movements of this device anticipated under acceleration greater than 1G thus far preclude its application in this area.

The dilution of tracers or heat within a fluid-filled chamber can be used to estimate volume. The X-rays shadows cast by radiopacified cardiac chambers also appear to indicate reliably changes in ventricular volume, especially if the areas of the shadows cast in two directions are measured (fig. 7); such an approach has been successfully employed under acceleration as high as 15G (6). The principal disadvantage of this technique is the intermittent nature of the measurement, since the dye is soon washed out

Figure 7



BIPLANE ANGIOCARDIOGRAPHY

of the chambers; moreover, frequency response is limited by the speed with which cassettes may be changed, and some uncertainty in outlining the irregular internal surfaces of the cardiac chambers appears unavoidable.

Another useful linear dimension measurement is that of phase shift between an ultrasonic source and receiver (7). Arterial diameter may be continuously recorded with a high degree of precision (fig. 8). If the sound is reflected from chest or abdomen, a subject's respiratory pattern may be recorded without actually touching him (fig. 9) (7).

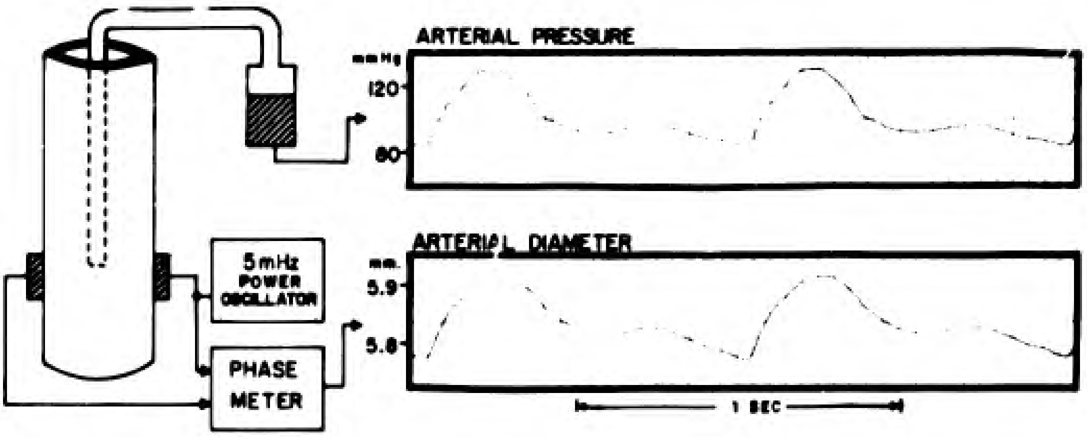


Figure 8

RESPIRATORY ABDOMINAL MOTION

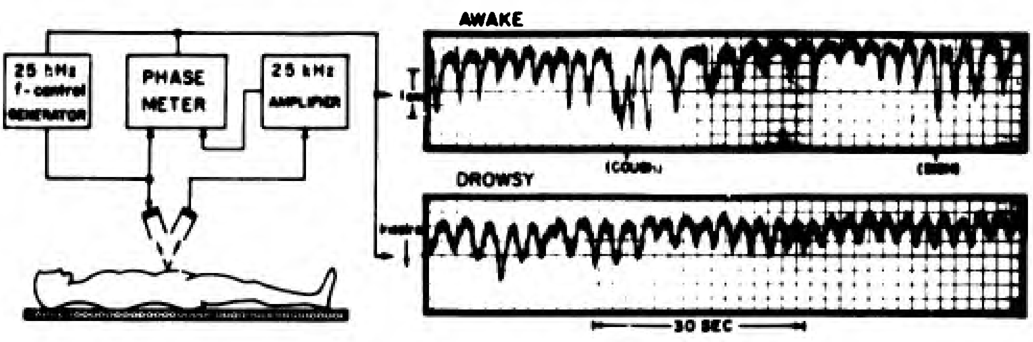


Figure 9

Flow

A recent pictorial summary of available methods of measuring blood flow in animals and man (8) is reproduced in figure 10. The simplest and most straightforward measurement takes advantage of relationship F + dV/dt; if one collects 100 ml. of fluid in a graduate in 10 seconds, the average flow rate is equal to 10 ml./sec. The same principle can be used to estimate flow in a hand, forearm, or other terminal part by means of a plethysmograph: a volume or circumference sensor is placed around the part, the venous outflow occluded with a cuff, and the initial rate at which the extremity swells is equivalent to the arterial inflow. Sampling rate is necessarily limited to about 1 per 10 seconds.

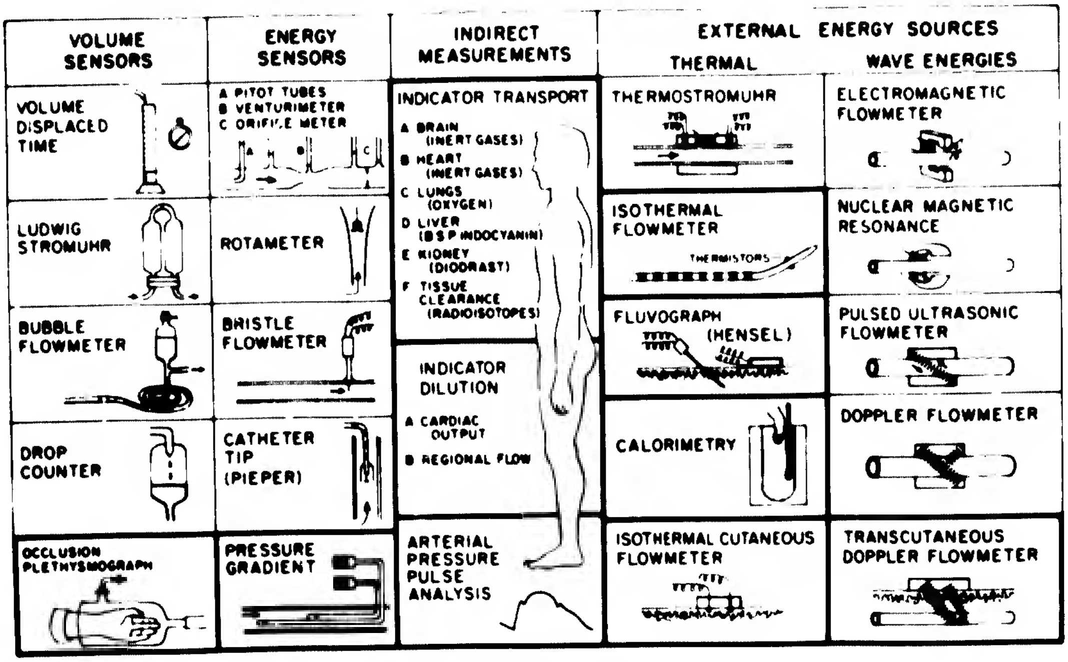


Figure 10

Since the flow of liquid through a tube involves energy loss, measurement of the pressure gradient between two points along the tube can indicate flow velocity; (9) although capable of high frequency response in the right hands, the method requires great care in preparing the double-lumen catheter as well as arterial puncture with all its disadvantages.

Several less direct techniques have been developed to measure flow through various organs. The familiar Fick and dye-dispersion techniques can be used to estimate cardiac output or, when an indicator is selectively removed by a single organ, organ blood flow. For example, when indocyanine green is injected intravenously, it is removed almost entirely from circulating blood by the liver in a single pass; if the hepatic extraction ratio does not change, changes in splanchnic blood flow will be reflected in changes in the rate at which the dye disappears from circulating blood. Dr. Stone will describe later the changes in hepatic blood flow which we have seen during acceleration stress.

Of the external energy sources whose properties may be modified by blood flow, the most widely used is the electromagnetic flowmeter. The necessarily massive transducer with its magnet pole pieces precludes its use in experimental animals centrifuged to appreciable levels. The most promising approaches to instantaneous measurement of flow velocity in centrifuged animals or man have been ultrasonic. Probes are actually lighter than water and need not restrict the vessel lumen to function properly. Either of two systems may be used: pulsed ultrasonic approaches measure the difference in transit time required for an ultrasonic burst to travel upstream and downstream, while the simpler Doppler approach measures the Doppler shift in sound backscattered from moving blood (much like the arterial wall motion sensor described above). Of the pulsed and Doppler systems, the Doppler offers several advantages: electronic circuitry is relatively simple and transducer construction noncritical, flow zero is readily identified and the output is calibrated by the Doppler effect equations. Major disadvantages of the technique are lack of distinction between forward and reversed flow, and sensitivity to velocity rather than bulk flow. Measurement of intravascular dimensions within the probe may allow the second of these two objections to be satisfied, but we still do not have directional Doppler detectors.

Another advantage of the Doppler approach has been that the sensors could be mounted side by side so that flow velocity in subcutaneous vessels could be determined without pain or penetration of the skin (10) accuracy has been sacrificed somewhat, but simplicity and high frequency response (up to 30 Hz) suggest that application of the technique will allow investigation of flow patterns in man hitherto unattainable.

Of the techniques outlined, no single approach is ever ideal. For example, Dr. Stone will report later the forearm flows obtained via Whitney gage plethysmography during acceleration, but the slow sampling rate inherent in that technique precludes looking at transients or the time constant associated with the vascular response. The sampling rate for measurement of hepatic flow is even slower--about 1 per 15 minutes--and we must restrict its use to those circumstances in which a relatively steady state may be maintained for that time. One approach we are not evaluating for possible use in animals or human volunteers involves placing the small piezoelectric transducers for Doppler flow velocity measurement as a catheter tip (fig. 11); though use will require arterial catheterization, the device may allow continuous registration of flow velocity through the aorta and its major branches with an accuracy sufficient to determine transient responses to short-term accelerative forces. Working devices of this sort are now being evaluated, and our next attempt will be to incorporate a pressure sensor on the same catheter tip for simultaneous measurement of pressure and flow.

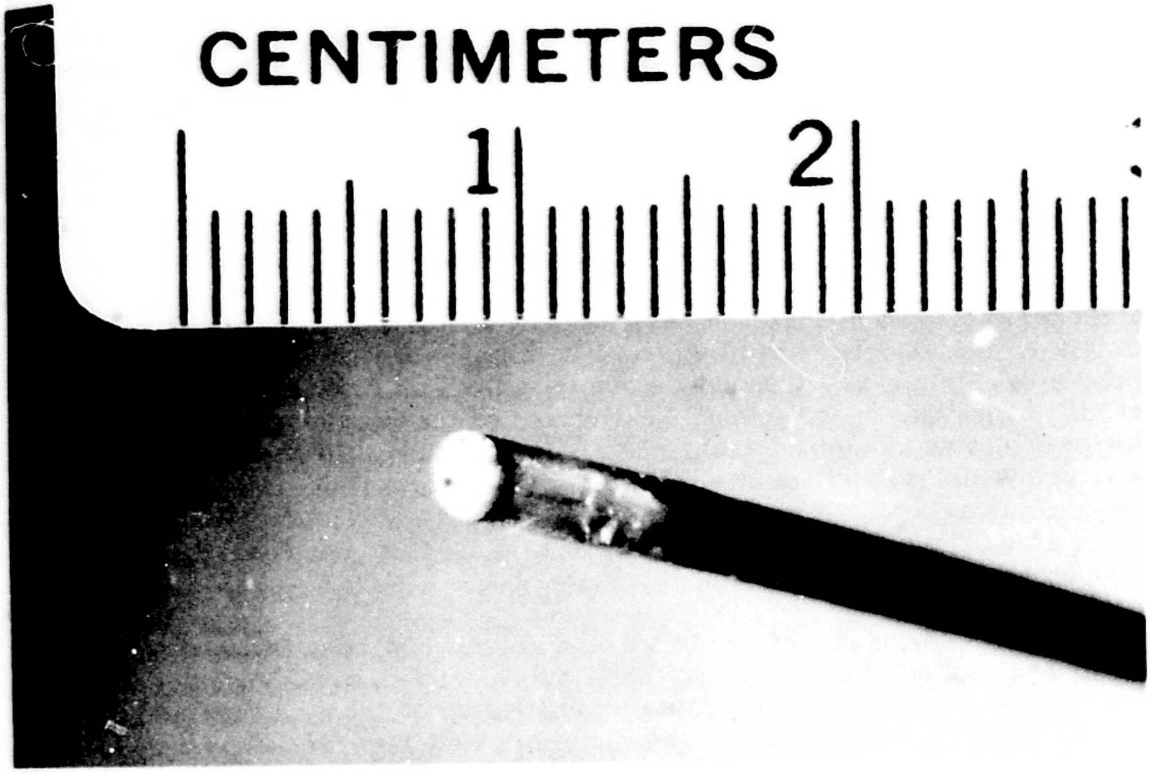


Figure 11

Conclusions

Recent advances in bioinstrumentation are bringing us closer to our goal of a complete description of the cardiovascular stresses and reflex responses seen during acceleration. Measurement of pressure, volume, flow, and vascular resistance in various sites by appropriate techniques, singly or in combination, is an essential part of this task. We must continue to extend these capabilities, where possible, under the difficult conditions of acceleration studies. Instruments and techniques meeting these criteria will find wide use in other stressful situations and will lead to a better understanding of the interaction of man and his environment.

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Cardiac Responses to Acceleration Stress:
II. Results in Human Volunteers and Experimental Animals

Dr Hubert L. Stone

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CARDIAC RESPONSES TO ACCELERATION STRESS: II. RESULTS IN HUMAN VOLUNTEERS AND EXPERIMENTAL ANIMALS

Hubert L. Stone, Ph. D.

The response of the cardiovascular system to acceleration is primarily governed by the magnitude and direction of the acceleration vector with respect to the body as well as the duration of application and onset rate. In talking about accelerations and vectors one finds a variety of terms used to describe the direction or resultant of a particular acceleration. To facilitate future discussion, the terms "G_X" and "G_Z" will be used as described in figure 1 for the remainder of this presentation. This is in conformity with the presently accepted terminology and it should be noticed that this describes the direction of the movement of body organs in response to an acceleration vector (1). Thus, "G_Z acceleration" would be one in which the body organs were moved either caudal (+) or cephalad (-) and "G_X acceleration" would be when the organs were moved either toward the vertebral column (+) or toward the sternum (-). The major discussion in this presentation will be the cardiovascular changes that are known to occur in the $+G_X$ and $+G_Z$ directions and combinations of these two quantities.

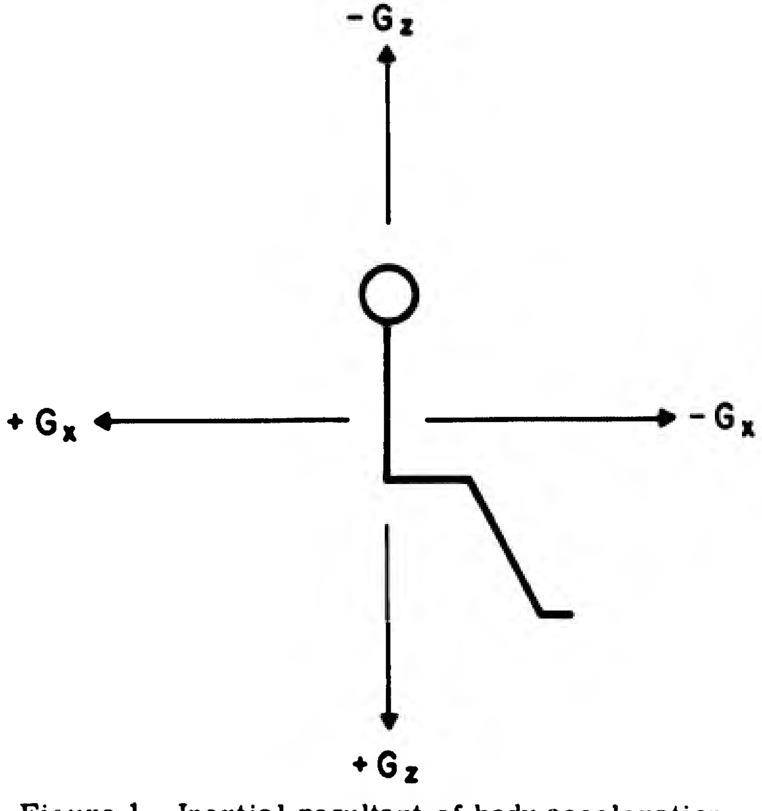

Figure 1. Inertial resultant of body acceleration.

First, we will ask the general question, "What do we know about circulatory changes taking place during $+G_Z$ exposure?" In this configuration the circulatory system is in essence elongated by an increased hydrostatic column of fluid equal to the increase in G. Pressures above the heart decrease and below the heart they increase. However, the magnitude of changes observed do not correspond to a closed elastic system, but rather to a system that is being regulated or has the capability to respond to the increased force field. One of the major symptoms of $+G_Z$ exposure is a loss of vision or "blackout" at levels which under present conditions determine the tolerance to $+G_Z$ acceleration. The loss of vision seems to be a result of retinal hypoxia depending upon the level of oxygen required to sustain retinal function. Therefore, as the head level pressure falls, so does the blood supply to the brain and retina; thus the end result will be blackout followed by unconsciousness if the $+G_Z$ acceleration is increased. The changes in head level pressure should be sensed by the baroreceptors in the carotid sinus area, thereby giving rise to a peripheral vasoconstriction and increased heart rate in the absence of afferent information from other sensory areas.

Table I gives values for the percent changes in cardiac output, heart rate, stroke volume, and mean arterial pressure in six subjects exposed to 2, 3, and 4 $+G_Z$ levels of acceleration (2). At $+2G_Z$ there was an increase in mean arterial pressure measured at heart level and also an increase in heart rate. The cardiac output decreased by 7 percent, thus giving a decrease in stroke volume. This same pattern of events was exaggerated at both $+3G_Z$ and $+4G_Z$ in this group of subjects. Again it must be pointed out that this pattern of events indicates stimulation of the carotid sinus mechanism. If this is the case, then the obvious question is "What vascular beds are constricting to increase mean arterial pressure and by what amount is there a vasoconstriction in these vascular beds?" This vasoconstriction, it must be remembered, is taking place in the face of an increased hydrostatic pressure load in many areas of the body.

We have been exceedingly interested here at the USAF School of Aerospace Medicine in the regional distribution of cardiac output during acceleration stress. To begin to investigate regional blood flow in man on the centrifuge during $+G_Z$ exposure, we have used the extraction of indocyanine green (ICG) by the liver as an index of splanchnic blood flow. This method has been used by Rowell (3) during exercise in man for the same purpose. This method involves the injection of 12.5 mg of ICG and the withdrawal of venous samples beginning 5 minutes after injection and followed by withdrawing samples every 2 minutes until 5 samples have been obtained. The concentration of ICG is then obtained from the plasma of each blood sample and plotted on semilogarithmic paper against the time of withdrawal following the injection. The half-time for the disappearance of ICG is then determined and this is converted to splanchnic blood flow. A representative experiment for a single subject is shown in figure 2.

TABLE I

Effects of acceleration on cardiac output, heart rate, stroke volume, and mean arterial pressure. All values are given as a percent change from normal.

G	Number of Subjects	Cardiac Output (%)	Heart Rate (%)	Stroke Volume (%)	Mean Arterial Pressure (%)	Referen
+ 2 G_z	6 (man)	- 7	+14	-24	+ 9	2
+ 3 G_z	6 (man)	-18	+35	-37	+21	2
+ 4 G_z	6 (man)	-22	+56	-49	+27	2
+ 2 G_x	6 (man)	-12	- 2	-10	+11	7
+ 3.5G_x	6 (man)	+ 9	+17	- 7	+18	7
+ 5 G_x	6 (man)	+27	+40	- 8	+25	7
+ 6 G_x	8 (dog)	-14	-14	0	0	8
+10 G_x	8 (dog)	-23	-28	0	-14	8
+14 G_x	8 (dog)	-23	-28	0	-20	8
+ 5 G_x	20 (dog)	-20	+37	-38	+22	9
+10 G_x	20 (dog)	-31	0	-33	+28	9
+15 G_x	20 (dog)	-37	0	-32	+27	9

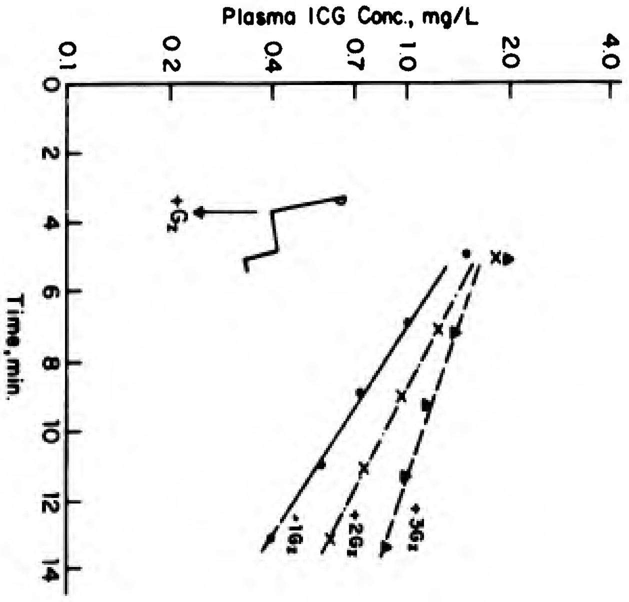

Figure 2. The logarithmic concentration of indocyanine green in plasma versus the time of withdrawal of blood sample during control period and at +2G_z and +3G_z in a single subject.

Six subjects from the centrifuge panel at the USAF School of Aerospace Medicine were used in obtaining the data on splanchnic blood flow as described above (3). Splanchnic flow was determined during a control period and then at $+2G_Z$ and $+3G_Z$. A catheter was placed in one anticubital vein for injection of the ICG and a second catheter was placed in an anticubital vein of the other arm for sampling purposes. The subjects were instructed in how to inject the ICG and then to manipulate a manifold for the required timed blood samples. During all determination of splanchnic flow the subjects were told when to sample so that no time delay would ensue from the procedure. The subjects were placed in the sitting position in the USAFSAM centrifuge with a table in front of them upon which the manifold and test tubes for sampling were placed. The levels of $+G_Z$ used were below the known blackout levels for all subjects since a total of 13 minutes was needed to complete the study.

The results of this study on six volunteer subjects are shown in figure 3 along with the arterial pressure recorded using a blood pressure cuff and microphone. The results were expressed as a percent of the control values for each subject and then all subjects were averaged together. The splanchnic blood flow was reduced by 33 percent at $+2G_Z$ and by 40 percent at $+3G_Z$ while the mean arterial pressure showed no change at $+2G_Z$ and increased by 18 percent at $+3G_Z$. The calculated splanchnic resistance increased by 40 percent at $+2G_Z$ and 90 percent at $+3G_Z$.

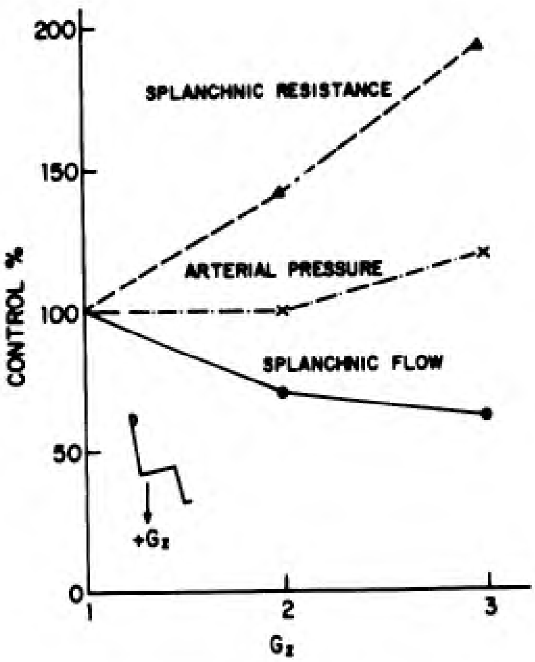

Figure 3. The average percent change from control level in splanchnic flow and resistance as well as arterial pressure versus the $+G_Z$ acceleration level in six subjects.

Following the results from this study we decided to measure forearm blood flow in the same group of subjects to determine what was happening in this vascular bed during $+G_Z$ exposure. Forearm blood flow was determined in the same six subjects as used above by placing a mercury in silastic strain gauge around the forearm as described a few moments ago (4). During all determinations the subject's arm was suspended at heart level. The results of this study are shown in figure 4. Again, the results have been expressed as a percent of each subject's control and then averaged together for all subjects. The forearm flow was found to decrease at each $+G_Z$ level studied while the arterial pressure changed very little during these short exposures. The calculated forearm resistance was found to increase progressively to a value of approximately 280 percent of control at $+3G_Z$.

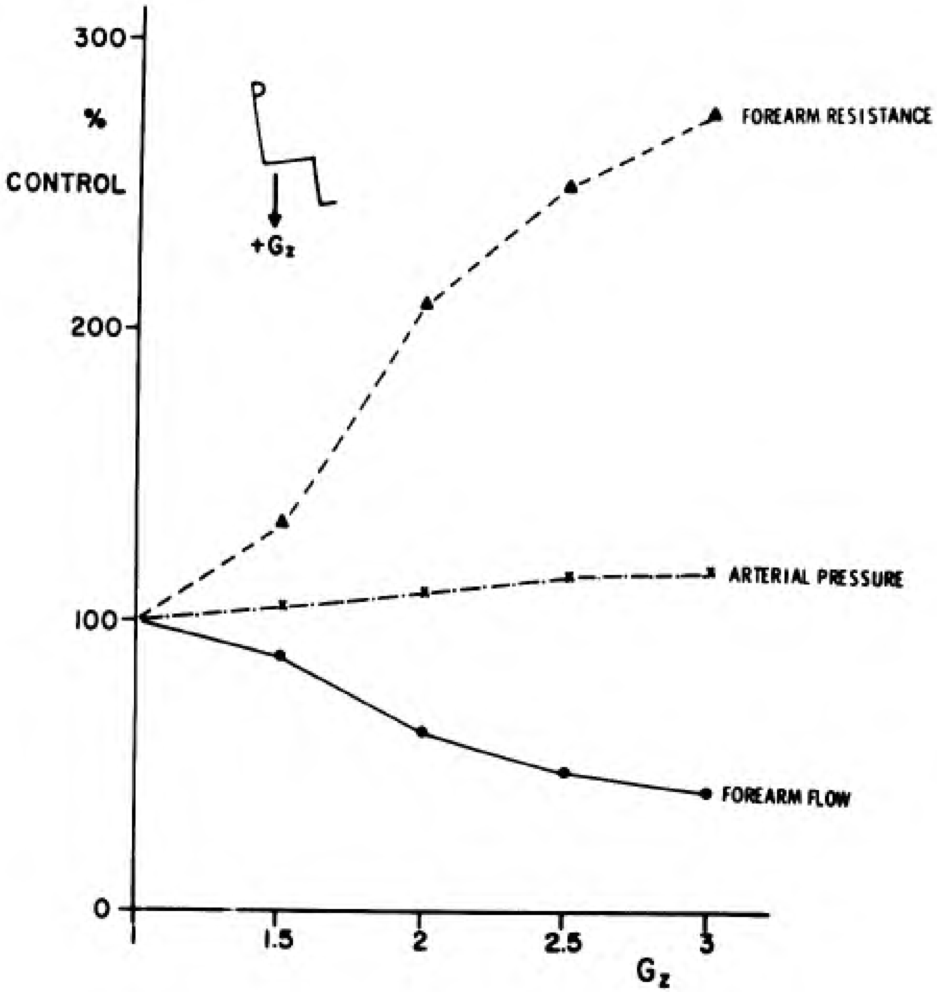

Figure 4. The average percent change from control level in forearm flow and resistance as well as arterial pressure versus the $+G_Z$ acceleration level in six subjects.

In work by others during stress, either uptilting or exercise (3, 5, 6), the splanchnic resistance and forearm resistance were found to increase much more than was observed in this study. Therefore, it appears that these two vascular beds are not constricted to their maximal extent. Assuming that the major drive for vasoconstriction is arising from a decreased pressure in the region of the carotid sinus, one wonders why a more profound constriction was not observed during $+G_z$ exposures. If we now compare the arterial pressure at heart level, sinus level and eye level, as is shown in figure 5, it will be observed that the pressure at the sinus level has changed relatively little while the pressure at eye level will have decreased by approximately 50 percent. This indicates that the carotid sinus is active in maintaining the pressure near its set point, but that the arterial pressure above this point probably is not sufficient to maintain cerebral pressure and flow relationships.

The cardiovascular effects of $+G_z$ acceleration can be circumvented by changing the orientation of the body with respect to the acceleration vector. This is accomplished by having the subject oriented so that the acceleration vector is applied through the short axis of the body instead of the long axis. In this position the organs will move either toward the backbone ($+G_x$) or toward the sternum ($-G_x$). The major complaints of $+G_x$ acceleration have been chest pain, inability to breathe, and choking from the tongue and saliva rolling into the back of the throat. Again, these are subjective symptoms of discomfort and do not portray anything concerning the cardiovascular system and its response to $+G_x$ acceleration.

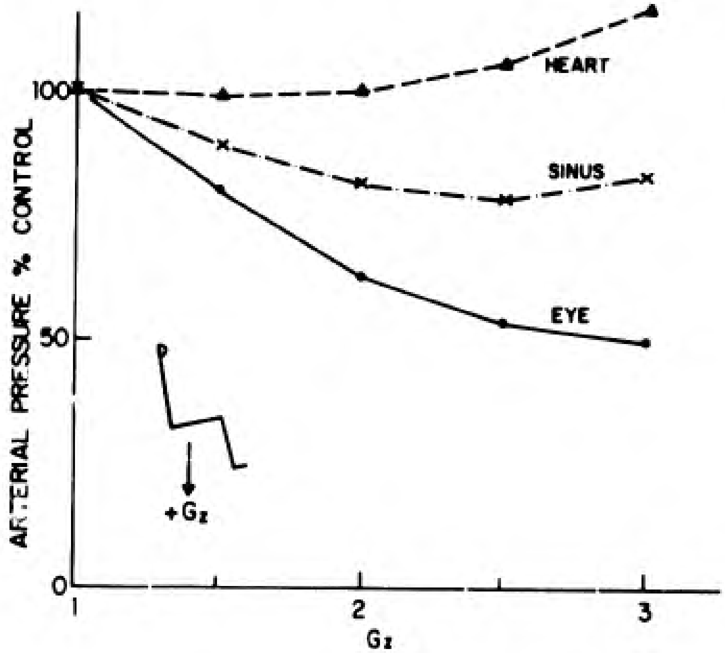

Figure 5. The percent of control arterial pressure at heart level, carotid sinus level, and eye level versus the $+G_z$ acceleration level.

Table I gives values for the percent change in cardiac output, heart rate, stroke volume and mean arterial pressure reported by others (6, 7, 8) on both experimental animals and man during various levels of $+G_X$ acceleration. The results in man indicate that there are increases in cardiac output and heart rate, but this is associated with decreases in arterial oxygen saturation. The decrease in arterial oxygen saturation has been shown to be the result of pulmonary shunting of blood in the dependent areas of the lungs and is observed by a continuing decline in arterial oxygen saturation as the level of $+G_X$ acceleration is increased (9, 10). As can be seen in table I, the results from animals present a different picture from the results from man in that a decrease in cardiac output has been found during $+G_X$ acceleration. This has been related to the movement of the heart and deformation of the chambers with high acceleration stress (8). Again, the distribution of cardiac output poses a very interesting question, particularly in the light of a change in cardiac output and arterial pressure associated with a decrease in arterial oxygen saturation in either experimental animals or man.

To investigate the regional distribution of cardiac output during $+G_X$ acceleration animals were instrumented with fine platinum needles coated with platinum black in the renal cortex, adrenal gland, and the serosal layer of the small intestines. Electrodes prepared in this manner are sensitive to various gases depending upon the voltage applied to the electrode. These particular electrodes were made sensitive to hydrogen gas that could be administered by allowing the animal to breathe small amounts of the gas with each inspiration during the determination of tissue flow. The desaturation of hydrogen gas from the tissue was recorded and replotted from the data on semilogarithmic paper and the half-time determined as described previously (11). The animals were placed in the supine position in the centrifuge and exposed to 2, 4, 6, 8, 10, and 12 $+G_X$. Control flows were determined in each animal before and 15 minutes after every exposure to acceleration. The acceleration levels were maintained long enough to insure that no change in heart rate and arterial pressure was occurring and also long enough for the tissue blood flow curves to be determined. In this same group of nine animals the position of the back was changed so that the head was raised toward the vertical by 10°, 20°, and 30°. This means that there is now a $+G_Z$ as well as a $+G_X$ component affecting the cardiovascular system.

Figure 6 shows the percent change from normal of the renal cortical tissue blood flow plotted against the $+G_X$ acceleration level. In the supine position there is essentially no change in tissue blood flow until a level of $+8G_X$ was attained; however, this pattern is changed when the head is raised above the horizontal. At all levels of back angle above the supine position there is a much more rapid decline in tissue blood flow until at 30° head-up a 68 percent reduction occurs at 3.7 $+G_X$. Figure 7 gives the percent change in adrenal gland tissue blood flow. In the supine position, there is a decline

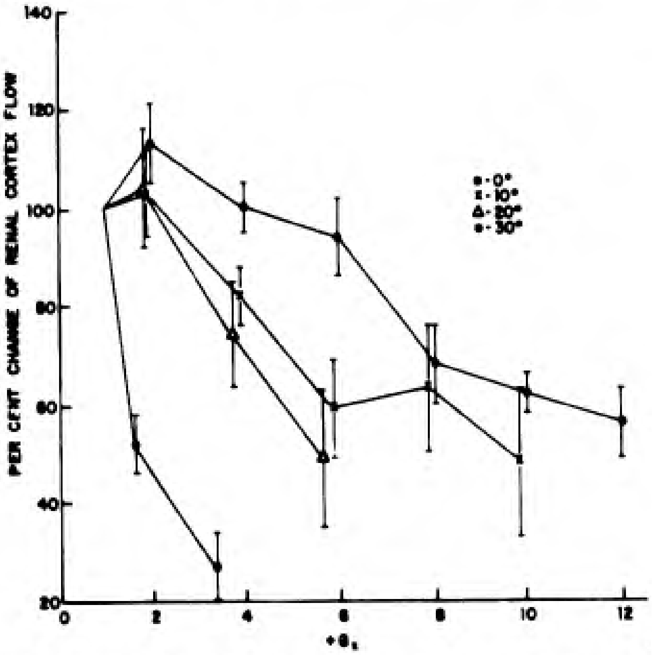

Figure 6. The average percent change from normal in renal cortical blood flow versus the $+G_x$ acceleration level at 0°, 10°, 20°, and 30° head-up positions in nine mongrel dogs.

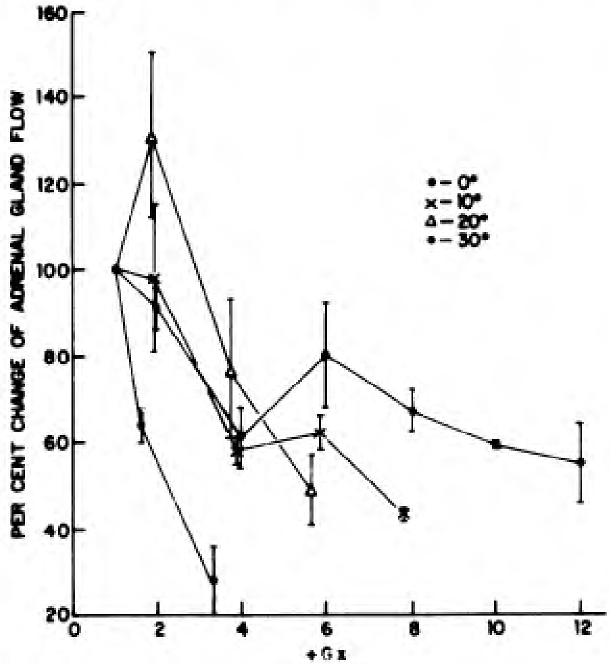

Figure 7. The average percent change from normal in adrenal gland blood flow versus the $+G_x$ acceleration level at 0°, 10°, 20°, and 30° head-up positions in nine mongrel dogs.

in flow at $+4G_X$, but a slight increase at $+6G_X$ and then a further decline at the remaining $+G_X$ levels. Again as the head is raised toward the vertical a more dramatic decline in flow occurs with increasing levels of acceleration until at a 30^0 head-up position there is a 72 percent reduction in flow at $3.7+G_X$. The intestinal tissue blood flow is shown in figure 8 and it can be seen that the flow declines in much the same manner as that of the adrenal gland. In the supine position there is almost a linear decline in

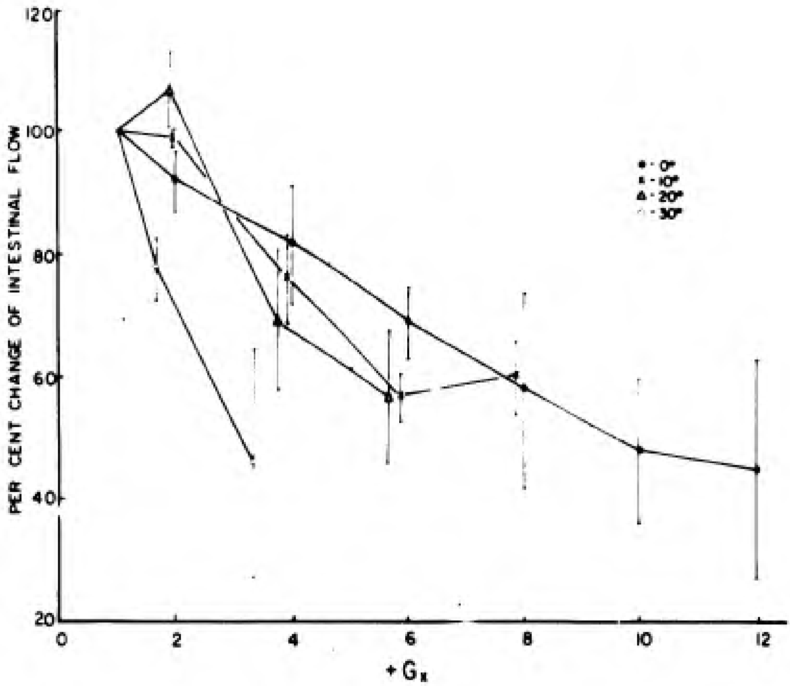

Figure 8. The average percent change from normal in small intestinal blood flow versus the $+G_X$ acceleration level at 0^0, 10^0, 20^0, and 30^0 head-up positions in nine mongrel dogs.

tissue flow with $+G_X$ acceleration, but this pattern is changed when the head is raised toward the vertical. The heart rate response can be observed in figure 9. In the supine position a maximum of 12 percent increase in rate was observed with a slight decline at $+12G_X$. At the 30^0 head-up position a decrease in rate was found at $3.7 +G_X$.

From the previous discussion of the known changes of the cardiovascular system to $+G_Z$ and $+G_X$ configurations several concluding remarks seem appropriate. In the $+G_Z$ configuration, the major area of interest is certainly the relationship between carotid arterial pressure and cerebral blood flow as has been discussed by others (12). The heart rate and mean arterial pressure are increasing while the cardiac output and stroke volume are decreasing. The response of the systemic flow in the forearm and splanchnic

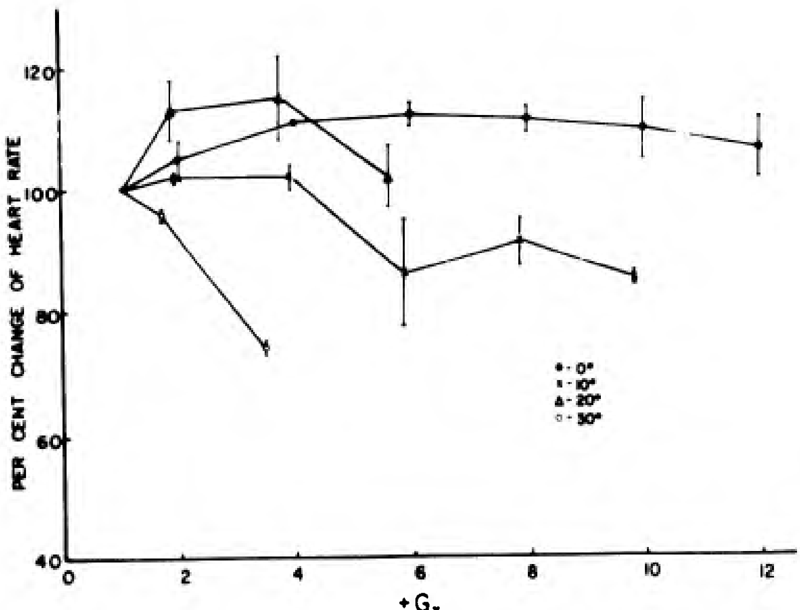

Figure 9. The average percent change from normal in the heart rate versus the $+G_X$ acceleration level at 0^0, 10^0, 20^0, and 30^0 head-up positions in nine mongrel dogs.

areas is a o decreasing, indicating a vasoconstriction in response to a sympathetic discharge since the arterial pressure and resistance are increased. However, the systemic vascular response is not a maximum vasoconstriction at $+3G_Z$ since larger reductions in flow in these same areas have been reported (3). Again, the major problem seems to be one of baroreceptor activity to maintain cerebral bloodflow and thereby prevent unconsciousness. A very different type of response pattern appears when the subject is oriented in the $+G_X$ configuration.

At this point a distinction must be made about the difference in cardiac response to $+G_X$ acceleration between man and dogs. In referring to table I it should be noticed that the cardiac output and heart rate response of this group of men and dogs are different. This could primarily be from the difference in the effect of acceleration on the movement of the heart within the thorax as has been excellently demonstrated by Sandler (9, 14). The heart of the dog will move posteriorly to a much greater extent than that observed in man at the same levels of $+G_X$ acceleration. With the deformation of the cardiac chambers in dogs a reduction in cardiac output and s. ke volume would be assumed to occur as observed by Sandler (9). The ı al problem in $+G_X$ acceleration seems to be the arterial oxygen saturation levels at any particular point in time. It does seem that in man the cardiovascular response in part may be from this hypoxic drive, but at present this is certainly not the complete picture. This leads to a thorough investigation of the regional distribution of cardiac output during hypoxia coupled with $+G_X$ accelerations. Again, basic studies of cardiovascular reflex activity and assessment of overall cardiovascular reserve are essential in determining those factors limiting man's response to acceleration stress.

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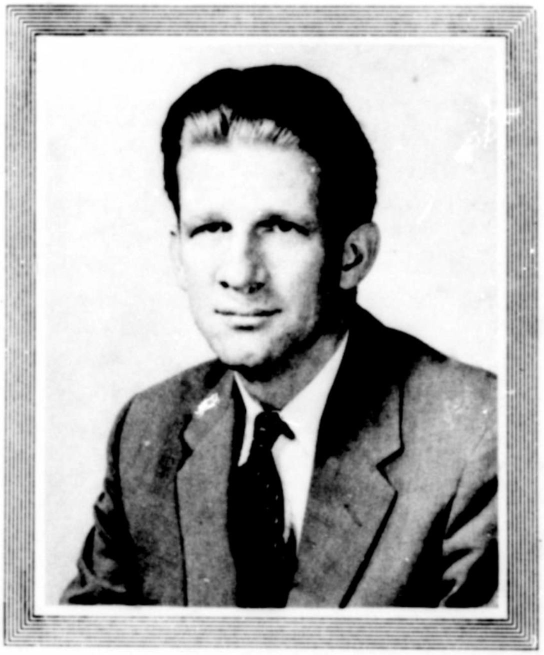
Response of the Body to Mechanical Forces—An Overview

Dr Henning E. von Gierke



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RESPONSE OF THE BODY TO MECHANICAL FORCES - AN OVERVIEW

Henning E. von Gierke, Ph. D.

INTRODUCTION

Environmental mechanical forces can act on man in many different ways (1) (2). First, there is the variation in force application: Forces can be air or liquid transmitted, as are blast waves, where more or less uniform pressure acts over large parts of the body or major segments of it. Or the forces can be applied locally to the body surfaces, as in most impact and blow conditions or when a projectile hits the surface. Finally, there are the inertial forces resulting from motions of the body as a whole acting on all tissue and also on all deep seated organs of the body. In blast exposure potentially all three types of force application are involved. Crash or impact iniury involves forces of both the second and third type while the acceleration forces encountered in aerospace flight are predominantly examples of the third type.

The second classification of forces would be according to their time function: The force functions can be non-periodic blast waves, or structure transmitted impacts lasting from a few milliseconds to several seconds or longer, or the forces can be more or less periodic or random continuous such as the pressure waves of sound or the vibration and buffeting in tractors, tanks, or aerospace vehicles.

The third classification is according to the physical amplitude of the force and, as a consequence, according to the biological response of interest. For example, blast biology is primarily concerned with the effects of shock waves of large amplitude, with the resulting physical injury, and with survival capability. A physically very similar shock wave of orders of magnitude smaller amplitude is responsible for the sonic boom generated by supersonic aircraft; here the biological questions of interest are quite different: The auditory phenomenon of loudness and the possible annoyance by too frequent occurrence (3). With respect to the effects of the forces of sound waves and structure borne vibrations ranging from the weakest environmental stimuli to the most intense, one is interested in all possible

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biological responses, from the threshold of perception through the wide range of possible interference by the environment with task performance or normal living (effect of noise on speech communication, effect of noise or vibrations on psychomotor performance, annoyance, etc.), up to the range of reversible or irreversible injury to the organism (4) (5).

It is obvious that in spite of the enormous differences among the environments of interest in the mode of force transmission, in the time function, and in the specific biological reaction of concern, there are many findings, facts, and principles which apply to several or all of these problem areas. It is primarily the physical reaction of the human body to the force environment, the tissue deformation resulting from the mechanical stresses, which makes this statement true. For in practically all cases it is not the pressure per se but the resulting relative displacement of adjacent tissue which leads to the stimulation of various receptors as well as to ultimate injury. Psychological reaction, physiological stimulation and reaction, and the final overall clinical injury are responses secondary to the primary body deformation. It is through this area of the body's mechanical response to the various force environments that the several technical fields concerned hang together and can benefit from one another. It is here where substantial progress has been made over the past ten years and where considerable cross-fertilization has been effected among research fields and interests which previously were completely separated.

It shall be the purpose of this discussion to briefly review some of the basic knowledge in this broad field of biomechanics and to indicate the common applications of this knowledge to the various force classification categories listed above. The broader understanding evolving from such treatment should be of particular benefit in assessing new environments, in evaluating and comparing animal and human data, in extrapolating and generalizing to set exposure criteria, and in engineering protection against the environments. It is also hoped that the thoughts to follow will supplement and correlate some of the specific findings on blast biology discussed in the other papers of this symposium. All data and calculations presented are to be taken as examples and general trend curves and not as statistically valid averages or detailed criteria. For such quantitative application of the data detailed study of the references and of the specific conditions is indispensable.

The Basic Data

An understanding of the body's response to mechanical forces must be based on physical measurements of the mechanical properties of various tissues. Quantitative data in this area which can be interpreted as material properties independent of the specific structure are still scarce. The ranges of the viscoelastic properties of soft tissue and the elastic properties of bone are fairly well established and examples are presented in figure 1 (1). However, less is known about the limits of linearity and the nonlinear

PHYSICAL PROPERTIES OF HUMAN TISSUE (APPROXIMATE)

	TISSUE, SOFT	BONE, COMPACT
DENSITY, G/CM^3	1-1.2	1.93-1.98
YOUNGS MODULUS, $DYNE/CM^2$	10^5-10^7**	2.26×10^{11}
VOLUME COMPRESSIBILITY,* $DYNE/CM^2$	2.6×10^{10}	1.3×10^{11} (Dry)
SHEAR ELASTICITY,* $DYNE/CM^2$	2.5×10^4	7.1×10^{10} (Dry)
SHEAR VISCOSITY,* $DYNE\ SEC/CM^2$	1.5×10^2	-
SOUND VELOCITY, CM/SEC	1.5-1.6×10^5	3.36×10^5
ACOUSTIC IMPEDANCE, $DYNE\ SEC/CM^3$	1.7×10^5	6×10^5
TENSILE STRENGTH	5×10^6-5×10^7	9.75×10^8
SHEARING STRENGTH, $DYNE/CM^2$, PARALLEL	-	4.9×10^8
SHEARING STRENGTH, $DYNE/CM^2$, PERPENDICULAR	-	1.16×10^9
BREAKING INDEX (STRETCH)	.2-.7	<.05***
BREAKING INDEX(COMPRESSION)	-	<.04

*LAMÉ ELASTIC MODULI **DEPENDING ON STRETCH

***SPINAL COLUMN

Figure 1. Physical Properties of Human Tissue (Approximate Values). (From Reference 1).

behavior of tissue. The breaking strength of various tissues has only recently been studies and examples of Nickerson's results are given in figure 2 (6).

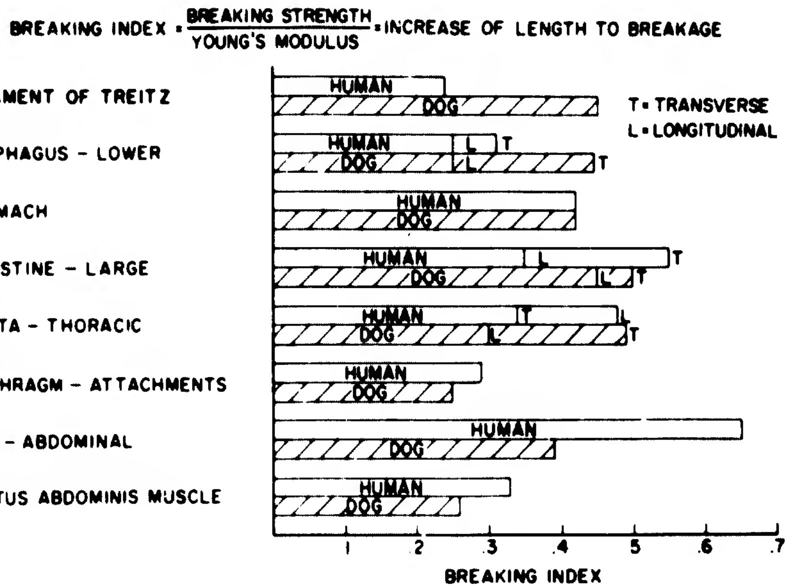


Figure 2. The Breaking Index of Various Excised Human and Dog Tissues. (Breaking index = breaking strength/Young's Modulus = percentage increase in length required to breakage). (Based on Nickerson and Drasic (6)).

Other types of physical measurement which can be taken on human subjects or living animals with the tissue properties under as close as possible natural conditions are mechanical impedance measurements (7). Driving point impedances as well as pressure impedances, as illustrated in figure 3, have been measured for many conditions and frequency ranges. The

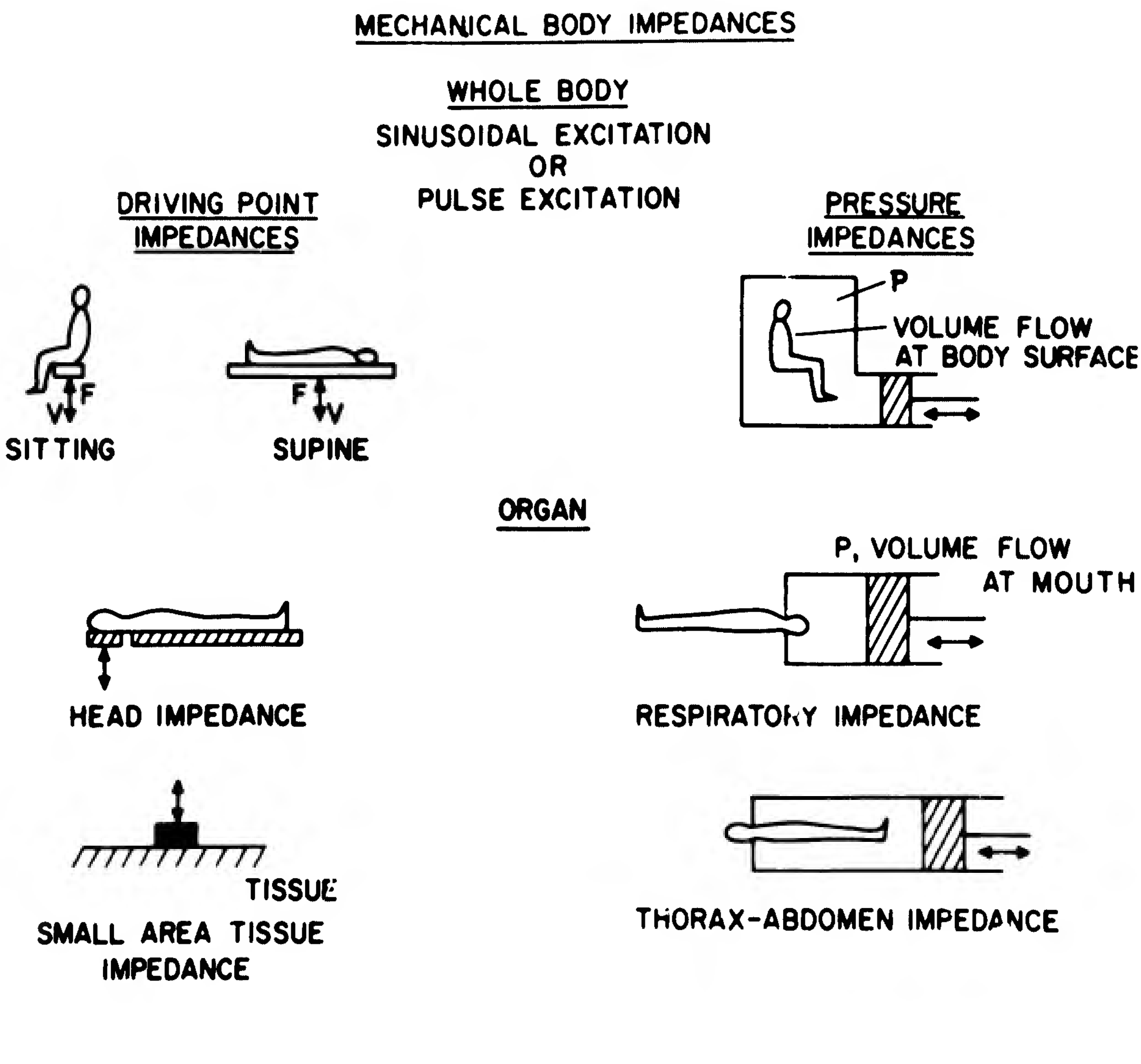


Figure 3. Impedance Measurements on the Human Body. The mechanical impedance is the ratio of applied force F to resultant velocity V; the specific acoustic impedance is the ratio of pressure on a surface P to the surface velocity; the acoustic impedance is the ratio of pressure P to the volume velocity at the body surface.

basic clues to the resonances of body structures and organs and to the mode of propagation of mechanical waves in tissue (shear waves vs compression waves) have been obtained from such measurements (8). Where impedance measurements are not possible, displacement or strain measurements on the body surface are also valuable and revealing. X-ray motion picture (cineradiographic) studies of internal organ movement and deformation under vibration and impact stress have been performed on animals (9) and have recently become feasible in human experiments with high enough frequency to be of value (60 pictures per second, 1/1000 sec. exposure) and with safe exposure doses, by use of image intensification (10).

Finally, there are physiological and psychophysical measurements as well as injury and mortality data which can give clues as well as support to theories regarding the body dynamics involved, although normally the deduction is supposed to work in the opposite direction; i. e., the physical observations and calculations are intended to explain the biological findings.

The Mechanical Analog of the Body

Based on the physical measurements, it is usually possible to derive mathematical models and mechanical analogs which describe the essential characteristics of the observations and allow insights into the reasons behind them (1) (11) (12). An example of such a model is presented in figure 4. It presents the human body as a lumped parameter system composed of

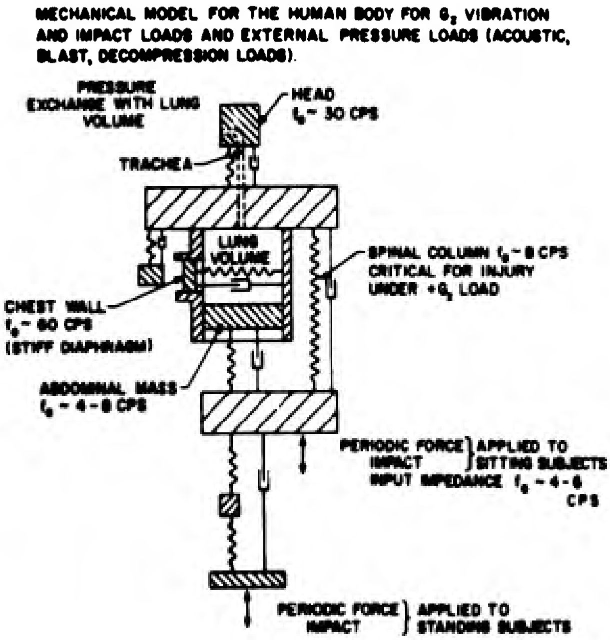
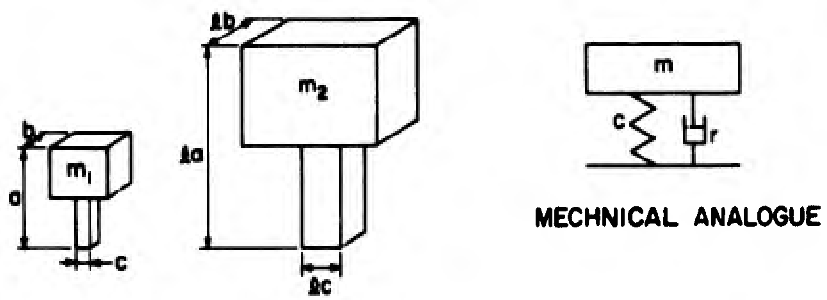


Figure 4. Mechanical Model of the Human Body Exposed to G_z (Longitudinal Vibration or Impact) and to External Pressure Loads (Acoustic pressure, blast, decompression loads) (From Reference 1).

masses, springs, and dampers; only the airways are represented by their fluid dynamic properties, i.e., acoustic impedances. Such a model can be used very successfully to describe the main tissue motions observed under linear accelerations (impact and vibrations along the body's longitudinal axis) as well as under pressure changes (blast and acoustic loading). Other models have been used to describe the response of subsystems such as the arm and hand alone or the phenomena observed in head impact and injury.

The insight obtained by the use of a model such as the one in figure 4 is particularly helpful in assessing differences in the effectiveness of specific mechanical environments when considering different species. Assuming equivalent tissue properties, a fact confirmed to a first approximation by measurements, and geometrically similar structures, the scaling laws of figure 5 apply. The results of these laws are illustrated in figure 6; here the main abdominal resonance of the system, i.e., the frequency at which the abdomen undergoes maximum displacement under linear vibration, is plotted as a function of body weight. The graph also shows the



	TISSUE	AIRSPACE
$\frac{m_2}{m_1}$	ℓ^3	ℓ^3
$\frac{c_2}{c_1}$	ℓ	ℓ
$\frac{r_2}{r_1}$	ℓ	ℓ^2
w_0	$\frac{1}{\ell}$	$\frac{1}{\ell}$
DAMPING $\frac{r}{w_0 m}$	$\frac{1}{\ell}$	CONSTANT

Figure 5. Scaling Laws for Geometrically Similar Structures Such as Mammals of Different Sizes.

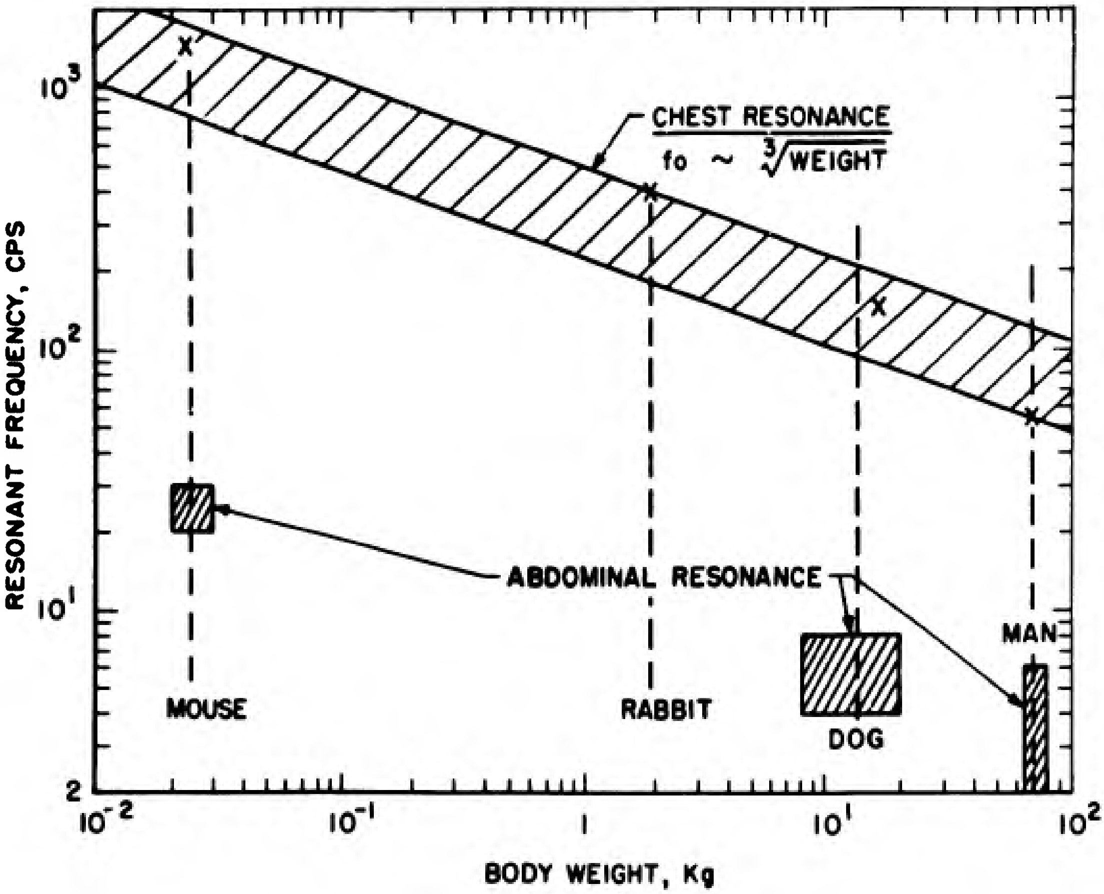


Figure 6. Approximate Resonance Frequencies of Chest (Acoustic Excitation) and Abdomen (Vibration Excitation) of Geometrically Similar Animals as a Function of Body Weight. (From Reference 1).

thorax resonance frequency for the different species, i.e., the frequency of maximum thorax compression or extension under periodic pressure loading. It is immediately obvious from these functions, which are broadly supported by available data, that the frequency or time scales must be shifted if corresponding mechanical phenomena such as resonances are to be compared in different species. A comparison of the biological effectiveness of a certain frequency range of vibration or blast wave of a specified duration among several species varying widely in size can be very misleading; due to the differences in body size, completely different injury or stimulation mechanisms and locations may be involved.

It is generally recognized that the treatment of the human body as a passive, linear system is an oversimplification not rigorously justified, and attempts are made in theory as well as in measurements to take into account the nonlinear features. Nevertheless, the simplified linearized approach describes very well the basic phenomena for one particular species as well as the inter-species differences. In the following, a few of these phenomena and their biological consequences will be discussed.

Curves of Equal Tissue Strain or Curves of Equal Sensitivity

Exposing the model of figure 4 to periodic forces applied to the buttocks gives the results shown in the curves on the left hand side of figure 7 for the displacement of the abdominal wall, the chest wall, and for the oscillating air flow being pushed in and out through the trachea by the periodic compression of the air in the lungs with the diaphragm oscillation. The calculated curves are in very close agreement with the actual observations on a man on a shake table. The large abdominal movement caused by resonance in this frequency range is the tolerance limiting factor in human vibration exposure subjectively as well as objectively. The graph also

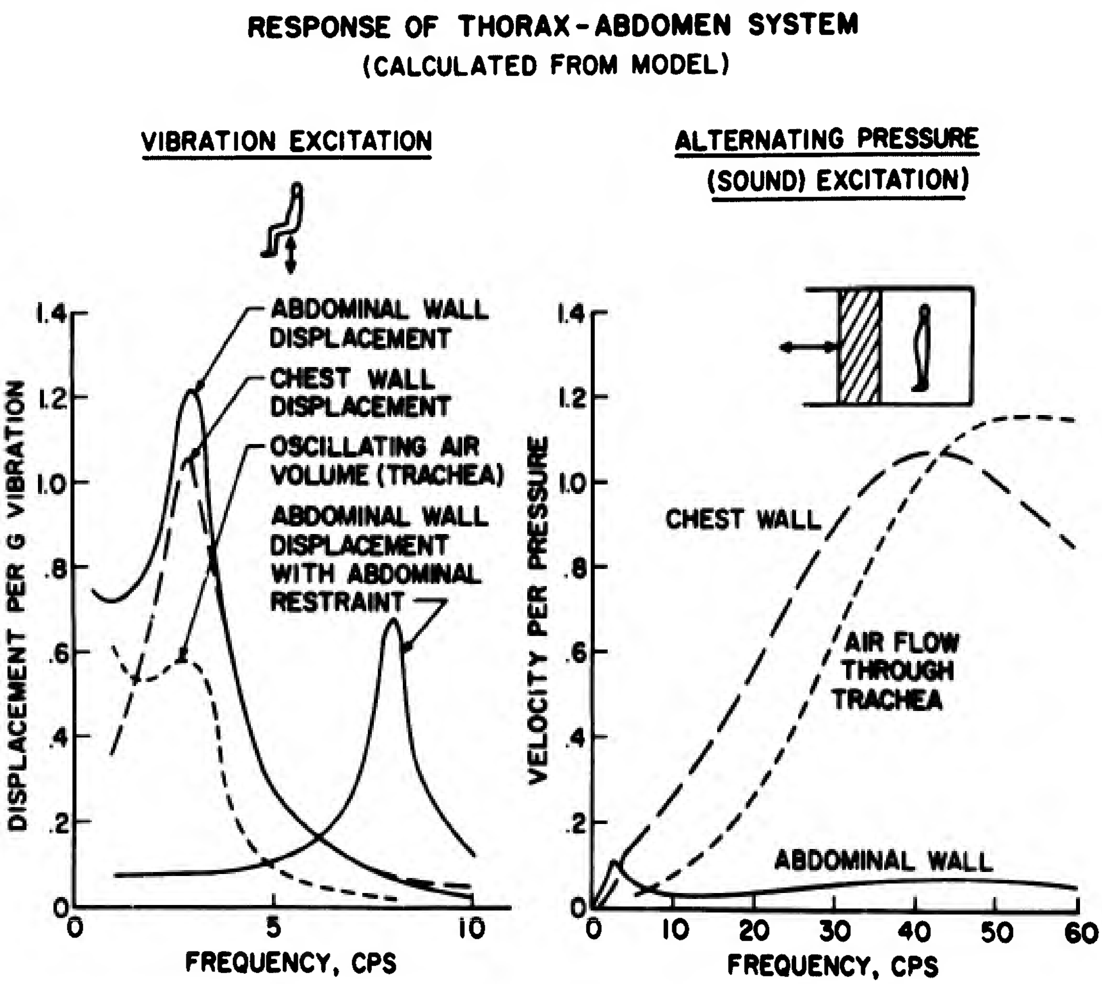


Figure 7. Calculated Responses of the Thorax-Abdomen System of the Model in Figure 4 When Excited With Linear Vibrations (Left) and With Alternating Pressure (Right). (From Reference 1).

illustrates how this resonance can be influenced by protective abdominal restraints. From curves such as these, curves for the forces required to produce equal tissue strain in the system can be calculated. Assuming that, for example, a physiological threshold curve is a curve of equal tissue strain or that mechanical failure or injury occurs at equal strain regardless of frequency, these curves should have a shape similar to a threshold curve, for example, for pain, or to a tolerance curve with respect to injury. Assuming further on the basis of data such as those in figure 2 that the tissue strength is the same for different animal species, it is possible to calculate such a tolerance or sensitivity curve for various species; and although the absolute level of these curves cannot be derived theoretically, the relative sensitivity difference between species can be predicted with some validity. Following this reasoning, the curves in figure 8 can be interpreted as tolerance curves for the various species: the curves predict that the smaller animal is more resistant to vibration stress and has its main (abdominal) resonance at higher frequency.

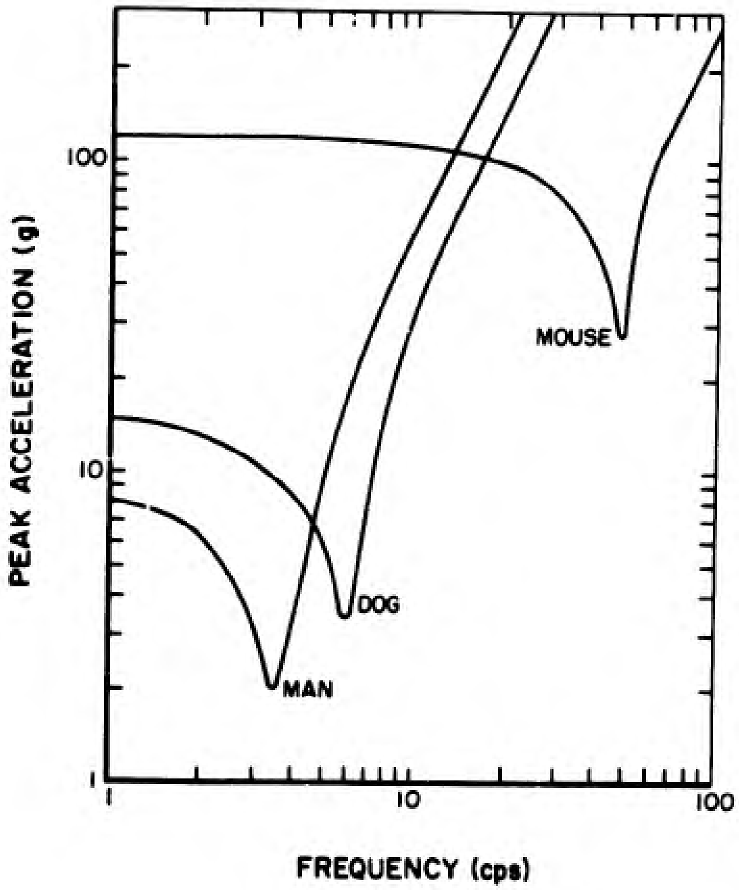


Figure 8. Curves of Equal Mechanical Strain in the Abdomen of Animals of Different Sizes as a Function of Vibration Amplitude and Frequency (Vibration Sensitivity curves for the thorax-abdomen system).

Insofar as they go, available data are in agreement with these predictions. It must be borne in mind that the curves in figure 8 represent curves of equal strain in the abdomen; consequently, they can agree with the vibration tolerance of the total organism only so far as this tolerance is determined by the abdominal system. However, we know that at frequencies above the abdominal resonance, symptoms in other subsystems, the spine and the head-neck area, determine human tolerance. Consequently, tolerance or sensitivity of the total body system would be obtained as the envelope to the curves of limiting tissue strain for all subsystems (13). Therefore, the overall sensitivity curves of man or animal to vibration do not rise as steeply above the main abdominal resonance frequency as the response curves for the abdominal system alone.

When the human body is exposed to linear impact acceleration, it is again the main body resonance which determines the shape of the sensitivity curve: for pulse durations shorter than a critical duration τ_{crit}, the system responds to the impulse ΔV of the force function ($\int G\,dt = \Delta V$ with G = acceleration, t = time, ΔV = velocity change), i.e., the tolerance acceleration levels increase with decreasing pulse duration. For pulse durations longer than τ_{crit}, tolerable acceleration levels are constant. The critical pulse duration τ_{crit} is dependent primarily on the steady state natural frequency of the system, secondarily on the damping coefficient and the pulse shape (14) (15). The smaller animal has the shorter critical duration but also the higher tolerance to long duration loads. In figure 9

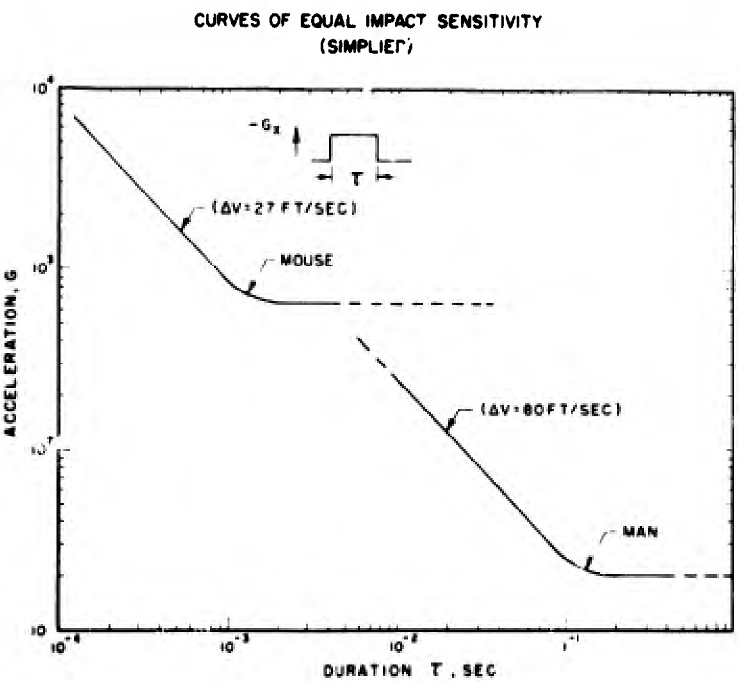


Figure 9. Curves of Equal Impact Sensitivity (Based on the comparison of experimental data by Kornhauser and Gold (16)).

curves of equal impact sensitivity for man and mouse are plotted as derived from biological data (16). Within the accuracy and comparability of such data, they support quantitatively the shape of the curve and its frequency and sensitivity shift as a function of species, which one obtains from the model concept and the scaling laws.

If the model of figure 4 is used to describe a human body exposed to external pressure change, the pressure acts on the piston (identified as abdominal mass) representing the abdominal wall, on the chest wall, and at the opening of the trachea, the mouth. Applying periodic pressure changes one obtains response curves of the type illustrated on the right hand side of figure 7 for chest wall motion, abdominal wall motion, and air flow through the trachea. The abdominal resonance is hardly detectable in these curves; however, the thoracic resonance between 40 and 50 cps characterizes the response leading to maximum tissue strain in this frequency range for constant sound pressure. This resonance was predicted by the theoretical model before it was verified - so far only very roughly - in high intensity sound fields. However, it is this resonance which is of utmost importance in describing the dynamics of fast events, such as blast exposure driving the pulmonary system. It is this resonance which determines the critical blast duration or the bend in blast sensitivity curves (1).

Such sensitivity curves for mechanical injury or other effects caused by blast, compression, or decompression can be calculated as curves of equal maximum strain in lung tissue in response to events of different duration. Examples are presented in figure 10, where the blast sensitivity for the model is also compared with the human sensitivity curve extrapolated by Richmond and White (17) on the basis of human and animal data points, and with the few available data points on blast lethality in water (18). The latter situation with the much shorter pulse duration also appears to be described in principle by the model calculations.

The absolute level of the curves in figure 10 was adjusted to agree with the average biological injury levels. In the case of the blast exposure this corresponded to a compression of the lung volume to one-eighth of its original value, reached under static compression at approximately 104 psi. For the damage mechanism in decompression the tearing of tissue under expansion was assumed and the absolute level of the curve indicated was adjusted to agree with the data on lung rupture under static overpressure (50 to 80 mm Hg.). So the difference in damage mode assumed (lung compression or extension) accounts for the difference by a factor of 50 between the otherwise identical curves.

All the examples discussed here were obtained by the use of a linearized model. The mathematical model used by Holladay and Bowen (12) to calculate lung pressure under blast exposure is basically identical with the more generally applicable model described here except for the fact that their

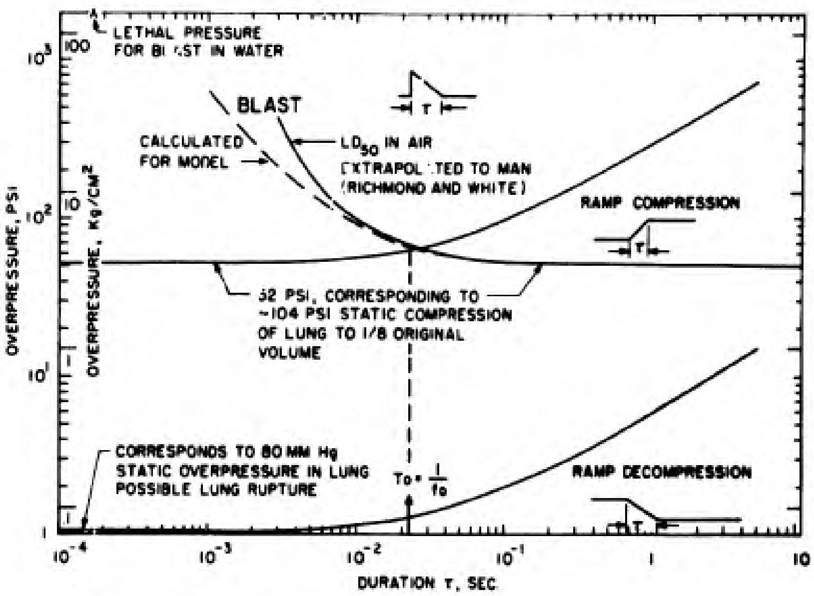


Figure 10. Calculated Curves of Equal Strain in the Human Lung in Response to Blast, Ramp Compression and Decompression (From Reference (1)).

equations for air flow and pressure in the airways account for large amplitude pressure nonlinearities. However, the results obtained by linear approximation (linear acoustics) appear to describe well enough the basic trend and phenomena and allow direct simple comparison with the small amplitude respiratory and acoustic phenomena in the system. (The primary effect of large pressure waves is the compression of the lung volume to such an extent that the resulting increase in the natural frequency of the thorax cannot be neglected. However, so long as peak deflection rather than fidelity of wave form is the primary goal of the calculations, this increase can be accounted for by linear approximation.).

In analyzing the calculated blast sensitivity curves for the different species one notices that shape, critical pulse duration, and relative sensitivity for the various species are predicted with approximate accuracy. The simple scaling laws without finer correction for species differences do not predict exactly the relatively small differences in blast tolerance for the horizontal long duration part of the functions. If this difference in the experimental curves presenting the maximum tolerable level for the various species is really significant, it might imply that small changes in the damping coefficients of the chest system or refinements of the scaling law for the damping coefficient are indicated. However, the general trend of the curves including the somewhat higher sensitivity of the smaller animal for long duration blast is correctly predicted by the simple model. In figure 11 the absolute level of the curves has been adjusted to fit the experimental curves of White and his co-workers (17).

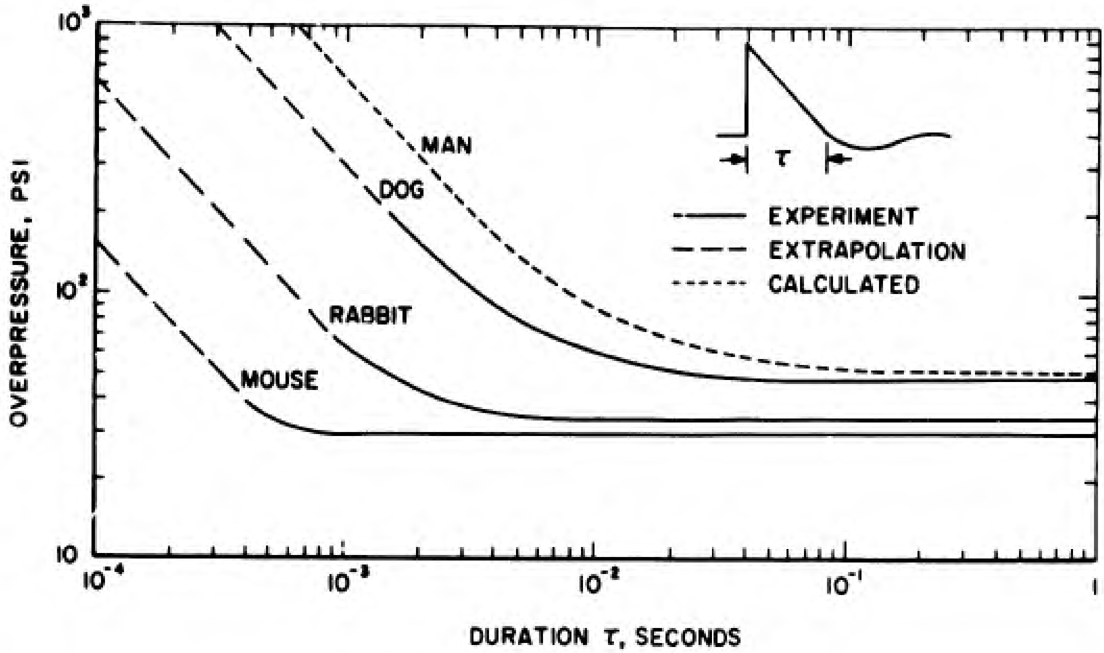


Figure 11. Sensitivity Curves for Blast Exposure (Experimental curves from White et al. (17)).

Mechanical Response of the Tympanic Membrane

The ear, as the organ most sensitive to environmental pressure changes, has always claimed special interest in blast biology. It will be briefly discussed here to illustrate that the scaling laws for the overall (abdomen-thorax) response cannot be indiscriminately extended to other parts of the body such as the ear. The ear, in general, is not scaled proportionally to body size. For example, the ratio of the tympanic membrane areas of man and guinea pig is approximately 2.2. This relatively small difference in size is clearly reflected in the acoustic impedances measured at the tympanic membrane surface for man (19) and guinea pig (20) (fig. 12). Estimating by the use of these impedance functions the blast sensitivity of the two tympanic membranes, one obtains the functions in figure 13 representing the pressures required to produce equal strain in the membranes as a function of blast duration (21). The estimated difference in blast sensitivity between the two species is very small and the two systems have almost the same critical durations. Unfortunately there are not yet enough experimental data to compare with the shape of the theoretical curves and with the inter-species sensitivity relations obtained theoretically.

The Non-penetrating Blow to Soft Tissue

If a relatively small object hits a body surface overlying soft tissue, the energy is absorbed in the surrounding tissue and does not bring about a

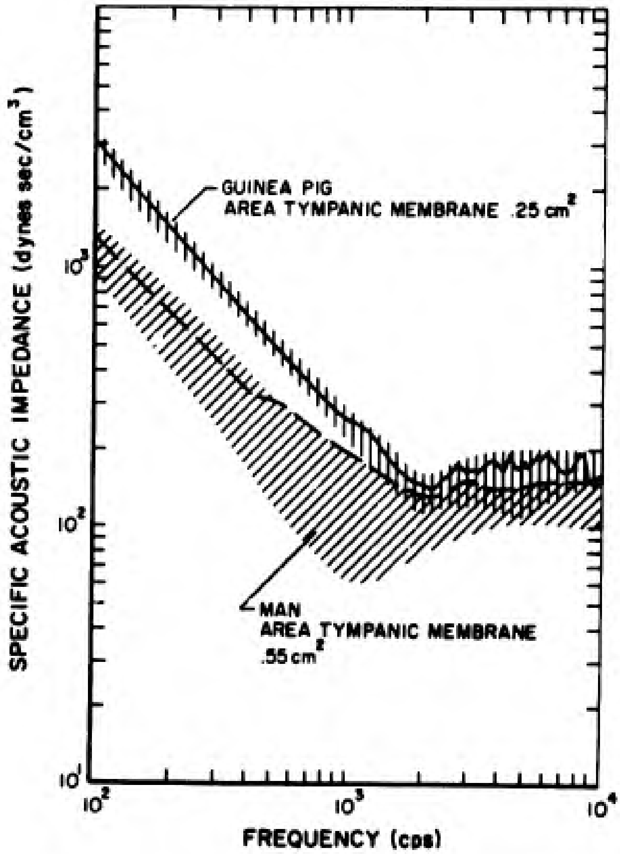


Figure 12. The Specific Acoustic Impedance Measured at the Human and Guinea Pig Ear (Data from References (19) and (20)).

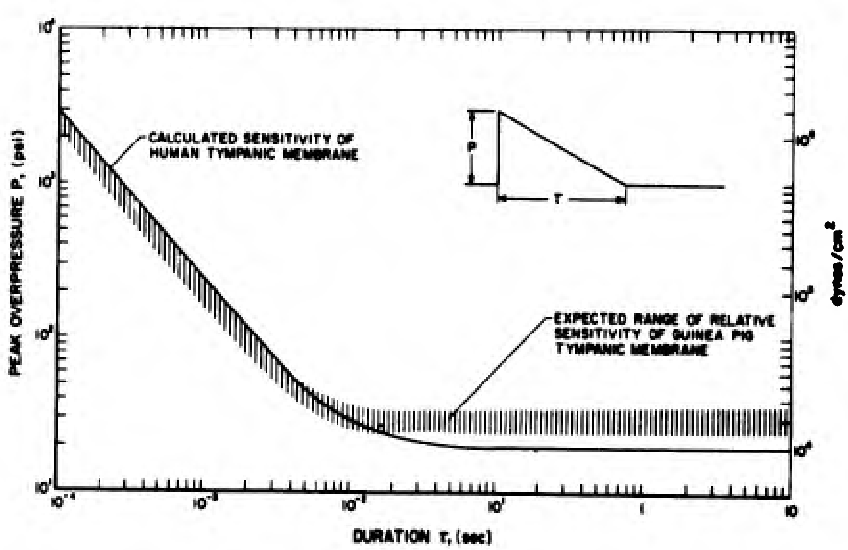


Figure 13. Blast Sensitivity of the Human and Guinea Pig Ear (Curves of equal mechanical strain in the tympanic membrane calculated from the impedance data of Figure 12).

motion of the whole body or a spreading of the energy over farther distances, thus exciting oscillations in subsystems formed as a cause of tissue or geometric discontinuities. Interesting insight into the phenomena occurring here can be obtained by treating the tissue as a homogeneous, infinite medium having the viscoelastic properties observed for body tissue (fig. 1). Results of such calculations indicate that most of the energy spreads through the tissue in the form of shear waves and not of compression waves. As an example the spectra of the energy transmitted to the tissue by three blows of different velocity but equal displacement (tissue indentation) are illustrated in figure 14 (22). The graph also indicates a dividing line between shear and compression waves, which can be obtained from the impedance function for the tissue surface of the area struck. For frequencies below the dividing line energy is propagated primarily in shear waves, for frequencies about in compression waves. Only very rapid blows produce compression waves of appreciable magnitude in tissue and it appears that in most practical cases the tissue damage from blows results from the shearing action of the transmitted energy. Calculations of the type illustrated in figure 14 were helpful in evaluating the physics of energy transmission in blows to brain tissue (head injury).

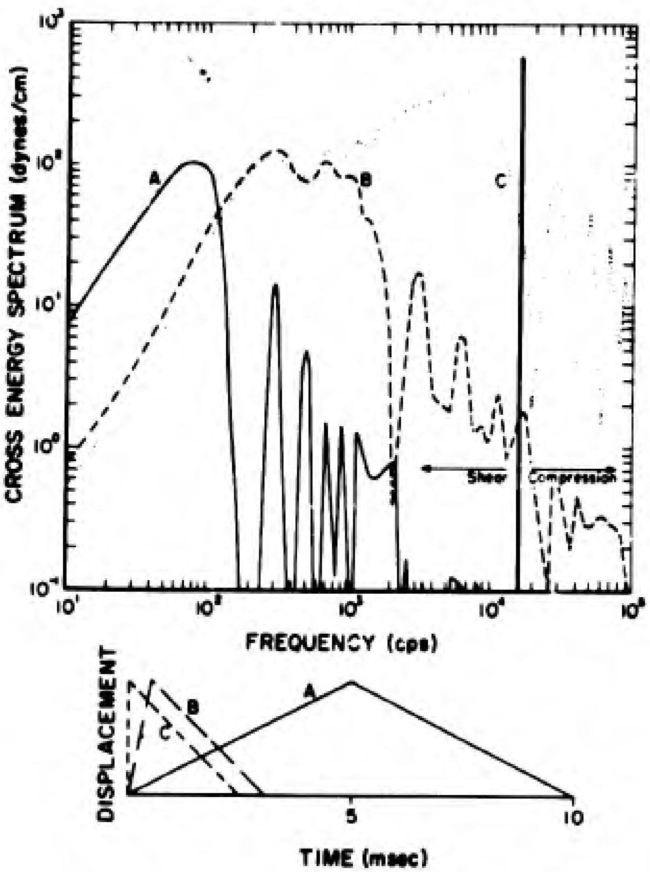


Figure 14. Transferred Energy Spectrum (Magnitude) for Constant Displacement Blows of Different Velocity to Soft Body Tissue. The displacement-time function is plotted on the lower part of the Figure (22).

Conclusions

It was the primary purpose of the foregoing overview to relate the body's mechanical response to blast to the response to other mechanical stress environments. The mechanical model of the human body has certainly proved to be extremely valuable for considering the dynamic effects caused by the various environments within the frame of one unifying concept and for explaining the relationships of some of the physiological phenomena observed. Work in mathematical modeling of the response phenomena has only been started and considerably more benefit, quantitatively and in detail, can be expected from further efforts along these lines and from continuing interdisciplinary cooperation.

In summary three obvious, practical applications of the model approach are worthy of special emphasis and elucidation: First, once the general validity of a model is confirmed, it allows the calculation of its response to very complex input functions by computer techniques. This includes functions which cannot be produced in the laboratory with presently available environmental simulators but are expected in operational situations, under emergency conditions or with further technological progress. For example, the acceleration-time history for emergency escape systems of high speed aircraft or space vehicles is best evaluated with respect to its injury potential by use of the model for longitudinal acceleration loading of the subject. The probability of spinal injury from vertebrae compression can be easily calculated for various acceleration profiles planned, anticipated, or observed in dummy experiments. The effects of rate of onset, repetitive peaks, and duration can be evaluated and compared with respect to the maximum strain in the vertebral column. This procedure is in practical use for the analysis of egress system profiles under consideration during development phases. Similarly, the severity of different blast wave time functions as modified by shelter characteristics could be calculated with the aid of such models. Second, the model concept is extremely valuable in interpreting and planning animal experimentation and in extrapolating human safety criteria from the results of animal responses. And third, the model provides the capability to analyze numerically the mechanical effectiveness and detailed mode of action of a protection or restraint system coupled with a biological system. In the above mentioned application of the model to the dynamics of ejection systems, the effects of seat cushions and restraint harnesses, for example, can be included in the treatment of the total system. Similar applications are certainly possible in blast protection efforts and in blast biology research.

Abstract

Starting with present-day knowledge of the dynamic and strength properties of various types of tissue, the dynamic response of the complex body structure to the various types of force application is reviewed. The differ-

ent methods for the collection of experimental data on man and animals are described and the combined information is used to give an integrated overview of the body's dynamic response to environmental pressure (acoustic loading, blast overpressure or decompression) as well as force changes (whole body vibration, whole body impact and small area impact). Examples of theoretical models describing the response of the whole body as well as models describing specific subsystems such as the respiratory system, the skull or the ear are presented. The discussion covers the status, value, and limitations of such theoretical models for explaining physiological and pathological findings, for predicting the body's response to force environments not yet experienced, for extrapolating biodynamic data among the mammalian species including man, and for aiding in formulating biomedical criteria for not only estimating various human hazards but for guiding those interested in safety and protection engineering.

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Space Cabin Toxicology

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Dr. Thomas received his M. D. degree from the University of Budapest in 1944. He practiced internal and industrial medicine in Hungary until 1951, when he left the country as a refugee. From 1951 to 1955 he worked for the United States Army as a Clinical Pathologist in West Germany, emigrating to the United States in 1956 to accept a post as a research toxicologist at the Aeromedical Laboratories, Wright-Patterson AFB, Ohio. Dr. Thomas became a citizen of the U. S. in 1962. He has been Chief of the Toxic Hazards Division of the 6570 Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, since 1965. Dr. Thomas has published numerous scientific papers on propellant and aerospace toxicology.

SPACE CABIN TOXICOLOGY

Anthony A. Thomas, M. D.

I. INTRODUCTION

Man's dependence on the earthly atmosphere required careful regulation of the atmospheric environment in sealed cabins or extraterrestrial shelters (1). Contaminants that can be generated either by construction materials, equipment, weapons, or by the crew can constitute a major limiting factor on habitability and mission duration.

The factors which can aggravate the contaminant concentration are far more numerous than those which can alleviate the problem (table I). The limited volume of usable atmosphere in space systems allows for very little latitude in air pollution control. Air purification and life support equipment are being heavily taxed with increasing mission profile and can, per se, change the total contaminant picture by incomplete processing of toxic materials (2) (3).

TABLE I

Important Factors Influencing Atmospheric Contamination

Aggravating	Beneficial
Continuous Generation and Exposure	Leak Rate of Cabin
* Reduced Pressure	Materials Selection
* Volume/Man Ratio	Preconditioning of Materials
* Power and Weight Limitation	
Filter Characteristics	
Complexity of Contaminants	
* Multi-Stress Environment	
* Escape Lead Time	

* Not significant in nuclear submarines

The state-of-the-art in environment toxicology does not allow valid predictions of human tolerance to any toxic materials for prolonged continuous exposure (4). Moreover, the bizarre mixture of any contaminants always carries the threat of potentiation of toxic effect by individual constituents within the mixture (5). Exotic environments such as low barometric pressure, oxygen-rich atmosphere and the multitude of physiological and psychological stresses are still unknown quantities which can have a profound influence upon man's resistance to chemical insults. Similar to our air pollution problems on earth, freak coincidences of relatively harmless factors could lead to severe biological embarrassment. It is also quite obvious that the problems on nuclear submarines are far less serious than in spacecraft environment (2). Finally, truly uninterrupted 90 day continuous exposure in ambient pressure air to contaminant concentrations not exceeding the Threshold Limit Value has resulted in 100% mortality of animals with certain chemicals such as hydrazine, decaborane, etc. (6), (table II).

TABLE II

Summary of Mortality Rates During 90 Day Continuous Exposure

Compounds*	Monkeys		Rats		Mice	
	# Dead / # Used	% Dead	# Dead / # Used	% Dead	# Dead / # Used	% Dead
N_2H_4	2/10	20	48/50	96	98/100	98
UDMH	1/10	10	3/50	6	6/100	6
NO_2	0/10	0	9/50	18	13/100	13
$B_{10}H_{14}$	6/10	60	25/50	50	82/100	82
Controls	1/10	10	0/50	0	1/100	1
CCl_4	1/10	10	0/50	0	0/100	0
Phenol	0/10	0	0/50	0	0/100	0
Indole	2/10	20	5/50	10	22/100	22
H_2S	0/10	0	12/50	24	26/100	26
Me· SH	4/10	40	5/50	10	43/100	43
Mixture**	16/20	80	32/50	64	99/100	99
Controls	0/19	0	2/50	4	38/200	19

* At TLV Concentrations
** Indole, H_2S, Me· SH, and Skatole

II. RESEARCH FACILITIES

A unique inhalation exposure facility has been built at the 6570th Aerospace Medical Research Laboratories to study the effects of low atmospheric pressure and oxygen-rich atmospheres on the characteristics of truly uninterrupted long term exposure to toxic gases and vapors that are encountered in the atmospheres of space cabins. This facility became operational in September 1964 and consists of four dome-shaped altitude chambers (fig. 1)

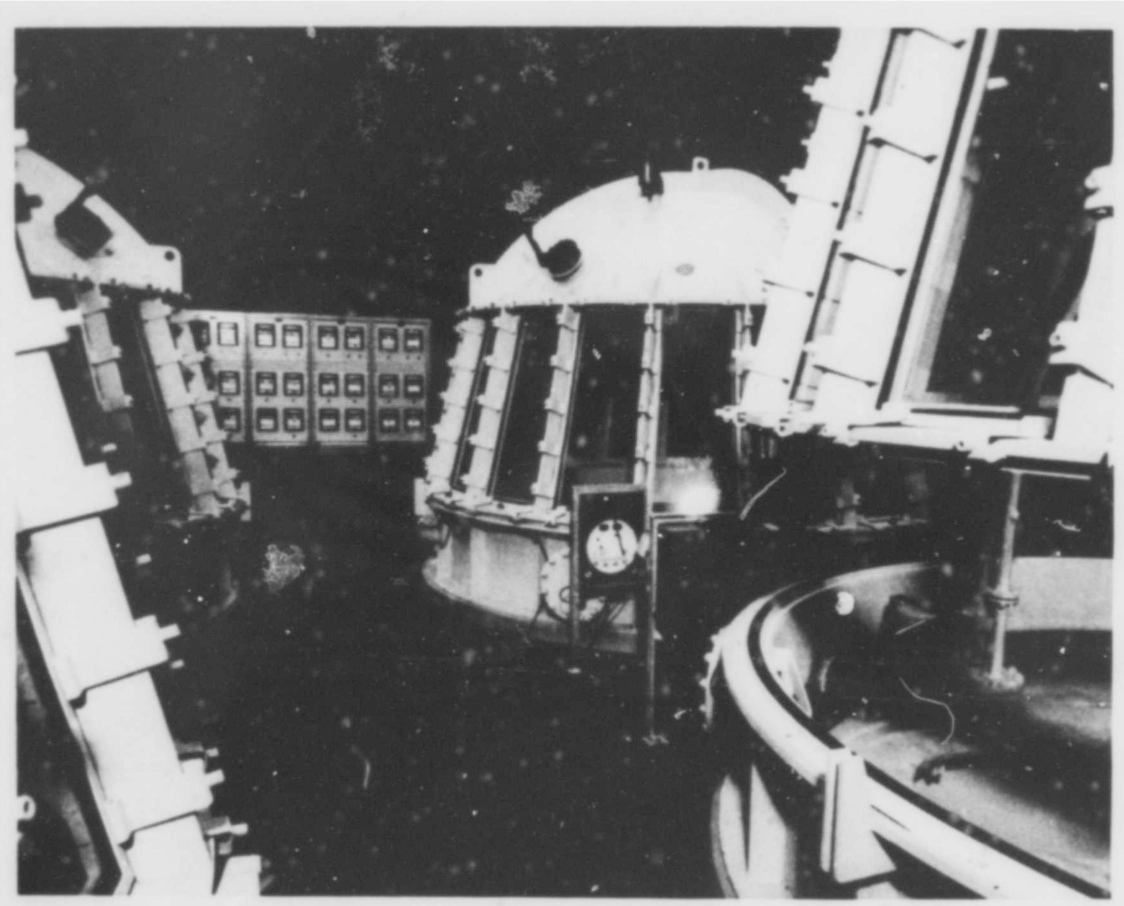


Figure 1. **Inhalation Exposure Facility, showing dome-shaped altitude chambers.**

with the necessary air lock, contaminant feed and drainage systems to facilitate continuous exposure of a large number of various species of animals without interfering with either the pressure or contaminant concentration.

These "Thomas Domes" were conceptually designed by the author (7) and were engineered, installed and are currently operated by the Aerojet-General Corporation under a contract with the Air Force. One of the desirable features of this facility, usually not encountered in other exposure chambers, is the capability to simulate environmental parameters that are peculiar to space cabin atmospheres. Within the 4-fold structural safety factor these domes can be operated with a pressure differential of 10 psi (i.e., from one atmosphere to one-third atmosphere pressure) and with either single-gas oxygen, or with mixed gas, oxygen-nitrogen, or oxygen-helium environments. For both safety considerations and versatility, the upper portion of the dome is mated to the lower portion by an O-ring arrangement, thus providing both a quick escape capability for the operators in case of a fire, and an unrestricted access during the loading of animals, cages and life support and specialized test equipment before and after experiments (fig. 2). An operating console continuously records oxygen and carbon dioxide concentrations, contaminant flow rate, oxygen flow rate, total pressure, temperature and humidity within each dome.

The middle section of the dome consists of one-inch thick, shatterproof glass paneling that assures unobstructed visual and photographic observation of the experimental subjects. The black ceiling, walls and floors facilitate both photographic work, through elimination of reflectance, and sensory deprivation studies. The facility is highly automated and can be operated by a single technician during the night-time hours. At the beginning of each experiment, the basic parameters such as contaminant flow, temperature, humidity and mixed vs. single gas atmosphere are adjusted in the basement of the facility, and from then on the entire operation is automatically controlled. The control console has manual override features and both visual and audible alarm system.

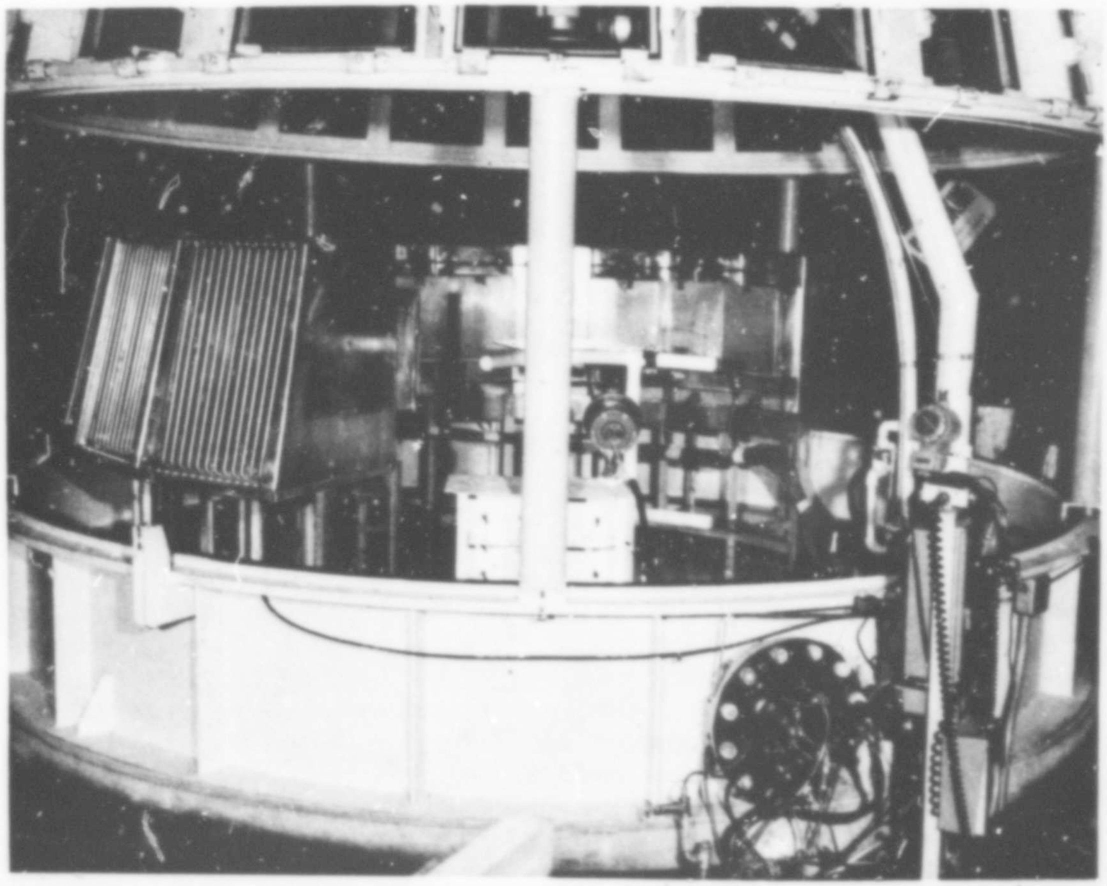


Figure 2. Primate performance cages loaded in chamber.

During exposure studies, chamber technicians enter the dome once daily through a vertical airlock system to clean cages, feed animals and obtain biological samples (fig. 3). Wastes are hosed down through a special drainage system which can handle the pressure differentials involved. There is also a water spray ring which can be activated from the outside to prevent accumulation of excreta during the 24 hour cycles. All dead animals are removed promptly and necropsied immediately.

A liquid oxygen storage cylinder with a 68,000 pound capacity supplies gaseous oxygen to the facility through a converter. All crucial support equipment such as air conditioning units, chillers, oxygen heaters, vacuum pumps, compressors for instrument air, etc., are redundant and, in case

Figure 3. Vertical airlock system, used by chamber technicians for entry to dome during exposure studies.

of a general power outage, a 160 KW diesel generator can supply the necessary AC power requirements.

The safety and occupational medicine aspects of this system require an altitude indoctrination training course for all chamber operators and other scientific personnel who must enter the altitude exposure chambers. Chamber technicians who must remain at altitude for prolonged intervals to perform the considerable physical work of lifting feed bags, cleaning cages, collecting biological samples, etc., are denitrogenated for a 30-minute period by breathing 100% oxygen to prevent occurrence of the "bends." A 30-minute period has been found satisfactory for the shorter entries required to remove dead animals. No operator may make more than four entries within a single 24 hour period and after each day of entry, he may not reenter for another 24 hours. During approximately three years of operation, we have encountered no serious medical problems due to altitude exposure.

With the oxygen-rich environment, safety considerations are primarily governed by the increased fire hazard. Automatic and manually operated water deluge and CO_2 fire extinguishing systems in each dome can be activated by either the console operator or the technician within the dome. Whenever technicians enter the dome, an overhead crane is engaged at the hook-lift portion of the dome top, and should an emergency arise, the dome can be repressurized by a 3-inch dump valve within 15 seconds. After pressure equilization, the top section can be lifted to facilitate rapid removal of personnel or animals. This dump valve is redundant and can be operated from either outside or inside the dome.

A triple-safe communication system includes a hard-line transistorized intercom using standard Air Force head gear and lip contact microphone, a hard-line system with amplifier and loud speaker system to alert the inside operator to any emergencies of which he may not be aware, and a wireless "walkie-talkie." All three systems are battery operated, as are the emergency lights which are automatically activated by a general power failure.

To avoid possible sources of fire, all fixtures are of explosion proof design, and 24 pairs of shielded cable are available for transporting biological signals to physiological instrumentation recorders located outside the domes.

III. RESEARCH OBJECTIVES

The mission of the facility is to provide both fundamental experimental capabilities in space cabin toxicology and a quick reaction capability in the toxicological qualification of space cabin materials. Since there is mutual Air Force and NASA interest in these areas, the toxicological information generated serves both military and civilian space requirements. A cost sharing Air Force-NASA research effort is currently exploring the following fundamental and practical questions:

1. Does a 5 PSIA oxygen rich atmosphere cause pulmonary irritation or functional impairment during long term continuous exposure?

2. Will such an atmosphere influence or modify tolerance to atmospheric contaminants?

3. Can cabin materials be screened for potential toxic effects in a practical and timely fashion?

IV. EXPERIMENTAL DESIGN

To answer the basic questions, three major groups of animal experiments were conducted in the past two years. Group I experiments consisted of 8-month continuous exposures of large numbers of various species to 5 PSIA 100% oxygen and to 5 PSIA 70% oxygen 30% nitrogen basic cabin atmospheres. In addition, 90-day continuous exposures of 12 trained primates working on performance tasks were also performed with both types of cabin atmosphere.

Group II experiments consisted of comparative toxicity studies on pulmonary irritants and systemic poisons. Large numbers of various species were continuously exposed for two weeks to graded high concentrations of such agents, and for 90-days to their representative industrial Threshold Limit Value (TLV) concentrations in both ambient air and in various cabin atmospheres.

Group III experiments consisted of analytical characterization of volatile contaminants generated by various cabin materials and continuous exposure of rats and mice for one week and 60-day duration of such gas-off products in a 5 PSIA 100% oxygen environment.

In the following discussion of results, these experimental groups will be treated as separate entities.

V. RESULTS

A. Group I Experiments: Fundamental Cabin Atmospheres

The basic criteria for environmental parameters, animal loads, and evaluation of toxicity are condensed in table III. While the 8-month experiments represent a classical toxicological approach, the 3-month study is solely for the evaluation of animal performance. Those enzymes studied in the classical experiments were transaminases, lactic dehydrogenase, and alkaline phosphatase.

TABLE III

Criteria For Group I Experiments

Exposure:	Continuous	
Atmospheric Composition:	Single Gas Oxygen or Mixed Gas ($68\%\ O_2$ - $32\%\ N_2$)	
Pressure:	5 PSIA	
Temperature:	72^oF	
Relative Humidity:	50% (Corrected for Altitude)	
Gas Flow:	Dynamic (No Recirculation)	
Animal Load:	8 Months Study	3 Months Study
	4 Monkeys 8 Beagles 65 Rats 40 Mice	Performance Testing on 12 Monkeys
Laboratory Procedures:	Hematology Blood Electrolytes Proteins (Serum) Enzymes and Isoenzymes	Hematology Blood Electrolytes Proteins (Serum) Enzymes and Isoenzymes
Behavior:	Spontaneous Activity	Continuous and Discrete Avoidance Tests
Growth Rate:	Pre- and Postexposure	Pre- and Postexposure
Pathology:	Gross and Histopathology	

Controls for these experiments consisted of similar numbers of animals held at ambient air conditions in the animal holding facilities with the exception of the 12 trained primates which served as their own controls on performance measurements.

A number of ancillary experiments were also conducted to serve as "positive controls." These consisted of continuous exposures to pure oxygen atmospheres at ambient pressure and gradually reduced pressures (760, 725, 695, 650 and 600 mm Hg) and utilized four monkeys (Macaca mulatta) per group (13). These animals furnished the classical morphological and clinical laboratory baseline materials for oxygen toxicity criteria. Again for the sake of positive biochemistry controls, large groups of rats were exposed to pure oxygen at ambient pressure and mitochondrial enzymes and morphology was studied (12, 14, 15, 16, 17, 18).

Both single and mixed gas fundamental 5 PSIA cabin atmospheres appear to be well qualified by animal toxicity tests for long mission durations. In general there was a paucity of abnormal clinical findings with both.

The 5 PSIA pure oxygen atmosphere has not produced any gross or clinical laboratory changes at the end of the 8-month exposure period. Histopathology by light microscopy indicates some toxic effects in dogs, consisting of pulmonary hemorrhage, edema and proliferation of alveolar walls, but this finding was not present in other species. Electron microscopy and subsequent morphometric analysis has substantiated these findings. There is some apparent healing and regression of pulmonary pathology if the dogs are removed to room air for 40 days following the exposure. Mitochondrial morphology in liver and kidney of rats shows some aberrations in the first two weeks of exposure but these tend to revert to normal by 90 days and 8 months. Mitochondrial chemistry does not show typical oxygen toxicity effects such as uncoupling of oxidative phosphorylation. Since the significance of ultrastructural aberrations is yet unclear, and they seem to be reversible, perhaps they reflect adaptive changes to protect the animals from hyperoxia.

The 8 month exposure to the 5 PSIA mixed gas atmosphere was completed on 3 January 1967 and the pathology reports are not yet available. The only obvious abnormality in clinical laboratory results which can be seen on first glance is an inverted albumin-globulin ratio in several beagle dogs. The significance of this finding has yet to be determined. On several occasions, some control dogs exhibited a downward trend on this test, but the mean average A/G ratio in control beagles stayed well within the normal limits.

The trained primates have performed well in both 5 PSIA oxygen and mixed gas environments for the 90-day test duration.

To summarize the conclusions from Group I experiments:

1. By extrapolation from the results of the 8 month animal exposures in this laboratory and interpretation of available information from shorter duration human experience in life support simulators (19) it appears now that both fundamental atmospheres are suitable to maintain life and preserve performance on extended missions of several months duration.

2. Strictly based on animal data, the 5 PSIA oxygen atmosphere has shown minor pulmonary effects but all other parameters studied, including chemistry, were within normal limits at the end of the 8-month exposure.

3. There is some uncertainty about the significance of the inverted

A/G ratios in dogs observed in the 8-months mixed gas study. Final evaluation will only be possible after thorough analysis of histopathology and electron microscopy data. It may be necessary to repeat this experiment to verify the reproducibility of this change. Fortunately, the trend toward an inverted A/G ratio has shown up as early as three months into the prolonged exposure, and this may shorten the length of the second experiment.

4. Last but not least, these animal experiments have demonstrated their great value in conjunction with the manned simulator experiments. Complete review of pathology in the animal biopsy and necropsy materials tremendously increases the confidence in extrapolation of tolerance from animals to humans.

B. Group II Experiments: Comparative Toxicity of Pulmonary Irritants and Systemic Poisons at Ambient Air vs. Cabin Atmospheres and the Study of Cumulative Effects from Continuous Exposure.

The basic animal loading criteria and evaluation of toxicity are similar to those used in Group I experiments previously illustrated in table III.

The toxic agents were chosen for the following considerations:

a. There was abundant information on toxicity of repeated daily 8-hour exposure in both humans and animals.

b. The mode of action was well defined; hence, nitrogen dioxide represented a pulmonary irritant without systemic effects; ozone was known to cause both pulmonary irritation and systemic effects; and carbon tetrachloride has no pulmonary irritant properties but is regarded purely as a systemic poison at the concentrations employed.

c. Since the TLV values for industrial exposure were well established and proven by occupational medicine experience, study of these agents could answer two basic questions: (1) How will oxygen enriched atmosphere influence toxicity during continuous exposure: and (2) What is the magnitude of cumulative effect from continuous exposure?

Although these studies are not yet complete, tables IV and V depict both the accomplished and planned comparative toxicity studies. As in Group I experiments, 90-day performance evaluation of trained primates was also included here, but only at the TLV concentration to prevent loss of these expensive trained animals.

TABLE IV

Exposure Plan, Comparative 2 Week Continuous Exposure Studies

Contaminant (mg/M^3)		Ambient Pressure: Air $pO_2 = 148$	Ambient Pressure: Air O_2 Enriched $pO_2 = 260$	5 P.S.I.A.: 68% O_2 32% N_2 $pO_2 = 148$	5 P.S.I.A.: 100% O_2 $pO_2 = 260$
NO_2	(38)	X	X	X	X
	(81)	X			X
O_3	(8)	X	X	X	X
	(15)	X			X
CCl_4	(35)	X			X
	(576)	X			X

X Denotes completed studies

These high concentration exposures were primarily designed to study the influence of these atmospheric mixtures on the toxicity of NO_2, O_3 and CCl_4. The doses were picked to assure mortality or severe pathological changes during 2 week continuous exposure.

TABLE V

Exposure Plan, Comparative 90 Day Studies

Contaminant T.L.V. (mg/M^3)		Ambient Pressure Air	5 P.S.I.A. 68% O_2-32% N_2	5 P.S.I.A. 100% O_2
NO_2	(9.0)	X		X
O_3	(0.2)	X	X (12 trained primates)	X
CCl_4	(32.0)	X		X

X Denotes completed studies

Early in these studies when comparing data from ambient air and 5 PSIA 100% oxygen exposures, we noted marked differences in toxicity under these conditions. This brought up the question of whether increased oxygen concentration or decreased total pressure is the responsible influencing factor. To clarify this point, ambient pressure air was enriched with oxygen to the point where the partial pressure of oxygen (pO_2) in the mixture was equal to the pO_2 in the 5 PSIA 100% oxygen experiments: that is, 260 mm Hg.

It would be impossible to present a detailed analysis of all test results in this presentation. They are, however, published in the Proceedings of the First and Second Conferences on Atmospheric Contaminants in Confined Spaces (20, 21).

As a brief summary of findings from these comparative experiments, the following conclusions can be made:

1. There is a clear-cut difference in the toxicity of pulmonary irritants at high concentration under various environmental conditions. Ozone and NO_2 are most toxic in ambient pressure air and least toxic in 5 PSIA 100% oxygen atmosphere during a 2-week continuous exposure. Mixed gas, 68% oxygen - 32% nitrogen at 5 PSIA pressure and oxygen enriched air (pO_2 = 160 mm Hg) at ambient pressure behaved differently; NO_2 was less toxic in mixed gas atmosphere at 5 psia than in O_2 enriched ambient air, while the reverse was true with ozone. Still, both of these atmospheres seemed to significantly reduce the toxicity of pulmonary irritants when compared to plain ambient pressure air environments. This was evidenced by either the absence of mortality or by prolonged survival times. Thus it appears now that both oxygen rich and reduced pressure environments reduce the toxicity of pulmonary irritants, and a combination of both seems to have the most protective effect.

2. In the 90-day studies, the TLV concentration of CCl_4 was definitely toxic in both ambient pressure air and 5 PSIA oxygen atmospheres. The 2-week high concentration CCl_4 studies indicated a more pronounced toxic effect in 5 PSIA oxygen than in ambient pressure air. In the case of ozone, one dog died on day 30 of the ambient pressure air exposure, but no animals were lost in the 5 PSIA oxygen environment. Even with NO_2, the TLV concentration seems to be marginally toxic under both conditions. Therefore, generally it can be concluded that 8-hour industrial TLV's are unsafe concentrations for prolonged continuous exposure. This statement does not necessarily imply that ensuing pathological changes are irreversible, but simply points out that they should not be used as design criteria for the control of atmospheric contaminants in space cabins. As a matter of interest, ozone at the TLV concentration in a 5 PSIA mixed gas atmosphere did not produce any performance decrement in the trained primates.

3. The most important implication of these findings is that the basic cabin atmosphere of 5 PSIA 100% oxygen is not likely to enhance the toxicity

of pulmonary irritants or systemic poisons upon long confinement to the cabin if levels are kept within a safe fraction of the TLV values. What precisely this fraction should be is hard to predict; very likely 1/10 of the TLV may be safe in most instances and even oversafe in many instances. Straight forward compensatory extrapolation for the 3-fold increase in daily exposure (8 x 3 = 24 hrs) will not yield a sufficiently safe design factor. Ultimately, levels must be set on the basis of mission length oriented animal exposure studies and careful extrapolation of these results to human. This approach is satisfactory for present systems where mission duration is not in excess of 90 days. With the advent of interplanetary missions, more efficient ways of extrapolation will be necessary to permit the use of shorter than mission length animal exposures in the prediction of safe atmospheric contaminant levels in the spacecraft. Obviously, there are not enough facilities in the country to allow the toxicologist to conduct a one-year long animal experiment on each contaminant before a level is recommended for design purposes; neither will the engineering leadtime allow for such delays in the biological leadtime.

C. GROUP III Experiments: Analytical Characterization and Toxicological Screening of Gas-Off Products from Cabin Materials

1. Analytical Characterization

There are many construction materials used in today's sophisticated spacecraft cabins and the attending environmental control or life support systems. Those groups of materials which are most likely to produce volatile contaminants, are listed in table VI.

TABLE VI

Volatile Contaminant Sources

Adhesives
Elastomers
Electrical Insulation
Finishes
Coatings, Paints and Varnishes
Markings, Inks
Foams
Greases, Lubricants
Moldings
Plastics and Laminates
Potting and Sealing Compounds
Thermoplastics

There are over 600 various materials used in the construction of the crew cabin. Rigid criteria have been set up for qualification of these materials before use in the Apollo and MOL systems. Again, these criteria cannot be reviewed here, but the interested readers can obtain the information from the references in this paper (20, 31).

The analytical identification of volatile contaminants is the final phase of the chemical acceptance program. To illustrate the categories of volatile products from the previously listed groups of cabin materials, table VII depicts both major types and the most frequent sources that were positively identified.

TABLE VII

Major Types of Gas-Off	Typical Sources + Products
Inorganics	Paints + Coatings:
Alkanes	Carbon Monoxide
Alkenes	Solvents
Alcohols	Plasticizers
Alkyl Halides	Resins:
Aryl Halides	Ammonia
Benzene & Homologues	Ethylamine
Carboxylic Acids	Silicon Greases
Aldehydes	Tetrachlorobenzene
Ketones	Polyurethane Foams
Aliphatic Nitrogens	Carbon Dioxide
Silicon Compounds	Lubricants
	Chlorine Substituted Fluoro-Carbons (up to C_6)

To further illustrate the complexity of contaminant mixtures in the atmosphere, we have analyzed concentrated freeze-out samples from one of the Thomas Domes during the performance of the 8-month 5 PSIA 68% oxygen 32% nitrogen mixed gas study (table VIII).

TABLE VIII

Analysis of Atmosphere of Thomas Dome #4 Containing Dogs, Monkeys, Rats and Mice in 5 PSIA 70% O_2 30% N_2

Compound	Level in MGS/M^3
* Combined Methyl and Ethyl Amines	12
* Methane	3
* Acetone	4

TABLE VIII (continued)

* Carbon Monoxide	2
Methylene Chloride (supply gas)	8
Benzene	0.2
Toluene	0.1
Xylene	0.2
* Diethyl Ketone	2
Methyl Isobutyl Ketone	0.1
Dimethyl Formamide (tentative identification)	0.004
* Phenol (tentative identification)	0.008
Carbon Disulfide	5
* Hydrogen Sulfide	5
** Solid Ammonium Salts - estimated	50 mg/m^3

* Biological origin possible
** Result of interaction with ammonia

The surprising findings in this analysis are (1) the relatively high contaminant content of the atmosphere in view of the fact that the oxygen source always meets the required purity standards as prescribed in the military specification for aviator's breathing oxygen and (2) that such accumulation does occur since we are not dealing with a recirculating system but with a 20 CFM open flow design, which should prevent substantial accumulation of contaminants. Many contaminants in this mixture are obviously of biological origin due to the animal loading in the Dome.

Another great potential source of unexpected contaminants is malfunctioning equipment. Overheating of electrical insulation and neoprene ducting for air-conditioning have already been identified during simulator runs as real problem areas. One malfunction can trigger a chain reaction of other malfunctions resulting in a true vicious circle and acute health hazard to the crew. This has actually occurred and has led to portion of the Project MESA experiment (Manned Environmental Systems Assessment) and has been a mystery for a long time until recently solved by R. A. Saunders of the U. S. Naval Research Laboratory, Washington, D. C. (21). During the manned trial, due to the increased humidity of the atmosphere water condensed in the aluminum canister containing sodium superoxide. This started a chain of events:

a. The moisture generated sodium hydroxide from the sodium superoxide.

b. Sodium hydroxide generated hydrogen in contact with aluminum.

c. To get rid of the steady generation of hydrogen into the atmosphere, the crew increased the flow rate through the catalytic hopcalite burner to a faster rate than specified.

d. The increased flow rate dropped the temperature of the catalyst bed, making it inefficient in combusting organic materials in the atmosphere.

e. The chamber had been cleaned prior to use with a relatively harmless solvent (trichloroethylene). Due to incomplete combustion in the catalytic bed, dichloroacetylene was produced, which is highly toxic and made the crew so sick they had to abort the mission on the third day.

The analytical identification and measurement of trace quantities of contaminants is a difficult and time consuming task. Cabin materials are sealed in large glass bottles, stored in a 5 PSIA oxygen atmosphere and allowed to off-gas for periods of 30, 60 and 90 days. The atmosphere containing the volatile contaminants is then analyzed by a combination of gas chromatography, mass spectrometry and infrared technics (20, 31, 22). In the case of environmental samples collected from cabins and simulators, several steps of sample concentration by freeze-out technics are necessary to obtain sufficient material for analysis (20).

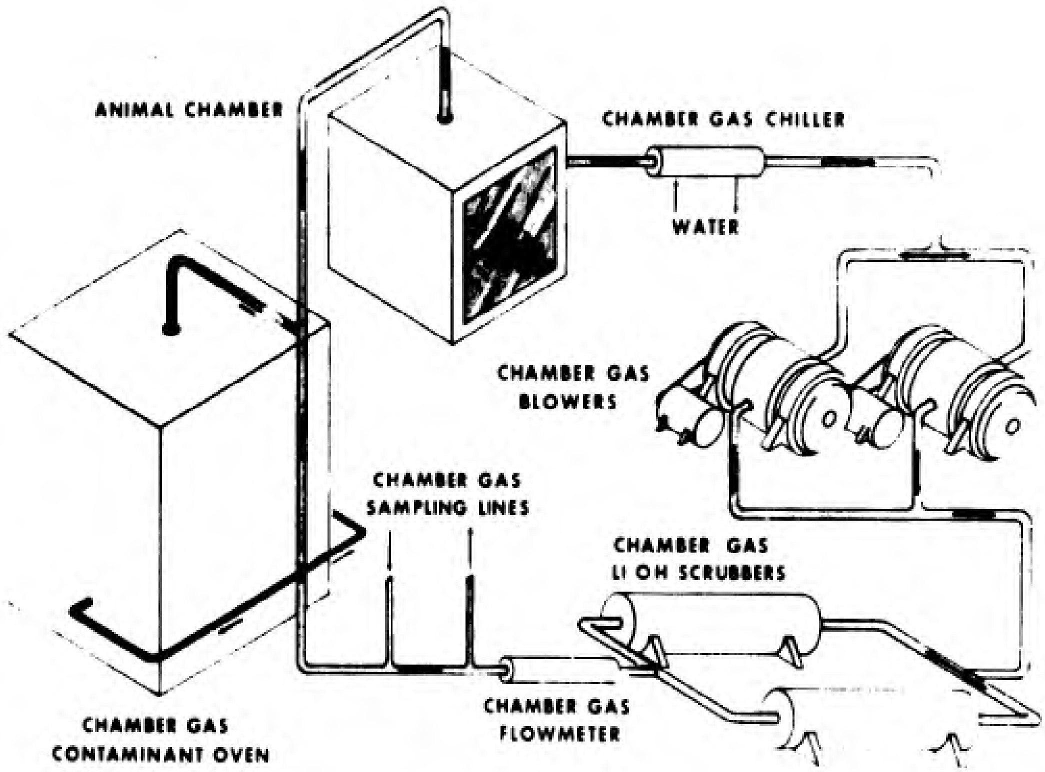
2. Toxicological Screening

Two types of studies are conducted by continuous exposure of 25 rats and 25 mice to gas-off products from cabin materials generated at 155° F in a 5 PSIA oxygen environment.

The acute exposure is of one week duration to a mixture of 10-12 various cabin materials; the chronic exposure is of 60 day duration, to a large mixture of about 100-120 materials which have been previously screened and accepted in smaller batches in the acute one week studies.

A dome is used as an environmental envelope at 5 PSIA pressure and maintains dynamic 20 CFM flow of pure oxygen. Small animal cages housing the 25 rats and 25 mice are inserted into a closed loop recirculating life support system consisting of CO_2 removal, humidity trap, and constant temperature ovens heating the materials (fig. 4). The loss of oxygen converted to CO_2 by the animals is made up from the dome atmosphere by an automatic pressure-sensitive valve admitting fresh oxygen into the closed loop.

The reason for screening materials in mixtures of one to 120 at a time is twofold. First, the tests have to be completed within the milestone schedules of system development. Secondly, employing large mixtures of materials enhances the detection of serious synergistic effects which could



APOLLO MATERIALS CONTAMINANT TOXICITY TEST FLOW SCHEMATIC

Figure 4

not be seen if materials are screened singly.

If a mixture shows toxic effects as determined by clinical observation, depressed growth rate, or gross and histopathological abnormalities, it is systematically taken apart until the culprit material or combination of materials is found which is responsible for the toxicity. This can be a very time consuming process, especially if the large mixture shows adverse effects, while the previously screened smaller batches did not demonstrate any activity.

Thus far we have only run into two small mixtures requiring this approach. In one instance the weightloss of animals could not be duplicated in the subsequent experiment. On the second occasion, a group of 12 materials which showed toxicity was sub-divided into batches of six; one of these smaller batches again exhibited overt toxicity and was further broken down into two sub-groups of three materials. At that time, a new supply of these materials was ordered from the various vendors, and the fresh supply failed to cause toxic effects. This variation between production batches of materials is not uncommon at all and has also been noted in the analytical gas-off studies. Consequently, one is faced with the frustrating task of testing a large number of production runs on the same material before the truth is found, if ever. To avoid such trials and tribulations, perhaps it may be wise to obtain, in advance of the actual hardware construction, sufficient quantity samples of the very same materials which are to be used in the cabin. Trends to accomplish this are promising. The Apollo system has established a good material screening program and all future systems are certain to follow suit. This will lead eventually to a good catalogue of tested and accepted materials which can be relied upon not to create serious health hazards in the closed atmosphere.

VI. HAZARD EVALUATION AND ENGINEERING CONSIDERATIONS

The crucial factors in contaminant build-up are generation rate, removal rate, equilibration time, and the maximum permissible concentration of a contaminant that can be tolerated for the total mission duration without ill effect on health or performance. Interrelation of all these factors can be expressed by the following mathematical equations:

Assuming perfect mixing, a constant contaminant generation rate, and a constant leak rate, the concentration of contaminant at any point in time can be calculated by using the following equation:

$$c = \frac{w}{b}\left[1 - e^{\frac{-(bt)}{a}}\right] \quad \text{where} \qquad (1)$$

c = contaminant concentration in mg/m^3
w = amount of contaminant generated in mg per day
b = leak rate in cubic meter per day at a particular cabin pressure
a = total effective gaseous volume in cubic meters
t = time in days
e = 2.718

When equilibrium conditions are reached, the above equation can be simplified because

$$\left[1 - e^{-(ba/t)}\right] = 1 \quad \text{and, therefore,}$$

$$c = w/b \qquad (2)$$

The time period required to reach a certain percent of equilibrium values can be calculated according to the formula

$$t = \frac{Ka}{b}$$ where K is a constant with a numerical value of 3 for 95% equilibrium and 4.6 for 99% equilibrium. (3)

The above equations are useful for the following purposes:

1. To calculate leak rates (controlled dumping) or removal (purification) rates needed to prevent buildup of a contaminant above the maximum allowable level, assuming that contaminant generation rate and total mission duration are known.

2. To calculate the Maximum Allowable Quantity of a certain material aboard, assuming a known generation rate, a known allowable concentration, a known removal rate, and a known mission duration.

3. To calculate Maximum Permissible Mission Duration if the contaminant generation and removal rates are unacceptable for toxicity reasons, assuming that an absolute "ceiling" concentration of a contaminant has been defined.

For example: Given a contaminant generation rate of 0.26 $mg/m^3/day$ and a cabin volume (a) of 8.49 m^3, w = 8.49 x 0.26 or 2.21 mg/day. Since the leak rate is known to be 1 lb/day (or 1.04 $m^3 O_2$ at 5 PSIA per day), b = 1.04. Therefore, the contaminant concentration at which the cabin will equilibrate (c) is

$$c = \frac{w}{b} = \frac{2.21\ mg/day}{1.04\ m^3/day} = 2.1\ mg/m^3$$

99% of this equilibrium concentration will be reached

$$t = \frac{Ka}{b} = \frac{4.6 \times 8.49\ m^3}{1.04\ m^3/day} = 37.5\ days$$

Should the value for (c) exceed the maximum allowable level for the mission duration from a toxicity view, and neither the generation rate (w) nor the leak rate (b) can be altered, the limiting factor is now time (t) which must be recalculated using equation (1) for the acceptable (c) value. To simplify this calculation (t) values can be read directly from figure 5.

To summarize the salient features of the contaminant build-up hazards, the following axioms are derived from these equations:

1. Given a certain cabin volume, the time of equilibration of contaminant concentrations in the atmosphere is independent of the final concentration attained, if contaminant generation and removal rates are held constant.

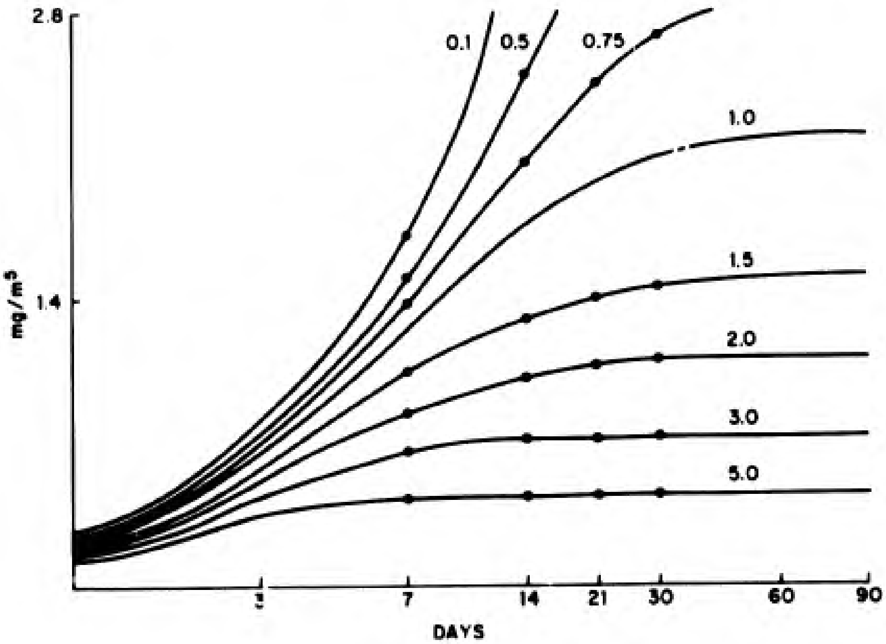


Figure 5. The effect of various leak rates between 0.1 and 5.0 pounds per day on contaminant accumulation (mg/m^3) as a function of time (days) in sealed space cabin at 5 PSIA pressure.

Under certain conditions, the virtual (but not the true) rates of contaminant generation can become constant since the decreasing rate of gas-off from materials is balanced out by the progressive loss of filtering efficiency.

2. The magnitude of the final equilibrium concentration of contaminants is directly proportional to the generation rate and inversely proportional to the removal rate in sealed cabins.

3. Contaminant concentration rises rapidly at first and then approaches a constant value (equilibrium concentration) at infinite time.

From a practical standpoint, the design engineer has primarily to worry about contaminant removal rates to keep the atmosphere habitable on long duration missions. Removal rates depend on what contaminants are lost together with the cabin atmosphere as the result of outboard leak and the amount of contaminants that are adsorbed on the various filter beds.

Leak rates are the most effective disposal methods for contaminants. They also have the greatest impact on the rate at which contaminants accumulate in the cabin (table I). Since large leak rates are undesirable from a logistics standpoint, other means of contaminant elimination must be found. To simplify calculations, "equivalent leak-rate times" can be used for rating filters, scrubbers or other air purification equipment. This "equivalent leak rate time" (ELRT) can be defined as the volume of atmosphere that has been "absolutely cleaned of contaminants" in one day's time, with specific consideration for the efficiency of the purification unit. For example: A filter operating at 50% efficiency would remove only 1/2 of the contaminants present in a unit-volume of air passing through it. On the second passage through, it would remove 1/2 of the remainder, etc.

The problem with filters is that their efficiency decreases with time as the filter bed saturates with contaminants and as the flow rates through the filter drop due to particles obliterating the free passage of atmosphere.

Figures 6 and 7 depict the typical characteristics of filter beds with regard to concentration vs. time profiles. It can be seen that with increasing time, filter efficiency decreases in an exponential fashion that is quite similar to the build-up of contaminants. Consequently, the inefficiencies of filters on long-duration missions will be greatly aggravated by the contaminant build-up if there is no substantial outboard leak or controlled dumping. Moreover, nuclear submarine experience indicates that adsorbent beds become saturated with high boiling hydrocarbons within two to three days and permit the low boiling point materials to pass through, even displacing these. Until specific adsorption coefficients become available for particular materials and periods of time, generous safety factors should be used in calculating the amount of adsorbents.

VII. SUMMARY

Space cabin toxicology is a new and challenging area of research in the conquest of extraterrestrial support of life. The most unique problem of this new branch of toxicology is the truly uninterrupted continuous nature of exposure to chemical toxicants. The fundamental research in the past two years has answered the most urgent basic questions.

1. Continuous exposure can lead to a "summation of interest" type of toxic effect, because daily recuperative periods from exposure are nonexistent.

2. The exotic atmospheric environment will influence the outcome of toxic damage; both reduced barometric pressure and oxygen rich atmosphere are influencing factors.

3. All cabin materials can and must be screened by analytical and biological methods to insure the health and performance of the crew in future manned space missions.

Recognition of these facts came none too soon. The toxicological problems involved in intraplanetary exploration are staggering and will require revolutionary approaches and many breakthroughs in the state-of-the-art in toxicology, pharmacology, aerospace medicine, and bio-environmental engineering. Undoubtedly, these improvements will have many spin-off benefits to modern medicine, industrial hygiene and environmental pollution control in our every day life. The better understanding of chronic toxic effects, new approaches to physical therapy, and contributions to the solution of community air pollution problems are just a few areas where this research already has produced significant and immediately applicable fallout benefits.

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Propellant Toxicology

Dr Kenneth C. Back

Dr. Back received his B.S. degree from Muhlenberg College, Allentown, Pennsylvania, his M.S. and Ph.D. degrees from the University of Oklahoma. He has worked at Warner-Lambert Research Institute and at the Pitman-Moore Company as a pharmacologist. Since 1960, Dr. Back has been associated as a research pharmacologist with the Toxic Hazards Division, 6570 Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, where he is Chief of the Toxicology Branch. He has served as an Air Force consultant to NASA, the National Academy of Sciences, the U.S. Public Health Service, and to various industrial organizations actively involved in the manufacture and handling of toxic agents. Dr. Back has published approximately 20 papers on propellant and space cabin toxicology.

PROPELLANT TOXICOLOGY

Kenneth C. Back,. Ph. D.

Rapid advances in propellant development have fostered upon toxicologists a situation which is quite similar to the one confronting pharmacologists and toxicologists in the drug industry. Our propellant chemists are manufacturing and developing new chemical species at a much greater rate than one can test them biologically. In order to give you some idea of the problem facing the Air Force in the area of propellant toxicology, I will attempt to define our philosophy, how we attack the problem, and at the same time bring forward pertinent data of interest to all who are manufacturing, handling, or blessed with the responsibilities of the medical aspects involved.

Since about 1960, we have approached the problems of defining the toxicological aspects of missile fuels and propellants in much the same way that pharmacologists would study the efficacy of a new drug being prepared for the open market. In this regard, then, we have used the team approach utilizing the services of most of the basic science medical disciplines which, of course, include pharmacology, biochemistry, physiology, neuroanatomy, and pathology. This is necessary since the toxicity of any compound is a direct result of its pharmacodynamic activity in the animal subject just as the therapeutic effectiveness of a new drug is a result of the overall pharmacological action. Its toxicology is involved with hypermanifestations of these effects.

For these reasons, then, we first look at the acute toxicity of the compound by presenting it to the animal by all possible routes of administration in single doses. Following the acute toxicity studies, we then progress on to subacute and chronic studies to determine long-term effects and at the same time find out something about possible accumulation of dose. Usually, concurrently with these studies and depending upon the compound, we study the effects of acute small doses on such parameters as blood pressure, heart rate, automonic nervous systems, central nervous system, and other pharmacodynamic areas using the old "cat-cannulla-kymograph" techniques with which you are all familiar from your medical school days. We also look at the absorption distribution, and excretion patterns of the compound to determine if any organ system preferentially handles the compound and to get some idea of whether the compound is excreted changed or unchanged. We utilize many methods for this kind of research including isotopically tagged compounds, if possible, or chemical and physical methods as necessary.

Since all compounds ultimately work at the cellular and subcellular level, we are acutely interested in the effects of each compound on metabolic pathways, enzyme systems, and subcellular elements. We, therefore, perform studies on possible changes in subcellular elements as they relate to enzyme systems and energy kinetics in order to correlate any changes seen with histopathology as evidenced by both light and electron microscopy. As we complete all these studies which should elucidate the absolute mechanism by which the compound is influencing the organism, we ought, by that time, have an idea about the possible therapeutic agents which may be effective in aborting such toxicity.

In order to point out some of the highlights of propellant toxicology over the last couple of years and to point out special interest items, I bring to your attention the list of compounds shown in table I. It is quite obvious from this table that many of the compounds of interest as possible propellant candidates are fluorine containing compounds and indeed many are of the type which were impossible to make or stabilize just a few years ago. This is especially true of the interhalogen compounds, chlorine trifluoride and chlorine pentafluoride. When most of us studied chemistry, I am sure no one contemplated the possibility of stable compounds such as these. Further, there was no indication until just recently, as to the effects of these com-

Table I

PROPELLANTS AND FUELS

Hydrazine - N_2H_4

1 - 1 dimethylhydrazine - $(CH_3)_2N\text{-}NH_2$

Monomethylhydrazine - $CH_3NH\text{-}NH_2$

Pentaborane - B_5H_9

Decaborane - $B_{10}H_{14}$

Fluorine Containing Compounds:

OF_2	NF_3	TAMA
ClF_3	N_2F_4	TVOPA
ClF_5	NF_3O	NFPA
BrF_5	PFG	Compound R

Beryllium Containing Compounds

Be
BeH_2

pounds from a toxicological viewpoint. The hydrazines, on the other hand, have been known for some time in the pharmacological literature and indeed many of them, especially the phenylhydrazines, have shown usefullness therapeutically as anti-tubercular compounds, phychic energizers and tranquilizers. The boranes, on the other hand, are completely foreign to any known pharmaceuticals but have very interesting pharmacological and toxicological effects as I will show later.

I should now like to point out a few of the recent breakthroughs we have had in the study of the pharmacology of some of these compounds and some of the agents we are trying as therapeutics. Obviously, I can't spend too much time on any single compound in the time allotted. I should like to point out at the onset that much of this work has been performed under contract with industrial or non-profit organizations, much has been accomplished by scientists here at the School of Aerospace Medicine and our group in the Toxicology Branch of the Aerospace Medical Research Laboratories at Wright-Patterson AFB. I shall try to give credit to all the individuals who so diligently performed these studies though there are many.

I would first like to talk about the hydrazines in general and dwell on monomethylhydrazine more specifically, since MMH is the one hydrazine that we are currently placing the greatest emphasis on. One would think that since there is very little difference between UDMH and MMH that we would have to do very little work to understand its toxicological actions; however, unfortunately, this is not the case. Previous work has indicated that UDMH is primarily a convulsigenic agent with relatively little effect on kidney and liver function except at extremely high doses (1, 2). Its toxic manifestations can be aborted except for its emetic properties by vitamin B_6 (pridoxine).

Lieutenant Colonel J. Reeves and others at the School of Aerospace Medicine first showed that pyridoxine was effective against the convulsions and death from large doses of UDMH (3). It became our responsibility to find a dose suitable for human use and also to see if there was any difference between pyridoxamine and pyridoxine and whether there were species differences (4). The group at SAM had found pyridoxamine to be more effective than pyridoxine in the rat. They tested only pyridoxine in the monkey. Figure 1 shows the dose response curves between pyridoxamine and pyridoxine in the mouse. It is evident from this curve that pyridoxine is almost twice as effective as pyridoxamine and further that pyridoxamine causes a biphasic response at higher dose levels. Figure 2 shows the effectiveness of the two compounds in rats exposed to approximately two lethal doses. It is quite evident here that pyridoxamine is about ten times more effective than pyridoxine. Here, then, we have a direct contradiction of effects between the two species. Our thoughts were directed to the dilemma of whether man is metabolically more like the rat or the mouse. To complicate matters, we then studied the two compounds against the lethality of UDMH in the dog and

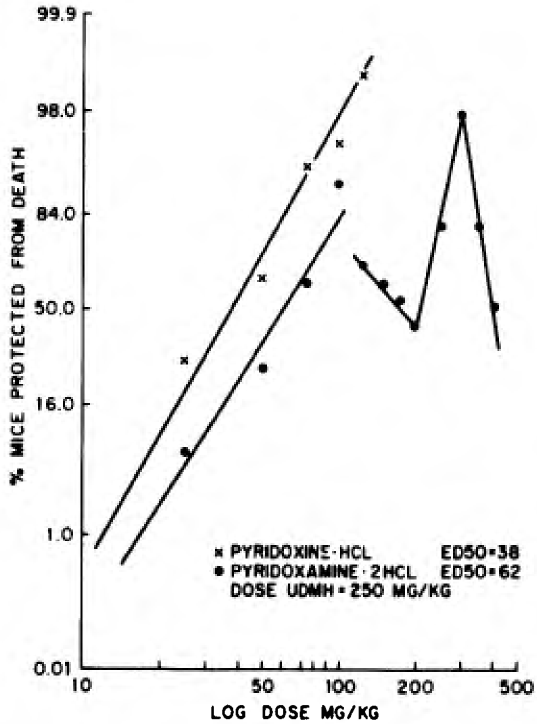


Figure 1. Antidotal Effectiveness of B_6 Analogues Against UDMH in the Mouse.

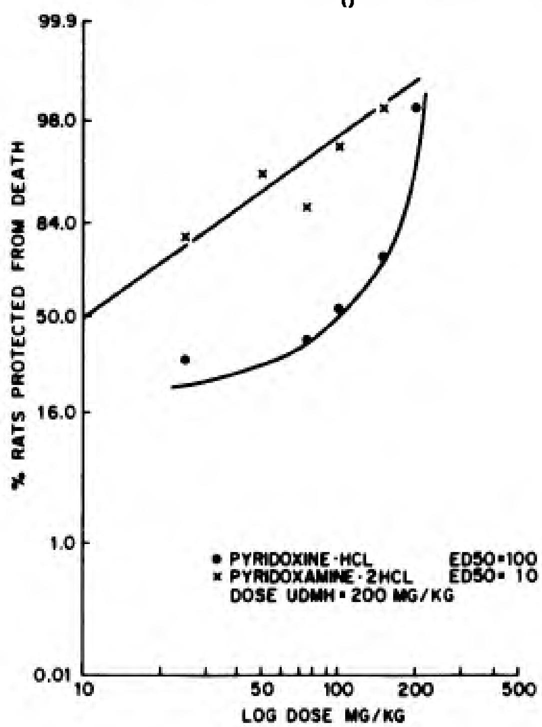


Figure 2. Antidotal Effectiveness of B_6 Analogues Against UDMH in the Rat.

the monkey. Table II indicates that the dog is less sensitive than the monkey to the effect of pyridoxine. The monkey was protected against convulsions with a single dose of 50 mg/kg while the dog needed 150 mg/kg to abort convulsions. Pyridoxamine, however, was relatively ineffective against convulsions in the monkey and as shown in table III, 200 mg/kg failed to abort all convulsions. As a result of these experiments, we concluded that man

Table II

THE EFFECT OF PYRIDOXINE
AGAINST A LETHAL DOSE OF UDMH (100 MG/KG)

ANIMAL	PYRIDOXINE MG/KG ROUTE	EMESIS	CONVULSION	DEATH
DOG	200 s. c.	3/3	0/3	0/3
DOG	150 s. c.	3/3	0/3	0/3
DOG	100 i. m.	9/9	3/9	2/9
DOG	2x50 i. m.	3/3	3/3	0/3
DOG	50 i. m.	3/3	3/3	2/3
MONKEY	100 i. m.	2/3	0/3	0/3
MONKEY	50 i. m.	8/19	0/19	0/19
MONKEY	25* i. m.	4/9	5/9	0/9

*With the exception of one animal, all convulsing monkeys received a second dose of 25 mg/kg Pyridoxine.

Table III

THE EFFECT OF PYRIDOXAMINE
AGAINST A LETHAL DOSE OF UDMH (100 MG/KG)

ANIMAL	PYRIDOXAMINE MG/KG	EMESIS	CONVULSION
MONKEY	200	5/11	3/11
MONKEY	100	4/6	5/6
MONKEY	50	0/3	2/3
MONKEY	25	1/3	3/3

All monkeys that convulsed were given a dose of Pyridoxine (25 mg/kg) to insure survival.

should be given 25 mg/kg of pyridoxine in case of a severe exposure to UDMH. This decision was made because we felt that the monkey was higher on the phylogenetic scale than the dog or rodent and was better controlled by pyridoxine than by pyridoxamine. Further, pyridoxamine is not currently available for therapeutic use and pyridoxine is on the market. This data pointed out that more than one species had to be used in order to come to these conclusions since there were obvious metabolic differences between species.

When we began to study the toxicology of MMH, we soon learned that it was about three times more toxic acutely than UDMH and that also it caused marked changes in liver and kidney function. These changes are confounding because they appear to be species specific. In other words, MMH causes marked kidney changes in the dog producing hematuria, and relatively few changes in the liver while monkeys appear to have no kidney involvement whatsoever. In addition, while UDMH does cause some effects on glucose metabolism, it is not nearly so potent as MMH in this regard. Some experiments being performed currently by Captain Gale D. Taylor in our laboratory have shown that blood glucose decreases markedly within an hour following a 30 mg/kg dose of MMH in the monkey. He has seen glucose levels as low as 20 mg%. This finding certainly makes a difference therapeutically and may account for some of the differences we find with vitamin B_6 between UDMH and MMH. It has been evident that pyridoxine alone was not sufficient to abort convulsions and death in monkeys exposed to high doses of MMH. It has been found that the administration of glucose is also necessary to protect against death.

Other studies which have been just concluded on the metabolism of C_{14} labelled MMH have shown that MMH is not handled remarkably different from UDMH in that about 40% of the compound is excreted unchanged in the urine (5). Some 20-25% appears to be excreted in the respiratory gases as CO_2. This work was accomplished by Dost, Reed and Wang at Oregon State University (6). Of interest is the fact that some of the compound is excreted as methane via the respiration. This is the first time that I am aware of this type of metabolism for a compound.

An aside, which really has nothing to do with the toxicology of UDMH and MMH, but does point out some of the unusual fallout from this kind of research is an interesting property of the hydrazines found by a member of the Agricultural Department at Oregon State University. It has been found that both compounds are diamine oxidase inhibitors. Reed, Dost and Wang have shown that the catabolism of putrescine-1-14_C is markedly depleted following the administration of either UDMH or MMH (figure 3). In looking for mechanism it became apparent that a diamine oxidase inhibition might account for the phenomenon. The fact that diamine oxidase is important for the metabolism of plant cells and hence their growth turned out to be of consequence and it was found that, if UDMH or MMH were added to a growing rose, the stems of the roses became shorter but the bloom remained

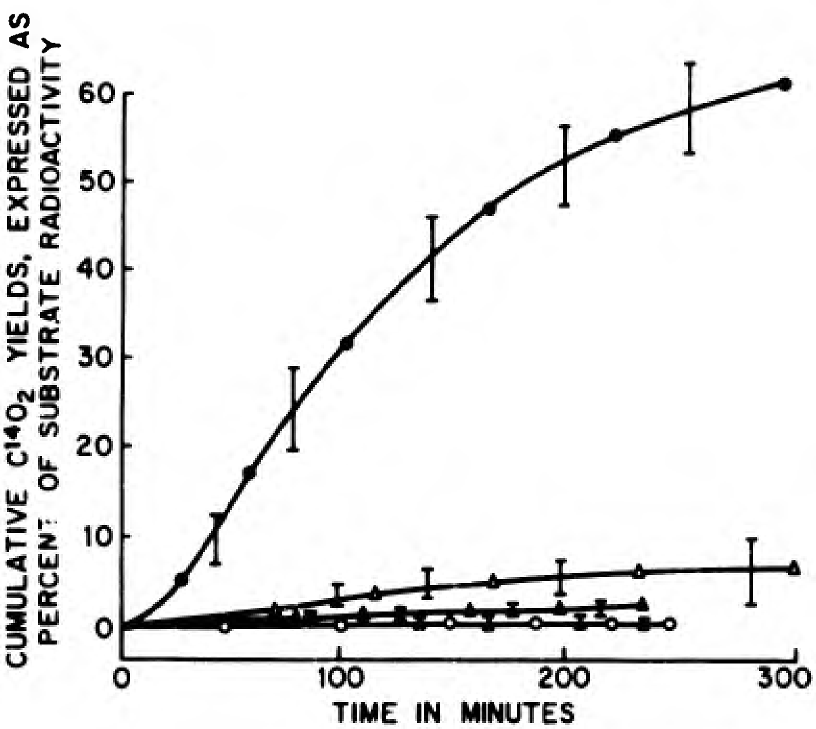
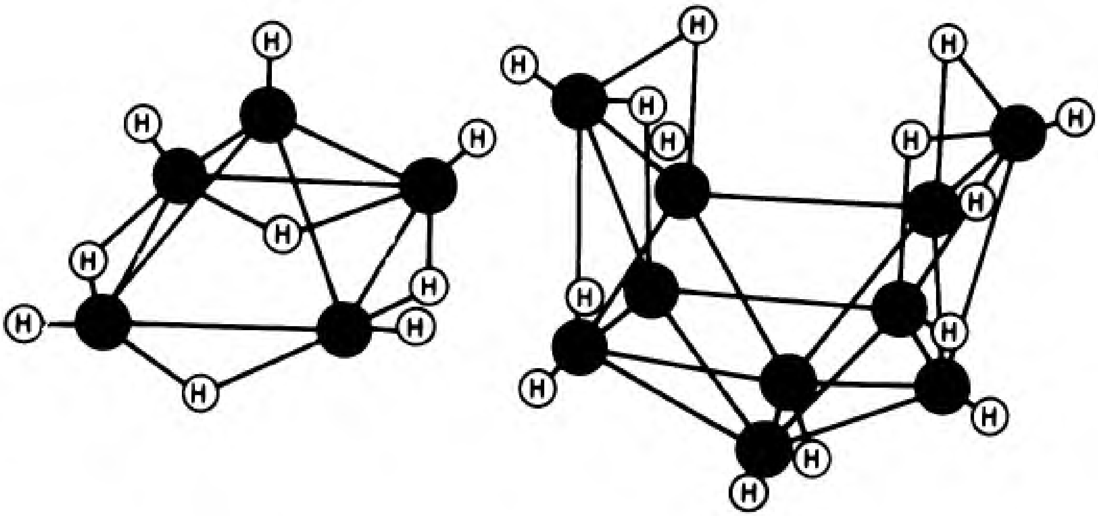


Figure 3. Effect of UDMH and MMH on the catabolism of putrescine-1, 4-C^{14} (6.2μmoles/kg) to $C^{14}O_2$ by rats. Symbols are as follows: ●, control rats; Δ, rats given 0.13 mmole/kg of UDMH by i.p. injection 30 minutes prior to putescine-1, 4-C^{14}; ▲, rats given 1.33 mmole/kg of UDMH by i.p. injection at the same time as putrescine-1, 4-C^{14}; O, rats given 0.04 mmole/kg of MMH by i.p. injection 30 minutes prior to putrescine-1, 4-C^{14}.
(AMRL - TR - 64 - 113)

the same. Hence, work is being done to see if this phenomenon can be used to stunt the growth of other plants including trees without effecting fruit. This has obvious economic importance.

I should now like to turn to some of the recent work which has been performed on borane toxicology. For those of you who are unfamiliar with the steric chemistry of pentaborane and decaborane, they are found in figure 4. Since pentaborane is relatively difficult to work with because of its flammability characteristics, we have chosen to do most of our work with decaborane, a solid. Pharmacologically, the differences between these two compounds are not too great. It has been known for quite some time that the effects of decaborane were manifested by marked depression, catatonia, muscular fasciculations, and occasional convulsions (for a review, see Merrit, 8). Dr. Delgado and I have shown that electroencephalographic chang-



B_5H_9
PENTABORANE
(LIQUID)

$B_{10}H_{14}$
DECABORANE
(SOLID)

Figure 4

es seem to be localized in the hypothalamus or structures intimately associated with these areas (9). In addition, Dr. Reynolds and myself had shown that primate performance using trained monkeys was markedly changed for long periods of time following the injection of single doses of 2-4 mg/kg decaborane (1). Table IV shows the performance of an animal who is given single doses of 2 mg/kg over a period of 4 months. It is obvious that there was no accumulation of effects of the compound since the animal returned to baseline performance in about the same time period following each injection.

Table IV

PERFORMANCE DECREMENT IN MONKEY WITH REPEATED INJECTION OF 2 MG/KG DECABORANE I. P.

DATE INJ.	HOURS AFTER INJECTION PERFORMANCE BELOW BASELINE	HOURS AFTER INJECTION NO PERFORMANCE	RETURN TO BASELINE
10 FEB	29	51	144
24 FEB	22	27	99-164*
9 MAR	27	29	80-96
6 APR	24	24	104-168*
20 APR	24	25	104-168*
4 MAY	24	24	104-168*
RANGE	22 - 29	24 - 51	96-177

*Weekend intervened

At the same time that we were performing these experiments, Dr. Hine and co-workers and Drs. Wykes and Merritt at SAM were trying to elucidate the exact mechanism of action of these central nervous system effects (11, 12). Without going into minute details both groups have shown that decaborane decreases both brain serotonins and norepinerine levels in the rat (Figure 5). This is similar in some respects to the effects of reserpine and LSD. In considering some of the behavioral activity of decaborane in

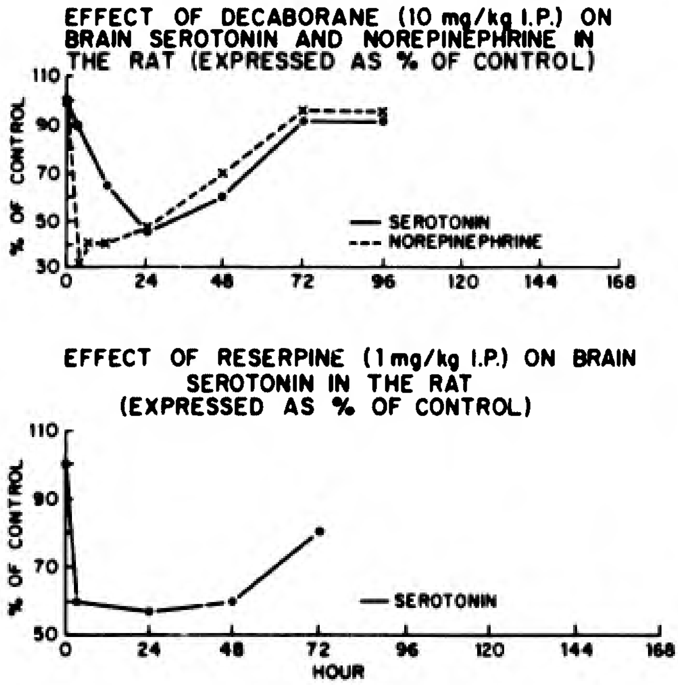


Figure 5

the monkey, it occurred to me that this compound may also be halucinogenic, and therefore, a poor man's LSD. To bolster some of the ideas on mechanism of action, Dr. Wykes has published on the efficacy of pargyline (an MAO inhibitor) as an antidote against the toxicity of decaborane (13). I consider the works of Merritt and Wykes to be major breakthroughs on the pharmacology and therapeutics of decaborane. Of interest is another property of decaborane which we have studied quite by accident in our laboratories (14). Major R. Ziegler and I have studied the lactogenic properties of decaborane in monkeys and dogs (Table V). While we were studying performance decrement in monkeys at Holloman AFB, we found that the only female monkey used began to lactate spontaneously a couple of days after injection. On returning to our laboratory, we gathered all the female monkeys we had at the time and exposed them to 4 mg/kg decaborane. As can be seen, the animals lactated within 24-72 hours after injection lasting from 9-40 days. The dog was not effected so easily and only two of six animals lactated. More recently, Captain Gale Taylor, in our group, exposed a female goat to multiple doses of decaborane and did obtain some milk. As

Table V

LACTOGENIC ACTION OF DECABORANE IN MONKEYS AND DOGS

ANIMAL	SECRETION (HRS) FIRST	PEAK	DAYS DURATION
MONKEY (Dose = 4 mg/kg ip)			
R15	36	72	--
1	72	120	10
2	72	--	9
A19	36	168	40
A17	36	96	15
A21	24	96	26
A29	48	120	10
U63	48	144	10
DOG (Dose = 2 + 2mg/kg ip in 72 hrs)			
1	48	--	18
2	24*	--	--
3-6	N O N E		

*Following second dose

far as I know, the only other compound with this kind of activity is reserpine.

I should like to spend the remaining time briefly outlining some of the work being performed on fluorine containing oxidizers and propellants. Some of the compounds are classified. However, we will use letter designations for classified compounds. Since we do not know exactly which fluorine containing compounds may be picked for future use, we have tried to study at least some of the compounds by chemical grouping much the way that pharmaceutical analogues are studied pharmacologically. For instance, F. W. Weir, Dr. C. H. Hine, et al., have studied the acute toxic effects, metabolism, and pharmacological activity of 4 organic NF compounds designated as NFPA, TVOPA, PFG, and R. It was found that these compounds were relatively highly toxic (15). The intraperitoneal LD_{50} in rats were 25, 215, 140, and 155 mg/kg, for NFPA, TVOPA, R. and PFG, respectively. Excretion of fluoride at the administration of NFPA or TVOPA accounted for approximately 15-30% in the urine. Pharmacological studies in anesthetized dogs demonstrated respiratory, cardiovascular, and hemodynamic changes after NFPA and TVOPA. Hypertension, tachycardia, and hyperpnea were observed immediately after administration followed by hypotension, increased hematocrit, and continued tachycardia and hyperpnea. Pretreatment with phenoxybenzamine blocked the pressor response; bilateral vagotomy eliminated the respiratory effects. Further studies now in the process of publication indicate that NFPA and TVOPA are degraded in the body to inorganic fluorides and cyanide ions which are responsible for the majority of the toxic effects seen (16). PFG and R on the other hand appear to act by different mechanisms and PFG has been demonstrated to block oxygen uptake by hemoglobin while Compound R produces methemoglobin (17). Both PFG and R also appear to metabolize to cyanide. To give you an idea of the concentration necessary to produce toxic effects, the median lethal concentration for 4-hour exposure to PFG was 4.4 ppm. The Threshold Limit Value for fluorine is 0.1 ppm and the TLV for HG is 3.0 ppm, so one can see that this compound is highly toxic.

As you all are aware, the subject of fluorine toxicity has great national importance since many communities are upset with regard to purposely placing fluorine in drinking water. We in the Air Force, therefore, must look at all aspects of the use of fluorine containing compounds. Of high present interest is a compound which we have called AMOX (NF_3O). Dr. C. C. Lee of Midwest Research Institute has studied the toxicological and metabolic aspects of this compound and has contributed greatly to some new aspects of the metabolism of fluorine of which we were not aware in the literature heretofore (18).

The acute inhalation toxicity of AMOX appears to be due to severe pulmonary irritation as evidenced of edema formation and extensive pulmonary hemorrhage. The LC_{50} of AMOX for adult male rats at the end of 7 days after acute exposure for 4 hours, 60, 30, and 15 minutes was 24.2, 87-104, 119-140, and 202-240 ppm, respectively. The acute inhalation toxicity of AMOX was greater for mice; the LC_{50} for a 4-hour exposure being 17.5 ppm. Of marked interest was the finding seen in Figure 6. The total fluoride concentration of the thyroid increased quickly after AMOX administration and reached a peak level at the seventh day at which time the concentration was 17 times higher than that of blood. The concentration of fluoride in the thyroid returned to the normal range of the control rats about 4 to 6 weeks after AMOX administration.

As expected, both the femur and teeth of control rats contained high concentrations of total fluoride. After AMOX administration, concentrations of fluoride in femur and teeth increased and reached peak levels at about 1 to 7 days. The total fluoride disappeared gradually from the femur and teeth, and concentrations in these two tissues returned to the normal levels of the control rats about 2 weeks after administration.

The majority of the administered fluoride following AMOX was excreted in the urine. An average of 61.1% of the administered fluoride was excreted in 7 days, with 33.6 and 20.2% of the dose excreted during the first 2 days, respectively. These rats excreted a total of 9.7% of the administered fluoride in the feces in 7 days.

The interesting phenomenon of fluoride concentration in the thyroid is being pursued further. Since the thyroid preferentially held increased a-

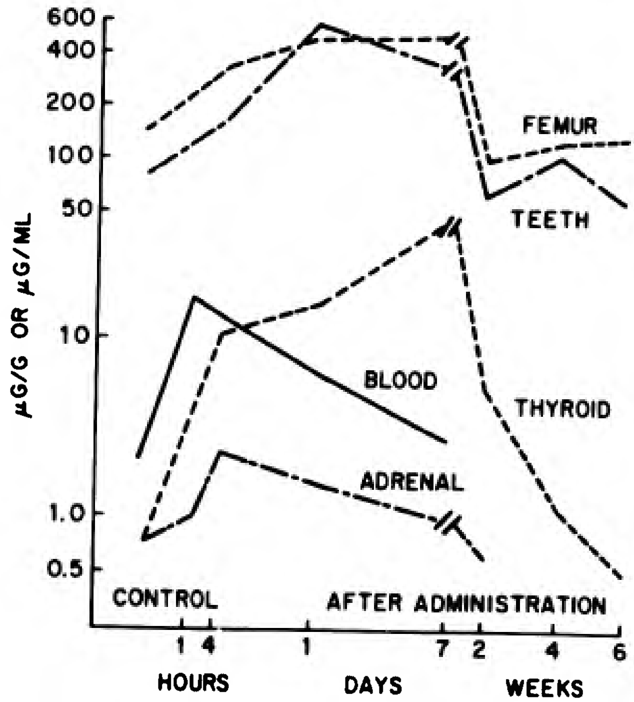


Figure 6. Total Fluoride Concentration in Blood, Adrenals, Thyroid, Femur and Teeth of Control Rats and Rats After AMOX Administration.
(Dr. C. C. Lee AMRL-TR-66-110)

mounts of fluoride for two weeks following administration, it will now be necessary to learn whether fluorine concentration physiologically affects thyroid function. Basic studies are currently being performed by members of our group to find out if the increased thyroid fluoride content is associated with basic metabolic rate changes, thyroid size, incorporation of thyroid fluoride ion into thyroid hormone, and/or effects of thyroid function on the pituitary-thyroid and pituitary-adrenal axes. Wouldn't it be extremely interesting if this uptake produced formation of a compound such as trifluorothyronine?

As one can see, we have enough work with the compounds now known to be of interest for future propulsion systems to keep us busy for many years. Each compound has its own individual pharmacological and toxicological peculiarities and must be treated as a single entity. It is quite evident that we must delve into many different facets of medical disciplines in order to supply the medical officer, the bioenvironmental engineer, and the systems managers with the necessary data needed to cope with the handling, storage problem, industrial medicine and occupational medicine aspects of missile propellants. Only with the combined efforts of the pharmacologist, toxicologist, biochemist, and pathologist can we supply the knowledge necessary to set emergency tolerance limits, Threshold Limit criteria and therapeutic measures involved with possible exposures of toxic compounds in the emergency situation around missile sites.

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Personal Hygiene and Sanitation In Aerospace Systems

Dr Alton E. Prince

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PERSONAL HYGIENE AND SANITATION IN AEROSPACE SYSTFMS

Alton E. Prince, Ph. D.

The medical-biological problems in any space system include those related to personal hygiene and sanitation. Some of us interested in the microbiological phases of these areas thought at first there might be severe problems to be solved before people should venture on long term space missions. Many of our earliest fears have not been substantiated to date, but I believe that we must develop design criteria from carefully planned, ground based experimentation so that problems, if there are any in these areas, are reduced to a minimum. We are attempting to answer some of our questions from information and data gained during a three year study presently being completed.

The primary purpose of this study was to elucidate the nutritional requirements of healthy young men confined for various periods of time under selected. simulated space system environments. More than forty healthy young men participated as subjects in the twelve experiments successfully completed during these investigations, which were a joint effort between the Air Force Aerospace Medical Research Laboratories and the National Aeronautics and Space Administration. Since some of everything we take into our bodies does come out and therefore establishes the requirements for personal hygiene and sanitation, it seems important to include, with the nutrition studies, integrated experiments which would assist in establishment of criteria for personal hygiene and sanitation in space systems. We were real good at dreaming up problems that might happen within the enclosed environmental conditions of space systems as we understood them, but I do not believe that any of us were prepared for one of our first lessons in practical microbiology. In the middle of our first experiment, from routine microbiological sampling, cultures on blood agar showed that one subject had haemolytic streptococci in his throat. The next day, when two more subjects reported sore throats, all four were sent to the hospital for a complete diagnosis and required treatment. The subject who had the strep infection never had a sore throat during the time he was under observation and treatment. The two subjects with the sore throats did not have streptococci that could be isolated, and the fourth subject had neither a sore throat nor the streptococci. Needless to state, following this experience, throat cultures were required from all candidate subjects for the remainder of these experiments.

During these studies we tried to measure everything we could that went into the subjects as well as that which came out. The information gained about the microbial bionomics of the forty healthy young men is unique and is being utilized to formulate preliminary criteria on personal hygiene and sanitation during extended space missions.

Procedures to be followed during the investigations were established first (1). The main portion of our microbiological studies were accomplished during the last two years of the nutritional experiments (2, 3). .We believed at first that one of the main sources of microbial contamination in a space system might be the human solid waste products, as well as body surface areas, and it seemed essential to have a better delineation than was in the literature as to the kinds and number of microbes that could be expected from these sources. Our studies were design·d as much as possible to give information and data that would serve not only to establish preliminary criteria in the areas of personal hygiene and sanitation, but also furnish guidelines for follow-on experiments.

To give a perspective as to the overall extent of the microbiological phaces of these studies, someone started counting the initial isolations and resulting cultures and found that there were about a nalf million primary cultures and over a million secondary isolates handled during the first year of these studies. I plan to present representative, pertinent facts, mostly on the body surface microbes resulting from our experiments.

Sampling was accomplished periodically and the frequency of sampling during some of our experiments is given in table I. The results showing

TABLE I FREQUENCY OF SAMPLING

Body Area	Experiment Number					
	V*	VI*	VII*	VIII*	IX*	Total**
Scalp	4	4	3	3	3	17
Ear	14	16	16	16	3	65
Eye	14	4	3	3	3	27
Nose	14	16	16	16	12	74
Gingival					12	12
Mouth	4	16	16	16		52
Throat	14	16	16	16	12	74
Axilla	14	16	16	16	12	76
Forearm	4	4	3	3	3	17
Umbilicus	14	4	3	3	3	27
Groin	14	16	16	16	12	76
Glans penis	14	16	16	16	12	64
Anal fold	14	4	3	3	12	36
Feces	10 (2) men 11 (2) men	12 (2) men 14 (2) men	14	14	12+1●	64-66
Toes	4	4	3	3	12	26
Electrode area				2	3+1 ●	5(6)
Room Areas						
Tables						
Fore	20+1●	16	19	16	13	84
Aft	20	16	19	16	13	84
Floor Personal Hygiene Area	20	16	19	16	13	84
Bed	20	16	19	16	13	84

● 1 extra sample taken
* Numbers represent one man, for total experiment multiply by 4.
** Totals should be multiplied by 20 for the total number of samples taken.

the total bacterial count from each body area sampled on one subject is given in table II. You will note the cycling in the total number of microbes present, and each area seems to be independent of every other area. The areas sampled included the scalp, ear, eye, nose, mouth, throat, axilla, forearm, umbilicus, groin, anal fold, and between the toes. Of these the groin and axilla seem to be the best to show differences. No matter what was done to the subjects, the overall microbial bionomics did not seem to change as shown in table III. In this experiment a sweat test was conducted to

TABLE II MICROBIAL POPULATIONS ON SELECTED BODY AREAS

Body Area	Dilution	Sampling Period															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A Areas																	
Ear	10^{-3}	3	15	2	0	2	1	0	360	4	22	10	3	0	58	8	0
Nose	10^{-3}	141	85	243	11	54	72	150	69	145	166	118	195	71	210	96	130
Mouth	10^{-5}	274	358	507	200	tntc	503	tntc	248	162	524	200	258	86	52	84	310
Throat	10^{-4}	1000	905	400	114	tntc	550	148	511	tntc	390	300	185	316	257	550	56
Axilla	10^{-3}	500	250	19	80	16	450	312	500	tntc	550	tntc	650	625	tntc	650	tntc
Groin	10^{-4}	71	840	1150	2	45	80	374	tntc	193	525	800	258	94	277	86	165
Glans penis	10^{-4}	92	109	675	0	2	36	47	500	36	40	225	220	75	448	161	22
Feces	10^{-5}	125	72	33	217	42	70	100	n. s.	2000	500	206	n. s.	33	480		
B Areas																	
Scalp	10^{-3}	10	n. g.								24					42	
Eye	10^{-3}	6	13								3					18	
Forearm	10^{-3}	53	1								1					7	
Umbilicus	10^{-3}	0	1								0					90	
Anal fold	10^{-4}	230	tntc								99					500	
Toes	10^{-3}	350	tntc								n. s.					n. s.	

tntc = Too numerous to count
n. g. = No growth
n. s. = No sample

TABLE III MICROBIAL POPULATIONS ON SELECTED BODY AREAS
Subject 33

Body Area	Dilution	Sampling Period															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
A Areas																	
Nose	10^{-4}	224	167	100	130	303	100	21	3190	23	43	2600	3300				
Gingival	10^{-4}	810	13	20	2	6	133	156	970	380	103	49	880				
Throat	10^{-4}	590	670	8600	1950	2720	1060	Cont.	5530	3260	1210	1590	1760				
Axilla	10^{-4}	21	>8000	1320	3750	10000	4550	1300	>6000	7920	870	4700	>8000				
Groin	10^{-4}	2380	6550	5400	15100	10300	3680	7200	>10000	69700	14000	72400	15500				
Glans penis	10^{-4}	1	144	1	36	12	34	26	381	1810	318	753	850				
Anal fold	10^{-4}	1200	5630	1650	18000	5000	11600	3700	1810	6120	2400	7030	2840				
Feces	10^{-6}	141	153	217	131	106	> 511	147	96	579	187	165	399				
Toes	10^{-4}	8500	>14000	n. s. sweat test	5000	n. s. sweat test	3400	7800	39600	22500	47400	>110000	>45000				
B Areas																	
Scalp	10^{-4}		21							280			760				
Ear	10^{-4}		1							250			151				
Eye	10^{-4}		5							1			3				
Forearm	10^{-4}		1							179			>527				
Umbilicus	10^{-4}		2450							8670			-4290				
Electrode	10^{-4}		not wired							1			400				

Feces - additional count taken prior to start of experiment - 275 measure body loss of nutrients by this means. The test involved very careful and repeated bathing procedures. If the periods were not marked it would not be possible to prove with any degree of certainty that special cleansing of the body surfaces was accomplished. The relative numbers of microorganisms at the axilla and groin of four subjects are shown in table IV. Table V presents a summary of the kinds of microorganisms found on the axilla, and table VI shows those that were found in the crotch and anal area. While there are some differences, other body areas were

TABLE IV TOTAL AEROBIC MICROBES AXILLA AND GROIN

EXPERIMENT IX

		Sampling Period											
		1	2	3	4	5	6	7	8	9	10	11	12
33	Axilla	21	>8000	1320	1550	9680	4550	1300	6000	7920	870	4700	> 3000
	Groin	2380	6550	5400	25100	10300	3680	7200	10000	69700	14000	72400	15500
34	Axilla	222	149	140	~9000	4070	174	644	8330	~7000	tntc	780	4130
	Groin	1110	3280	2960	6520	23300	2070	4750	6950	3060	6700	15500	15300
35	Axilla	1040	4110	1280	2490	5140	2140	2960	~6400	Contam	960	7000	> 6020
	Groin	130	2900	2470	13700	540	930	6650	~12000	22500	22000	5000	11800
36	Axilla	N. G.	670	1450	X	4480	58	130	3260	123	250	175	2640
	Groin	2120	2050	5760	8000	4100	2040	2750	8800	17800	4800	3500	14000

X = Spreader
N. G. = no growth
tntc too numerous to count

TABLE V OCCURRENCE OF VARIOUS MICROBES ON THE AXILLA

	Subject Number																			
Microflora	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Aerobacter		x	x	x																
PPLO													x							
Streptococcus	x																			
Corynebacteria	x	x	x	x		x	x			x	x	x	x	x	x	x	x	x	x	x
Micrococcus	x		x	x																
Bacillaceae	x			x		x	x		x	x										
Proactinomyces	x		x	x	x	x	x	x	x			x								
Neisseria		x	x	x	x										x					
Staphylococcus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Sarcina	x	x															x			
Obligate anaerobes	x																			
Facultative anaerobes		x	x																	
Mimae		x																		
Yeast							x													
Gaffkya																x				
Helminthosporium sp.									x											
Mycelia sterila											x									
Nitrate negative rod									x											
Haemophilus								x												

TABLE VI. OCCURRENCE OF VARIOUS MICROBES - ANAL AREA

Microflora	Subject Number																			
	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
E. coli		x	x	x		x	x		x						x					
Aerobacter				x		x														
Alcalescens dispar						x									x					
PPLO	x	x	x	x					x	x			x	x						
Streptococci			x	x	x	x	x	x	x	x	x	x								
Corynebacteria	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Micrococci	x		x																	
Clostridium					x															
Alcaligenes				x																
Lactobacillus							x	x												
Bacillaceae		x				x	x	x												
Proactinomyces				x	x		x	x												
Neisseria											x									
Anaerobes	x	x	x	x																
Staphylococcus	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Obligate anaerobes	x	x	x	x																
Facultative anaerobes	x	x	x	x																
Candida					x															
Trichosporium							x			x	x									
Sarcina	x	x													x					
Scopulariopsis sp.									x			x								

found to be much less complicated as to their microbial populations. One of the more common and important microbial relationships was found to exist between the staphylococci and corynebacteria. It appears from these studies that the corynebacteria, at least, in part, control the population growth of the staphylococci. This needs verification but what we saw many times is illustrated in figure 1. This shows that the corynebacteria are keeping the staphylococci under some degree of control. I call it natural control. In our studies, even though the subjects were using the very minimum of body cleansing procedures, except in the first experiment, the microbial bionomics of the individuals never reached a stage where special treatment was required.

I would like to follow the corynebacterial - staphylococcal relationship, as we saw it, a little farther. In table VII is shown the relative numbers of these two microorganisms in the nose, on the axilla, in the groin and between the toes of one subject. An interesting point here is, that even though we changed the environment of the subjects twice, there is no evidence that the

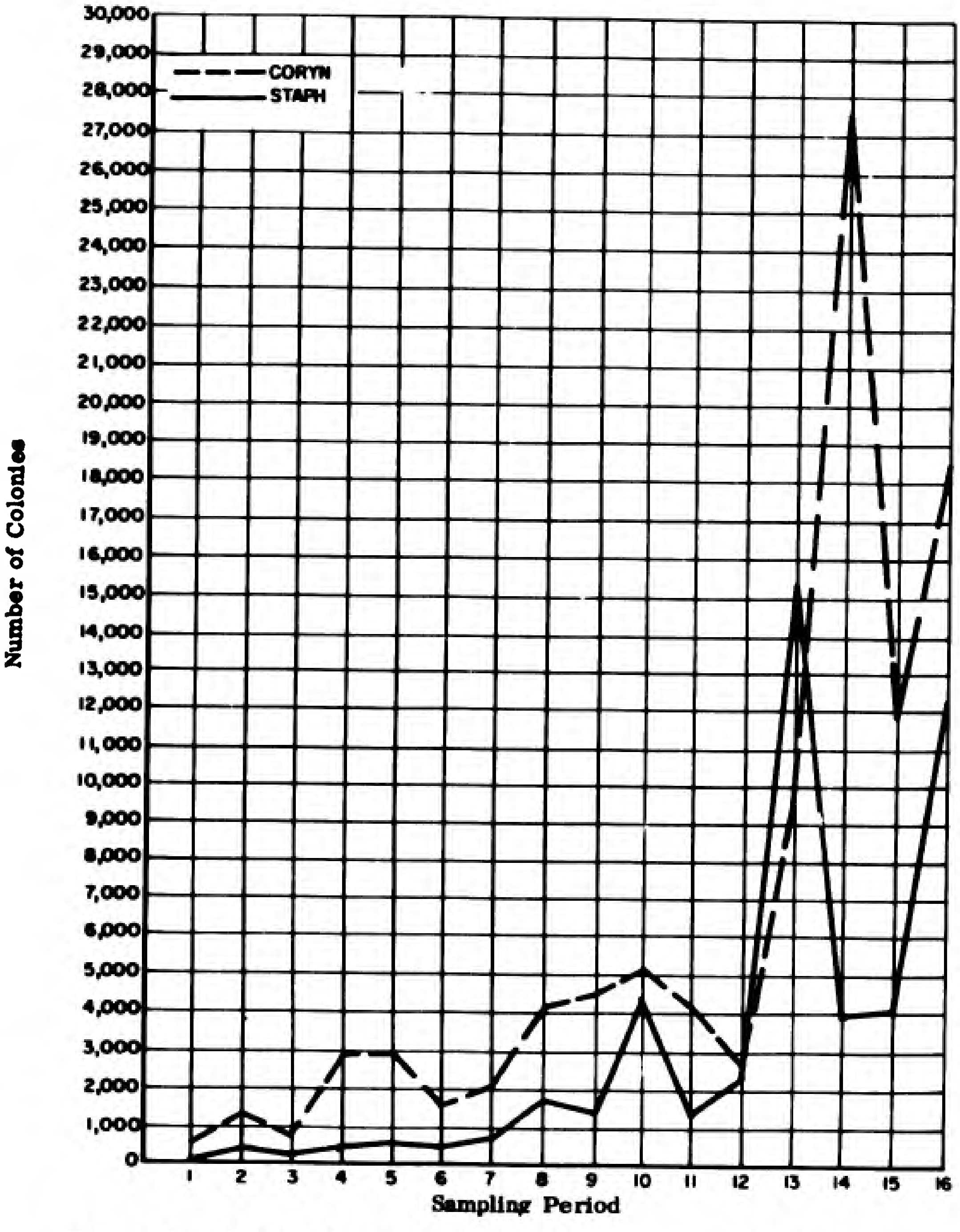

Figure 1. Relative Populations of Staphylococci and Corynebacteria.

TABLE VII OCCURRENCE OF CORYNEBACTERIA AND STAPHYLOCOCCI

Subject 37

		Sampling Period										
		1	2	3	4	5	6	7	8	9	10	11
Ear	Coryn.							5000				0
	Staph.	1						30				0
Nose	Coryn.	230	1000	9320	92	8800	192	569	205	480	289	10
	Staph.	159	34	320	47	2810	12	17	64	620	55	480
Groin	Coryn.	2700	>1000	0	146	>8000	4540	> 8000	3170	>5000	2370	3860
	Staph.	1100	544	230	36	2130	2220	3600	470	4650	640	2350
G.P.	Coryn.	4500	2440	0	0	155	5500	4550	256	60	1000	740
	Staph.	250	1970	20	500	334	3500	3320	13	2	20	180
Axilla	Coryn.	0	0	0	0	10	110	153	130	10	0	11
	Staph.	3	2	7	103	750	1950	660	560	700	230	52
Toes	Coryn.	25000	300	3000	520	NS	NS	NS	2100	940	5300	52400
	Staph.	16200	25100	20200	150				1540	680	3000	28800

NS = No sample; subject in evaluator

Data x 10^4 - total bacteria/gram

kinds and numbers of microbes on the body surfaces were altered by the changes. The distribution of some gram-positive rods, which includes the corynebacteria, is shown in table VIII, and the biochemical reaction patterns used in the identification of the corynebacteria studied are in table IX.

In the last of our series of experiments we had the same four subjects for a total of ninety days. The microbiological phases were carried out during the first sixty of these days.

We believed that our efforts should be more concentrated than previously and elected to sample only the gingiva, groin and feces. We will examine the results obtained from the gingiva and groin.

The sampling was done Monday, Tuesday and Wednesday of each week. Sweat tests were conducted between sampling periods 9 and 10 and before, during and after 19, 20, and 21. For the first forty-five days, dry paper towels were the only form of cleansing utilized on the exterior body surfaces. Moistened wipes were utilized for the next ten days. The teeth were cleaned with a tooth brush and water which was swallowed. A rubber tipped inter-dental stimulator was used as desired. Now that is about the minimum in

TABLE VIII. OCCURRENCE OF GRAM-POSITIVE ROD BACTERIA

Subject 37

Experiment X

Sampling Period	Lacto-bacillus	Bacil-laceae	Corynebacterium						
			striatum	pseudodip-theriticum	Pattern A	Pattern A1	Pattern B	Pattern B1	Pattern B2
1	feces		groin, gp, anal	nose, forearm	umbilicus		toe	g. p.	
2			groin, gp, anal	nose	nose	anal, gp			
3			gr, anal	nose	nose, ax	gr, anal			
4	feces		gp, anal	nose	groin				
5	feces	anal	nose	gr, anal				g. p.	
6	throat, gingival feces	g. p.	groin, g. p. anal		nose groin, anal	anal			
7	feces		anal			groin			
8			g. p.		groin, gp, toe, anal	anal	g. p.		
9	feces		axilla	groin	groin, gp, toe, anal	anal g. p.			
10	throat feces		g. p.	nose, gp	nose, gr, axilla, gp, toe, anal	anal			
11	feces		umbil	g. p.	eye, g. p. gr, umbil	anal	groin		

TABLE IX BIOCHEMICAL REACTIONS OF CORYNEBACTERIA

Pattern	Litmus Milk	Gelatin	Starch	Nitrates	Glucose	Sucrose	Loeffler's	Nutrient Agar	Tellurite	Morphology
A	no change	growth negative no liquefac-tion	growth no acid	-	-	-	pinpoint to small colony almost translucent at the top of the slant but opaque and cream colored in the heavy growth areas	small grey-white slightly opaque	grey-black colonies	pinpoint almost translucent to small grey slightly opaque
A1*	no change	growth negative	growth negative	-	-	-	small raised cream	white-grey opaque	grey-black colonies	larger colonies opaque
A		growth no lique-faction		-	-	-				
B	negative	growth negative	growth ± acid	±	acid	acid	small raised glisening slightly trans-lucent at top but cream and opaque at bottom	small colony grey-white slightly opaque	black colonies irregular clumps	grey opaque
B1**	negative	growth negative	growth ± acid	+	acid	acid				
B2	ARC*** with prote-olysis	growth negative	growth ±	+	acid	acid	small cream	medium grey-white slightly opaque	black	grey opaque

* A1 almost identical to A except in colonial morphology

** B1 probably identical with B except acid is produced in sucrose

*** ARC - acid reduced curd

personal hygiene procedures we could devise. Of the four subjects, subject 44 had the greatest numbers of microbes, the other three had fewer and were similar to each other. I have elected to show the results obtained from subject 41. Table X contains these data, and it can be seen that microbial inhabitants never went out of control, and we did not expect them to increase beyond, what I consider, natural controlled populations. You can see the usual cycling effect and evident differences in numbers between the groin and gingiva. We do not believe that there are important differences in total numbers between the left and right side of the groin, but there was some evidence of different kinds of microbes in these two areas.

Let us look at the relationship between the staphylococci and corynebacteria of subject 41 as shown in table XI. Here again the corynebacteria seem to have the staphylococci well under control. To establish the natural control of potentially pathogenic kinds of microbes by pure saprophytes, a considerable amount of investigation is still needed. Natural control of potentially harmful microbes may be a desirable solution to microbe problems on very long space missions, since natural control would reduce the danger of microbic shock.

TABLE X BACTERIAL POPULATIONS GROIN AND GINGIVA

Subject 41

Body Area	Dilution	Sampling Period												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Groin (left)	10^{-4}	1080	9790	3330	750	2910	1120	1180	2950	2900	850	750	4280	3520
Groin (right)	10^{-4}	3280	-	-	5490	9000	5520	5060	16270	33500	1700	1380	4870	1640
Gingiva	10^{-4}	7000	tntc	193000	-	100	30	30	1359	2190	130	81	1111	285

Body Area	Dilution	Sampling Period												
		14	15	16	17	18	19	20	21	22	23	24	25	26
Groin (left)	10^{-4}	1990	1247	1140	986	1198	2100	520	2950	1950	2270	1970	1070	1840
Groin (right)	10^{-4}	350	583	800	1699	1133	2820	1090	1610	670	650	1790	1090	1790
Gingiva	10^{-4}	24	99	145	1051	828	202	363	566	82	30	750	69	575

Confluent growth

TABLE XI CORYNEBACTERIAL AND STAPHYLOCOCCAL POPULATIONS - GROIN

Subject 41

		Sampling Period												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Groin (Left)	Coryn.	960	9560	2850	740	2840	1110	1130	2870	2810	840	710	4060	3320
	Staph.	100	230	480	10	70	10	50	80	90	10	40	220	20
Groin (Right)	Coryn.	2900	-	-	5490	7000	5500	5000	16000	32700	1700	1340	4790	1420
	Staph.	370	-	-	0	2000	20	60	270	700	0	40	80	220

		14	15	16	17	18	19	20	21	22	23	24	25	26
Groin (Left)	Coryn.	1890	1000	1080	864	925	2090	450	2210	1630	1940	1070	780	1440
	Staph.	100	247	60	1	173	10	70	740	320	330	900	290	400
Groin (Right)	Coryn.	320	426	770	1576	1056	2810	1060	1600	560	510	1490	820	1650
	Staph.	30	157	30	123	77	10	3	270	110	140	300	270	140

- = Confluent growth

Data x 10^4 = total bacteria/gram

Representative isolates of Staphylococcus aureus were phage typed and the complex 52/52A/80/81 which is considered one of the strains resistant to antibiotics was found during 18 of the 26 sampling periods. It was isolated from both the environment and the subjects. This is an aspect that must be reviewed very carefully in future studies.

During our previous experiments, the room or chamber where the subjects were confined were all cleaned as carefully as possible, but during this experiment, the air was sprayed with distilled water and the flat surfaces, such as tables and floor, were cleaned as carefully as possible with a quaternary annonium compound.

Concerning individual cleansing of body parts by the subjects, only dry paper towels were used during the first 45 days. They were permitted wet wipes, paper wipes moistened with water as desired for the next 10 days, but one subject elected to use none, one subject used four per day and the other two subjects used two wipes per day.

I believe that our experiments have shown that for 30 days, body cleansing in a space system may be a matter of personal preference. This may be true up to 45 or 60 days but by then other factors such as hair growth on the head and face, nail growth on the fingers and toes, and contamination of work areas may well cause changes that will require routine cleansing schedules. It may be that properly treated continuous wear undergarments and socks may prove useful in the control of surface body microbes, if really needed.

We have evidence that the subjects contributed to the microbial populations of their environment, but our areas of confinement were not sufficiently sealed to be certain of this.

From the information presented and other work completed I would like to recommend the following personal hygiene and sanitation procedures for extended space missions up to 30 days.

1. Body surface should be cleansed with disposable paper wipes moistened with plain water as needed. An average three per day per person is considered sufficient.

2. Teeth should be cleansed once per day with a tooth brush and plain water which will be swallowed. The rubber interdental stimulator should be used as desired.

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Space Weather Forecasting

Brigadier General Ernest A. Pinson

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SPACE WEATHER FORECASTING

Brigadier General Ernest A. Pinson

It is indeed a pleasure to meet with such a distinguished international group of dedicated people who are working in the field of aerospace medicine.

I had an intimate acquaintance and association with aviation medicine back in the thirties and during World War II when it was my privilege to work with Captain Harry G. Armstrong, Captain Otis O. Benson and the late Doctor Randolph Lovelace at the Aero Medical Laboratory at Wright Field. As many of you know, Randy was one of the great pioneers in aerospace medicine and his life was devoted to advancing the knowledge in this highly specialized field of research.

Therefore, when Colonel Nuttall invited me to speak to you this evening I was delighted to accept and talk to you for a few minutes about some research we are doing in OAR today.

It is somewhat removed from aviation medicine, but I thought it would interest you. It's in the area of space environmental forecasting.

This research is conducted by the Air Force Cambridge Research Laboratories (AFCRL) which is OAR's largest in-house laboratory and the focal point for all environmental research in the Air Force.

In the spring of 1961, at the request of the Air Force Systems Command, we entered the age of space environmental forecasting. The Systems Command needed to launch space vehicles at times when they could be confident of having no encounter with any solar flare activity.

The early predictions of the dangers from solar flare activity expressed by Doctor John Evans, Director of the Sacramento Peak Observatory, as conditions green, yellow, red and purple were successful, and as a result the list of customers in the Air Force and outside it gradually grew.

Conditions green, yellow and red are obvious. In case you are wondering about condition purple, it was a color picked at random to indicate a proton shower was--in the opinion of the forecasters--inevitable. This places the forecaster in the same position as a doctor predicting a patient's heart attack before it occurs. I am sure you doctors can appreciate the problem of space weather forecasting.

The predictions were made daily for a five-day period at the request of the Air Force Systems Command. They wanted some assurance at least five days in advance that the unmanned satellites would not be affected by the hazards of solar flare activity.

The typical time for the hazards of solar flare activities to reach the environment of an earth orbiting satellite is from two to three hours. However, it can also range from 30 minutes to 12 hours. These same times also apply to the surface of the moon.

The conditions green forecasting no danger of proton showers, have been correct without exception from the beginning. At the outset, our scientists were inexperienced and cautious, and posted condition green only about 30 per cent of the days. As we learned more, about 70 per cent of the days were green. Since the space operators were primarily interested in condition green, the frequency and reliability of these green predictions made everyone happy.

However, proton showers were very rare between 1961 and 1965, occurring on less than one per cent of the days, so this prediction record is not as impressive as it might seem. Most non-green predictions were just false alarms. As long as there were enough green days for practical operations, the false alarms did not matter too much. But our scientists knew the day of reckoning was approaching, when there would be few green day predictions at all unless they could learn a lot more about the sun to distinguish between true danger signals and false alarms.

The predictions were relatively simple because the sun has been inactive. The kinds of active centers around sunspot groups that produce protons were few and far between, and their forecasts never had to deal with more than one at a time.

But things are now changing very rapidly. The sunspot cycle typically shows an abrupt rise from minimum to maximum. It is now about half way up to the expected peak in 1968. Our knowledge of solar activity has increased, and the false alarm rate has gone down, but the number of green days has also gone down simply because the frequency of proton showers is rising. Unless we learn a great deal more about the sun very quickly, we will not be able to post any green days at all within a year or so. The danger signals will always be present on the solar disk.

However, we are doing something about this. In 1965 the Air Weather Service undertook the operational task of forecasting and distributing the forecasts. With the assistance of the Cambridge Research Laboratories and the Sac Peck Observatory, the Air Weather Service has augmented the solar observing network in order to maintain a 24-hour worldwide watch on the sun. Many of their personnel were trained to the job at Sac Peck by Doctor Evans and his staff.

Solar proton showers with appreciable fluxes in the energy range up to several million electron volts are a serious hazard to the increasingly delicate and complex technical devices used in space, and to men in space.

Our minimum goal is to reliably predict at least half of the five-day intervals that will be free of such showers. Our ultimate target, of course, is accurate prediction of the time and intensity of each shower.

Proton showers always originate in major solar flares. Hence, the first problem is to predict such flares. The second problem is to predict which one out of every three big flares will produce a proton shower.

Throughout the sunspot minimum -- 1961 to 1965 -- we have done fairly well with a seat-of-the-pants operation. Here we depend on the "intuition" of experienced observers who, over earlier years, somehow managed to be sitting at the business end of a telescope with cameras cocked and ready for practically every big flare that came along.

The flares always occur in the exceptional sunspot groups surrounded by regions of high activity. By this I mean rapid changes in the sunspots themselves -- the presence of highly structured magnetic fields with steep gradients and a mixture of opposite polarities -- the frequent occurrence of small flares and the peculiarly active loop and surge prominences -- and the emission of certain types of radio burst.

Experience at Sac Peck and elsewhere shows that these are are preconditions for proton flares. Our predictions are simply a matter of identifying these peculiar active centers and distinguishing them from the far more numerous innocuous sunspot groups. The process is not quantitative nor really objective, but it works better than any other method so far devised.

Note that we are depending here on empirical relations discovered by experience, without reference to the physical processes involved. This is certainly a valuable approach, which should be susceptible to considerable improvement.

Doctor Fred Ward at AFCRL has undertaken to systematize the empirical method. He is trying to determine the objective and quantitative relations necessary to remove it from the realm of personal judgment and experience. However, we believe that a real understanding of the flare phenomenon, including the ejection of fast protons, is the soundest approach to the problem. While we continue to look for additional empirical relations, our big effort is in the study of flare physics, and the identification of necessary and sufficient pre-flare phenomena that are observable.

Unfortunately, no one knows just what makes a flare flare. There are a dozen theories awaiting further observational checks during the presently upcoming sunspot maximum. Two of these which were formulated by the

Sac Peak staff to fit the observations, are susceptible to fairly crucial tests with carefully designed observations of a few examples. If either (or both) is basically correct, it would at once provide observational criteria for predictions of dangerous conditions several days in advance, and the nearly certain occurrence of a flare one or more days in advance.

Both of these theories of flare activity rely on the magnetic energy of the active center for motive power. They differ in the method of conversion to kinetic and thermal energy, and it is quite possible that both processes actually occur. The observational tests will involve measurements of solar magnetic fields in active centers and the Doppler velocities of the associated dark filaments. These are well within our present observational capabilities. Naturally, we hope for clear-cut yes or no answers, but are more likely to find the usual ambiguities, requiring minor theoretical modifications leading to further observational checks.

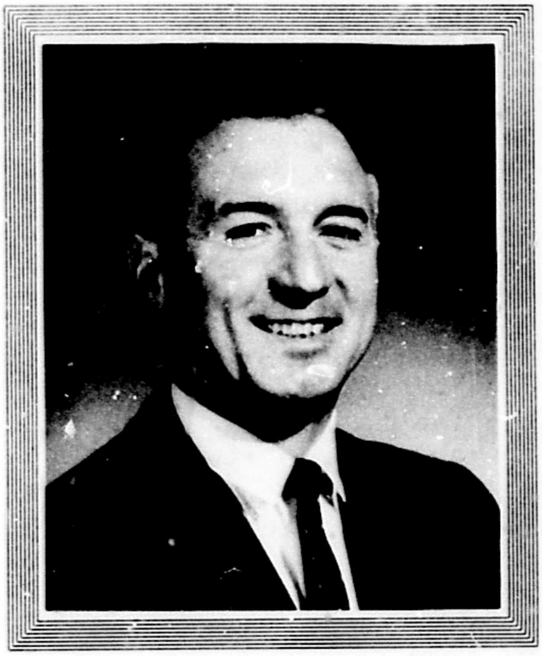
In the process, we will obtain data highly relevant to other flare theories that have been proposed and will be able to help sort out the promising ones.

The primary Sac Peck function now is to do the research required to improve the predictions. For this purpose, we are building the most advanced solar telescope we know how to design. Unfortunately, it will not be finished until late 1968. However, with the fine observing equipment and the competent people we have, we will continue the intensive research program on flares, and I confidently expect substantial improvement.

In the meantime, as you in the field of aerospace medicine investigate ways and means for man to survive, live and work in space, we in the Office of Aerospace Research will work very hard to describe to you the environment that man can expect in space.

Synopsis of the Magnetosphere

Dr R. Stephen White



Dr. White received an A. B. degree from Southwestern College in 1942, an M. S. degree from the University of Illinois in 1943, and a Ph. D. degree in physics from the University of California in 1951. He served in the U. S. N. R. 1944-46, held a position as Head, Nuclear Effects Group, Lawrence Radiation Laboratory 1952-1961, and was a National Science Foundation Senior postdoctoral fellow, Max-Planck Institut fur Physik and Astrophysik 1961-1962. He has been in his present position as Head, Space Particles and Fields Department, Space Physics Laboratory, Aerospace Corporation, since 1962. Professional societies include Phys. Soc. Geophys. Union, American Association for the Advancement of Science, Fields of specialization are mass spectroscopy, photomeson production, electron linear accelerator, K mesons and strange particles, space physics; earth's high energy proton, low energy proton, and electron belts.

SYNOPSIS OF THE MAGNETOSPHERE

R. Stephen White, Ph. D.

I. INTRODUCTION

Exciting new discoveries in the last three years have changed our ideas of the magnetosphere. Magnetic field experiments at more than 30 earth radii, R_e, have given us a new description of the magnetic field around the earth. We now know that the magnetic cavity has a blunt spherical nose in the direction of the sun and a long comet-like tail away from the sun and is not a sphere as we thought prior to 1961. A wind of electrons and protons continually blows from the sun and forms a shock front of 14 R_e from the earth. The solar wind particles are thermalized behind the shock front then continue on to form the boundary of the magnetic cavity.

The magnetic cavity with its boundary at 10 R_e on the sunlit side is shown in figure 1. The magnetic field lines near the Poles are swept back

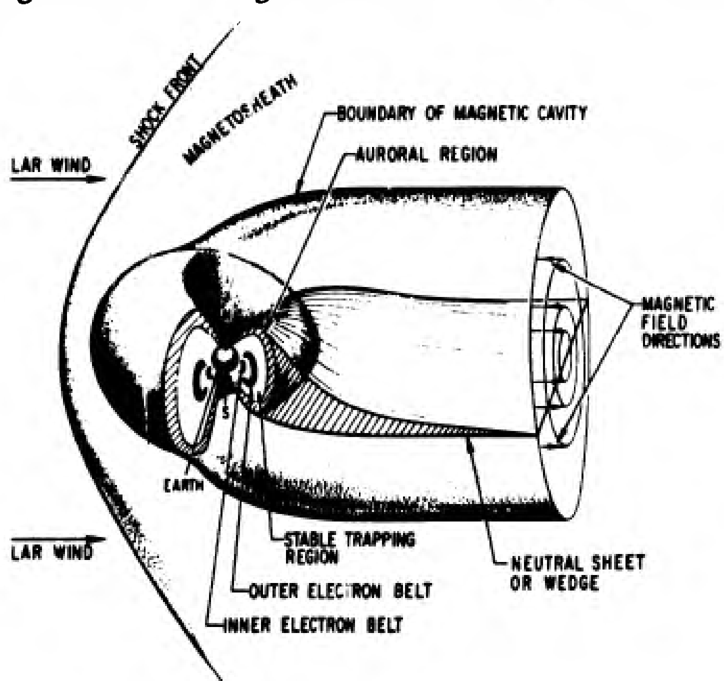


Figure 1. The magnetic cavity. A section shows the earth and the inner and outer electron radiation belts and the region of stable trapping in the sun and anti-sun directions. The neutral sheet or wedge separates the upper half-cylinder where the wind points toward the earth from the lower half-cylinder where it points away from the earth. The neutral wedge connects to the auroral region.

by the solar wind to form the tail. A neutral sheet or wedge extends from the dusk to the dawn side in the magnetic equator of the tail and separates the magnetic field lines that point toward the earth in the north from the magnetic field lines that point away from the earth in the south. The neutral sheet is connected to the auroral zone, a ring about the North and South Poles at 56 deg to 70 deg geomagnetic latitude. In closer to the earth are trapped radiation belts where electrons and protons travel on magnetic shells and have lifetimes that vary from days to years. Extending throughout the magnetic cavity is an atmosphere which is much more dense at altitudes close to the earth.

II. THE ATMOSPHERE

The atmosphere surrounding the earth is necessary for man's survival. It furnishes the oxygen we breathe and protects us from the heat of the sun. The atmosphere varies rapidly in density, temperature, and composition with the height above the surface of the earth. In figure 2, the regions of

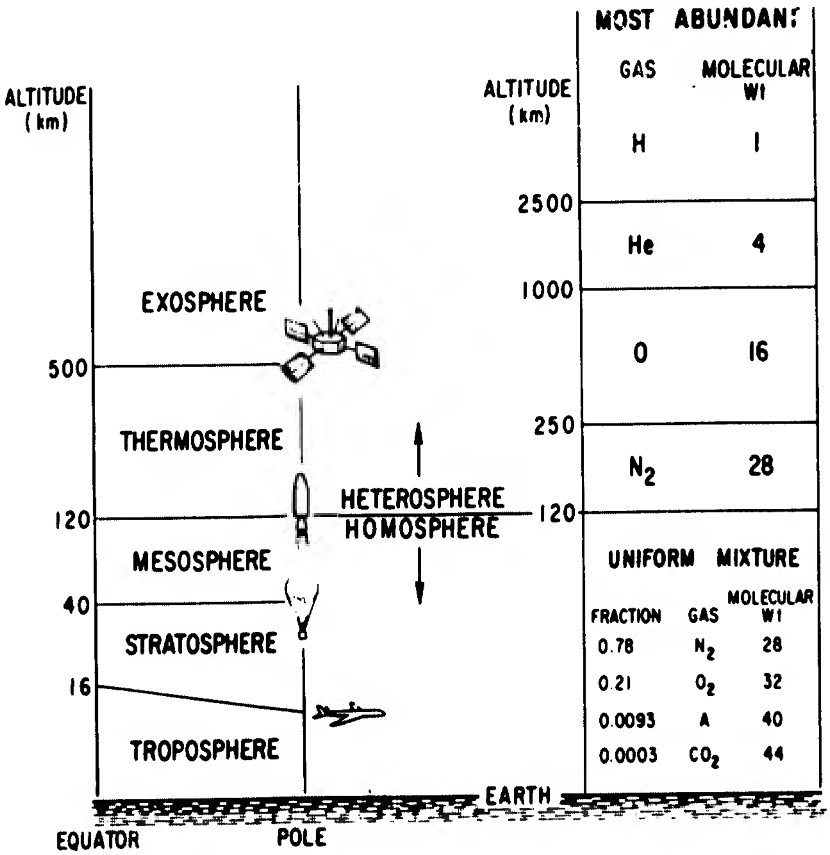


Figure 2. A diagram of the regions of the atmosphere and the most abundant gases. The left half shows the regions of the atmosphere, the right side, the most abundant gases and their molecular weights. Below 120 km there is a uniform mixture of the gases, except for water, which varies with height.

the atmosphere are shown and the major constituents at different heights are indicated. Because of the mixing of the gases close to the earth, the composition is constant up to 120 km except for water vapor.

The earth acts like a giant mass separator for the molecules and atoms of the atmosphere. The gravitational force of the earth pulls the heavier gases in close to the earth so the light gases are higher up. For the atmospheric composition and density here we incorporate the following models: (a) up to 10 km the composition given by List (1), (b) from 10 to 120 km the model of Sissenwine (2), (c) from 120 km to 800 km the CIRA 1965 atmosphere of Harris and Priester (3), (d) from 800 to 3,500 km the drag data of Fea (4), and (e) above 3,500 km the theoretical calculations of Johnson (5). Figure 3 shows the fraction of the gases at different altitudes at an average atmospheric temperature of 1320° K. The altitude is given as a log scale on the ordinate and the fraction of the gas as the abscissas at the boundaries for the particular gas at a desired height. For example, oxygen atoms are 90 per cent at 600 km but only 45 per cent at 1,000 km, where helium is of equal abundance. Above 2,000 km, hydrogen is most abundant.

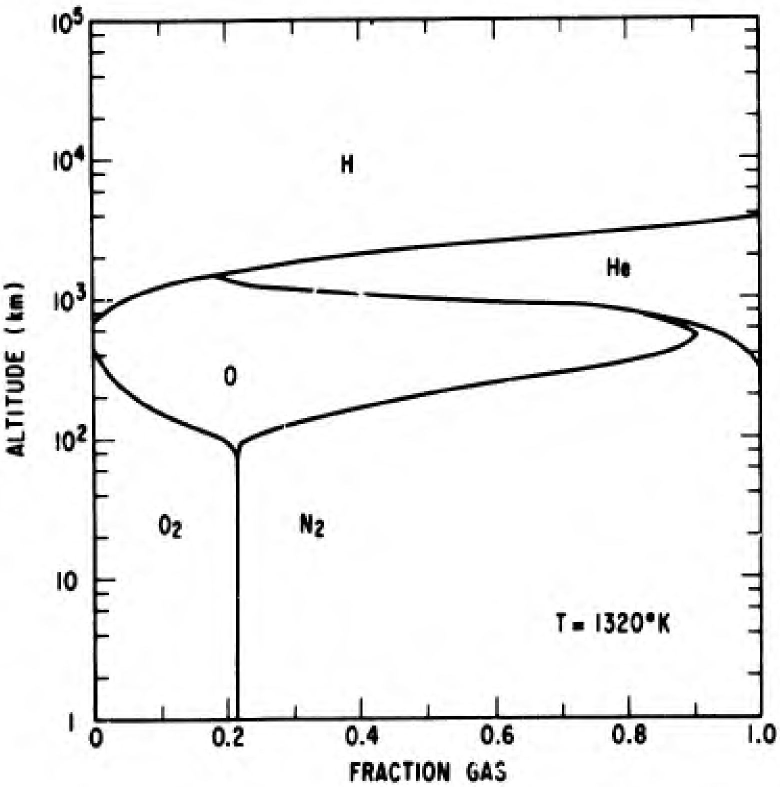


Figure 3. The fractions of atmospheric gases at altitudes from 1 to 10^5 km for temperatures of 705° K, 1320° K, and 1970° K. The fraction of a given gas is found from the horizontal distance on the graph between its two boundaries.

The abundances depend upon the heat input to the atmosphere. This in turn depends on whether it is day or night, or whether it is maximum or minimum of the solar cycle of 11 years. It also varies with the 27-day rotation period of the sun and with magnetic storms. When the heat input is large, the atmospheric temperature is high and the density is higher at higher altitudes. The densities for various temperatures for times of maximum heat input to times of minimum heat input at altitudes between 100 km and 1,000 km are shown in figure 4. The atmospheric density varies extremely rapidly with altitude. At 200 km a factor of 3 change in density occurs with a change in height of 50 km and at 1,000 km a factor of 3 change takes about 200 km.

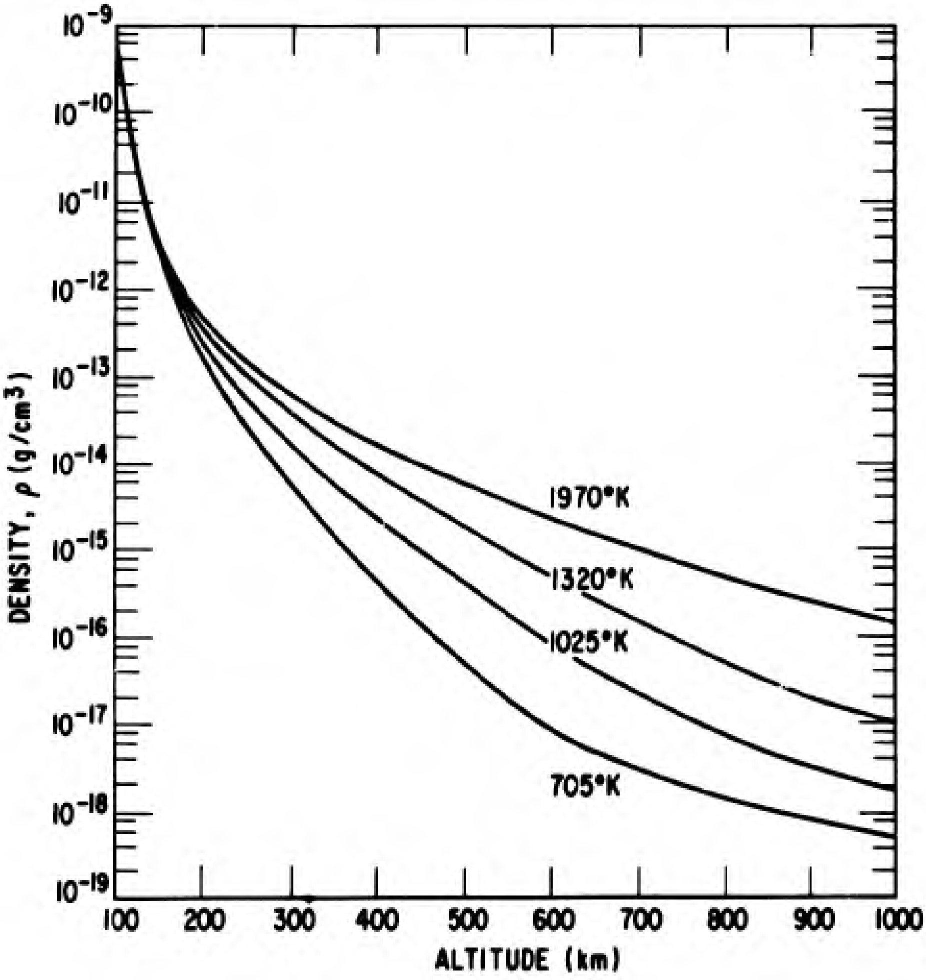


Figure 4. The atmospheric densities versus altitude from 100 to 1,000 km. These densities incorporate the following models: 1) up to 10 km the composition given by List,[1] 1957; 2) from 10 to 120 km the model of Sissenwine,[2] 1962; 3) from 120 to 800 km the CIRA 1962 atmosphere of Harris and Priester,[3] 1965, and 4) from 800 to 3,500 km the drag data of Fea,[4] 1965.

III. RADIATION BELTS

A. High Energy Protons

The earth's radiation belts were discovered in 1958 by Van Allen and co-workers (6) with Geiger counters on the Explorer 1 satellite. They found two large belts, the lower one most intense at 1.5 R_e from the center of the earth and the outer one strongest at 5 R_e. These belts and the motions of radiation belt particles are shown in figure 5.

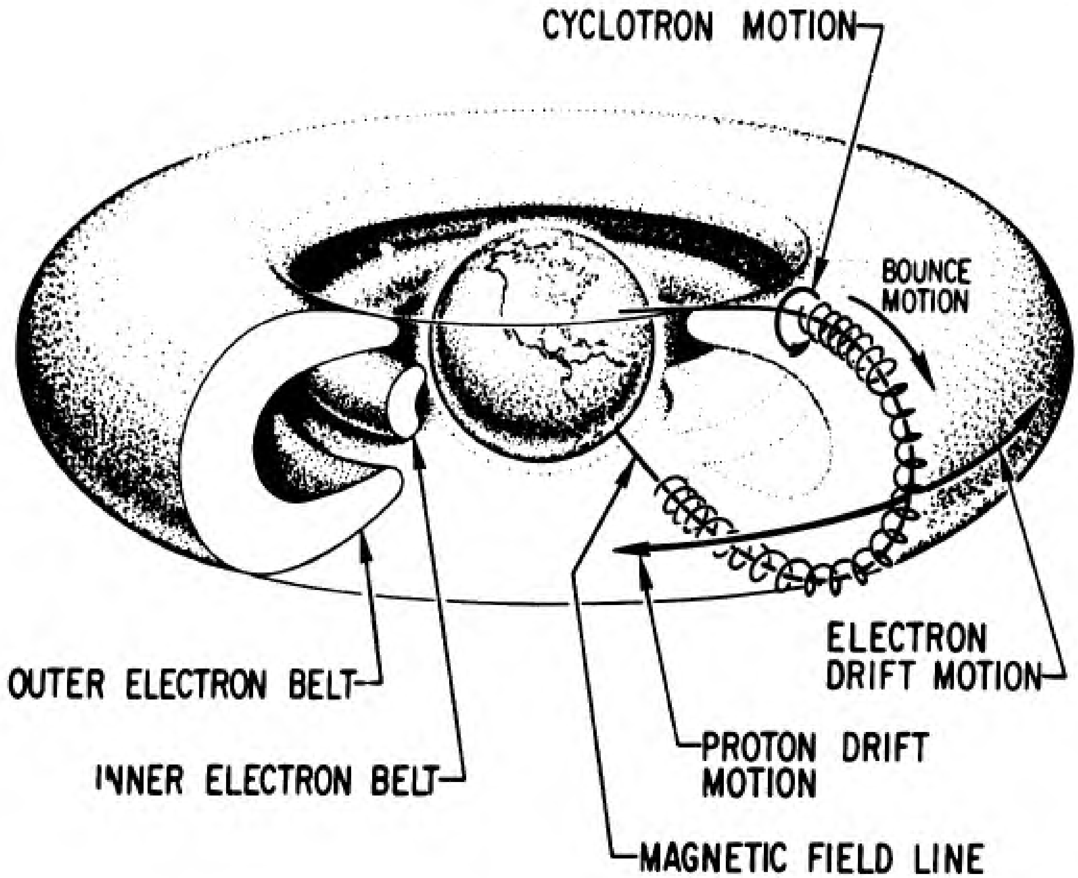


Figure 5. The two electron radiation belts. They appear horseshoe shaped in the cutaway. The cyclotron motion about the magnetic field line, the bounce motion along the line, and the drift motion around the earth are shown. Protons drift westward, electrons eastward. A magnetic L shell is formed by rotating a magnetic field line about the earth's magnetic dipole field change the shape slightly. L is the distance to the shell in earth radii. Each particle always mirrors at its same value of B. The particle motion is thus described by the L shell on which it moves and the B value at which it mirrors. The magnetic shell for L = 5 is labeled. B values in gauss are noted. L values on a radial line are indicated. Taken from White,[7] 1966.

Dr R. Stephen White

A particle trapped in the earth's magnetic field has a circular motion about the magnetic field line called the cyclotron motion. The period for this motion is about a microsecond for an electron and a millisecond for a proton. The particle also bounces along the magnetic field line from one hemisphere to the other. This motion is called the bounce motion and its characteristic time is about one-tenth of a second. In addition, the charged particles move around the earth. Electrons drift east and protons west. The drift motion is present because the magnetic field is weaker outside the magnetic field line than inside and because of the curvature of the magnetic field lines. The characteristic time for the drift motion is about an hour.

It is useful in correlating data to change the three-dimensional system of altitude, latitude, and longitude to a two-dimensional system of the magnetic field, B, at which the particle mirrors and the magnetic shell on it moves, L (8). The shell for L = 5 is shown in figure 5. It has the shape of an automobile tire casing and cross-section of a horseshoe. The particles will continue to mirror at the same value of B and move on the same L shell indefinitely if they experience no additional outside forces.

In 1959 Freden and White (9), with nuclear emulsions from a recovered Thor-Able nose cone, identified the protons in the inner radiation belt and measured their energies up to 700 Mev. Singer (10) suggested that the sources of these protons were the cosmic ray albedo neutron decays; i.e., cosmic ray interactions in the atmosphere which gave neutrons that decayed in the earth's magnetic field into electrons and protons that were trapped, as shown in figure 6. The trapped proton energy distribution (11) was in agreement with this idea and early calculations gave approximately the right fluxes of protons.

The Cosmic Ray Albedo Neutron Decay Theory gives an equilibrium flux of trapped protons that is proportional to the flux of cosmic ray albedo neutrons leaving the surface of the earth and to the injection coefficient. The injection coefficient is the probability that an albedo neutron could decay to give a trapped proton. The flux of trapped protons is inversely proportional to the average atmospheric density experienced by the protons in their trajectories around the earth. The most recent calculations (12) have shown that the calculated flux is a factor of 50 lower than the experimental flux of protons at 55 Mev when the present accepted values for the neutron flux and the atmospheric density are used. Since the neutron flux has not really been measured in the energy interval required, from 20 Mev to 100 Mev, the uncertainty in the neutron flux is quite large. Likewise, the mean atmospheric density is very sensitive to the magnetic field expansion used in the calculation at low altitudes and to the large uncertainties in the atmospheric density model at high altitudes. While the current estimates of the albedo neutron flux and mean atmospheric density indicate that the cosmic ray albedo neutron decay injection is too small to explain the high energy trapped protons, a final decision must await better measurement of the neutron albedo flux and the mean atmospheric density.

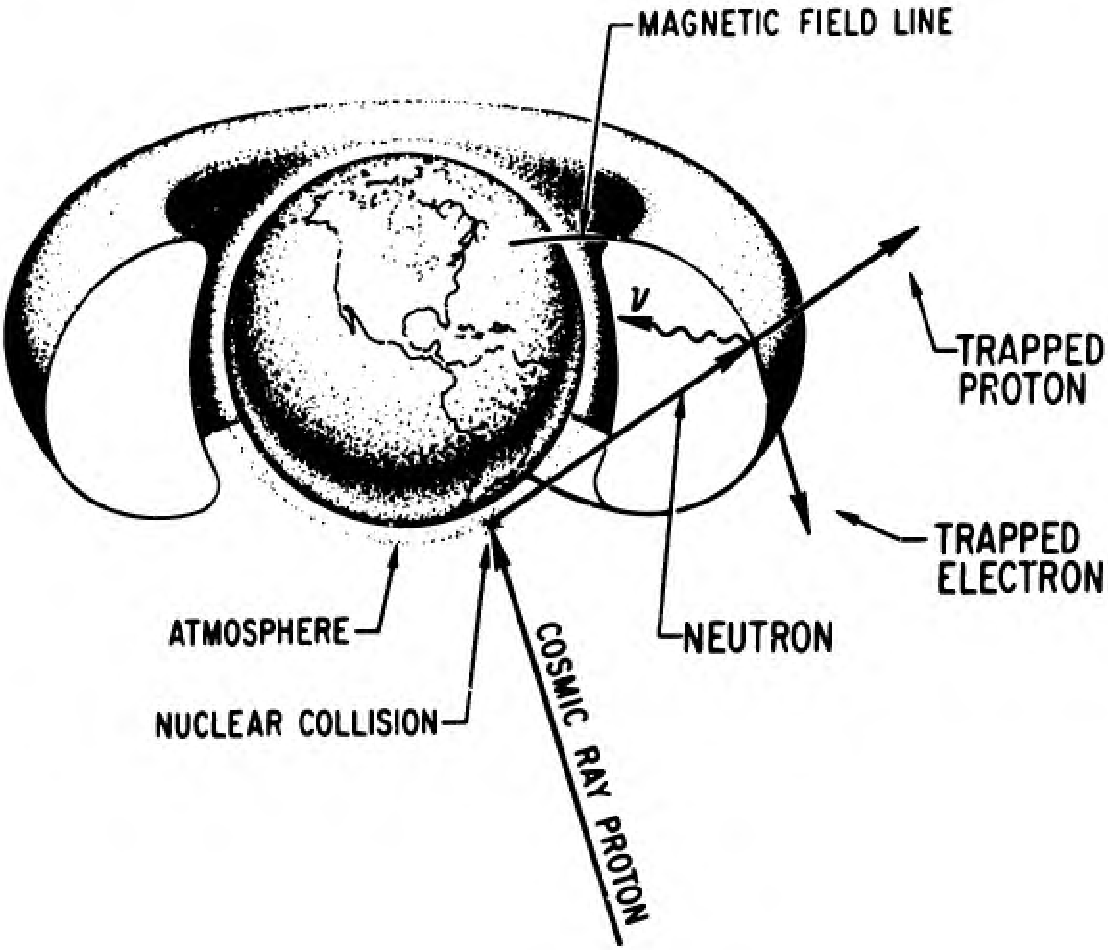


Figure 6. The high energy proton belt. Actually the proton belts are displaced for different energies. 75 Mev protons peak at L = 1.5 but lower energy protons peak farther out. The cosmic ray albedo neutron decay injection, CRAND, is shown. The cosmic ray proton makes a nuclear collision in the atmosphere and emits a neutron. The neutron decays into a proton, electron, and neutrino. The electron and proton are trapped in the earth's magnetic field. Taken from White,[7] 1966.

B. Low Energy Protons

Davis and Williamson (13) in 1962 discovered a large flux of low energy protons with energies from 100 kev to 2 Mev on shells from L = 6 to L = 2. Mihalov and White (14) studied these protons and found that they were concentrated on layers about the earth like the skins on an onion with the lowest energy protons on the highest L shell and the highest energy proton on lower L shells. The separation of these protons is shown in figure 7. Belts at L values of 4.5, 3.5, and 2.5 are shown. The energies of these protons are

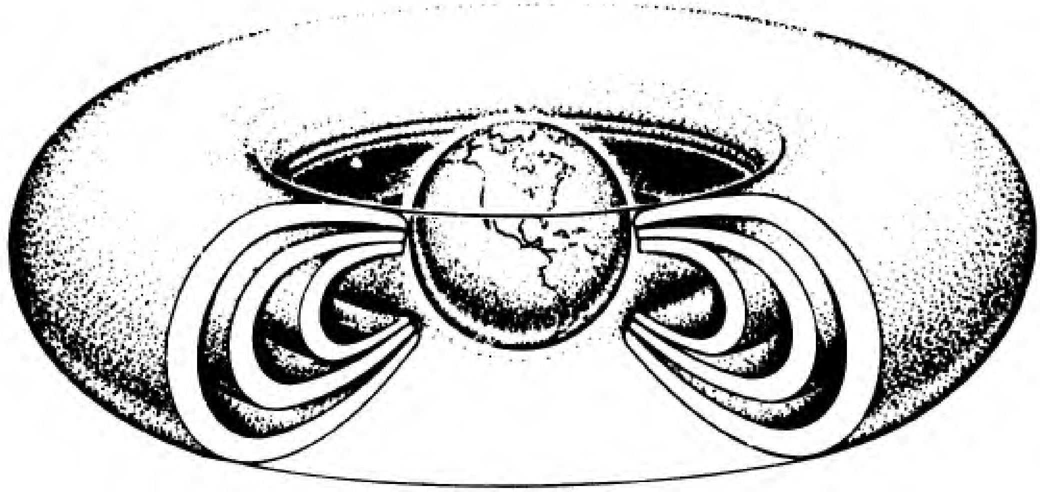


Figure 7. Three low energy proton belts at L = 4.5, 3.5, and 2.5. The belts overlap so that there are no gaps. The lowest energy protons peak at high L values and higher energy protons peak closer in. These belts probably originate from diffusion inward from the solar wind across field lines. Taken from White,[7] 1966.

0.2 Mev, 0.4 Mev, and 1.5 Mev. The shells are not really separated in space as shown here, but merge continuously from one to another. For example, the protons of 0.3 Mev peak between the belts at L = 4.5 and 3.5.

If the protons diffuse inward from the edge of the magnetic cavity at the equator, keeping their magnetic moments constant, the energy increases proportional to L^3, so that EL^3 = constant. This was found to be true down to L = 3, but at lower L values the relationship was no longer satisfied (14).

A mechanism for causing the protons to diffuse inward was suggested by Parker (15). Magnetic field fluctuations at times of magnetic storms cause betatron acceleration in the drift motion. This causes some protons to drift inward and others out. In addition to the diffusion, Nakada and Mead (16) considered the losses of protons by charge exchange and ionization and derived energy and position distributions for protons that drift in at the equator. The data of Mihalov and White (14) off the equator was compared to these theoretical distributions. The general ideas of diffusion inward keeping the magnetic moment constant appear to be satisfied down to about L = 3, but there are disagreements in detail between the experiment and the theory.

If the low energy protons originate in solar wind protons that diffuse inward from the magnetic cavity boundary, they must start at L = 10 with about 10 kev. Thus the problem is not solved, only transferred to explain how and where solar wind protons of 1 kev are accelerated to 10 kev.

C. Electrons

There are presently two large electron belts separated by a large slot, as shown in figure 5. The inner electron belt with a peak at L = 1.35 was produced by the injection of electrons in the Starfish nuclear explosion at 400 km on July 9, 1962. These electrons have a fission spectrum with a peak at about 1 Mev. There were initially about 3 x 10^8 electrons/cm^2-sec but they have since decayed away with a mean lifetime of one year. Electrons from the Russian high altitude explosions on October 22, 28, and November 1, 1962, also injected electrons at L values from 1.75 to 2.2 but these rapidly disappeared with much shorter lifetimes. The earliest artificial injections were those from the Argus explosions in 1958 at L values of 2.5 and these also decayed away in a few days.

The lower edge of the lower belt is cut off by atmospheric losses. There is an additional large loss mechanism that cuts off the upper edge of the Starfish electron belt. It is not understood. There is an indication that low energy electrons are now appearing above the Starfish electrons (17). These low energy electrons have a much steeper spectrum. If their lifetimes are long (18) the source could be cosmic ray albedo neutron decay injection. If short, a strong source like the solar wind with diffusion inward from the boundary of the magnetic cavity is required.

The electrons in the outer radiation belt peak at L = 5 and have very steep energy distributions. Diffusion of electrons inward has been observed to decrease from the rate of 0.4 R_e/day at L = 4.7 to 0.03 R_e/day at L = 3.4 (19). If electrons diffuse inward from the boundary of the magnetic cavity they do not satisfy EL^3 = constant and therefore do not conserve their magnetic moments (17). Furthermore, if the solar wind electrons are responsible for injection of the electrons they must be accelerated from 1 eV to 100 kev near L = 10. And as in the case of the low energy protons the problem of the electron injection is not solved, only shifted to finding how and where solar wind electrons are accelerated.

IV. THE MAGNETIC CAVITY

A. The Shape

The first measurements of the outer parts of the earth's magnetic field were made by Sonnett and his colleagues (20) on Pioneer I. On a trajectory near the sun-earth line, they found that the magnetic field was close to that of an undistorted dipole from 3 to 7 R_e. However, at greater distances it was larger than expected. Definitive measurements of the shape of the magnetic cavity in the region of the tail were made by Ness and his associates (21) on the Imp 1 satellite. These demonstrated that the magnetic field of the earth forms a long tail with a radius of about 20 R_e in the direction away from the sun. See figures 1 and 8. Ness (22) found a thin neutral

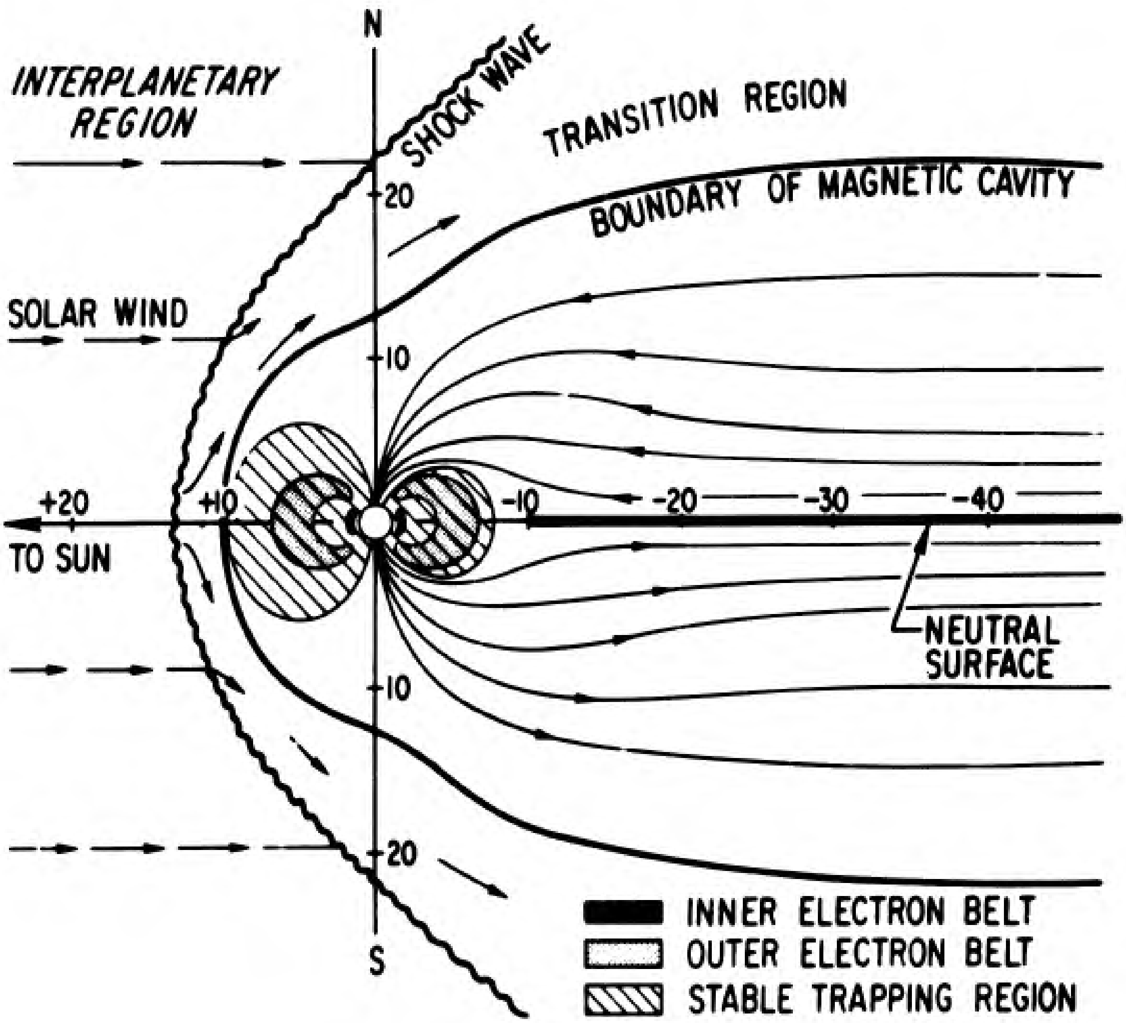


Figure 8. Section through the magnetic cavity taken from Ness,[22] 1965. The shock wave is shown as a wiggly line and the boundary of the magnetic cavity as a solid line with the transition region between. The very heavy line in the direction away from the sun indicates the neutral surface which separates the magnetic field in the northern half-cylinder of the magnetic tail from that of the southern half. The field lines reverse in crossing the neutral surface. The stable trapping region is indicated with slanted lines, the outer electron belt with dots, and the inner electron belt with a black area.

sheet about 600 km thick, where the magnetic field reversed from a direction toward the earth in the northern half-cylinder of the tail to a direction away from the earth in the southern half-cylinder. Out of the sheet in the tail the magnetic field was 20 to 30 γ ($1\gamma = 10^{-5}$ gauss) and gradually decreased at greater distances from the earth.

On the sunlit side of the earth a shock front is formed at the interface between the solar wind and the earth's magnetic field at 14 R_e on the sun-earth line. It flares out at 22 R_e at the poles. Between the shock front and the magnetic cavity the solar wind particles are thermalized in the region called the magnetosheath. Here the magnetic fields and particles are turbulent and varying. The magnetic cavity has a spherical nose with a boundary at 10 R_e on the sun-earth line in the sun's direction which increases to 17 R_e at the poles.

Electron bursts with $E > 40$ kev were found (23) in the tail and were called "electron islands." Low altitude "spikes" (24) of electrons were detected at low altitudes at magnetic latitudes higher than the outer radiation belt. And it was discovered that the fluxes of electrons fell off with the distance from the neutral sheet (25) and that fluxes of electrons were more intense on the dawn side than on the dusk (26).

B. Magnetic Storms

At the start of magnetic storms, the magnetic fields at the earth show slight increases called "sudden commencements." They then decrease by as much as a few hundred γ during the "main phase" and recover to their pre-storm values within a few days. During these storms the aurora moves to lower latitudes. The high latitude trapping boundary to the outer radiation belt decreases with increasing K_p (27) as seen in figure 9. In the outer electron belt electrons with $E > 40$ Kev for $L > 3.0$ increase and decrease

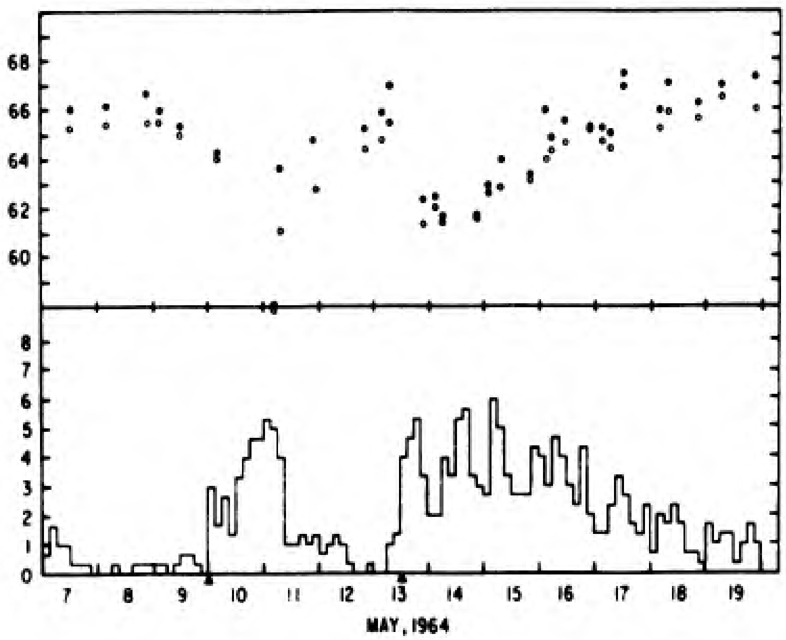


Figure 9. The high-latitude trapping boundary, Λ_c, for electrons with $E > 280$ kev correlated with the magnetic field disturbance index, K_p, during May 1964. The solid dots represent the boundary defined by 1 count/sec and the open circles by 10 c/sec. Taken from Williams and Ness,[27] 1966.

with K_p, as seen in figure 10. But those with $E > 1.6$ Mev decreases as K_p increases (28).

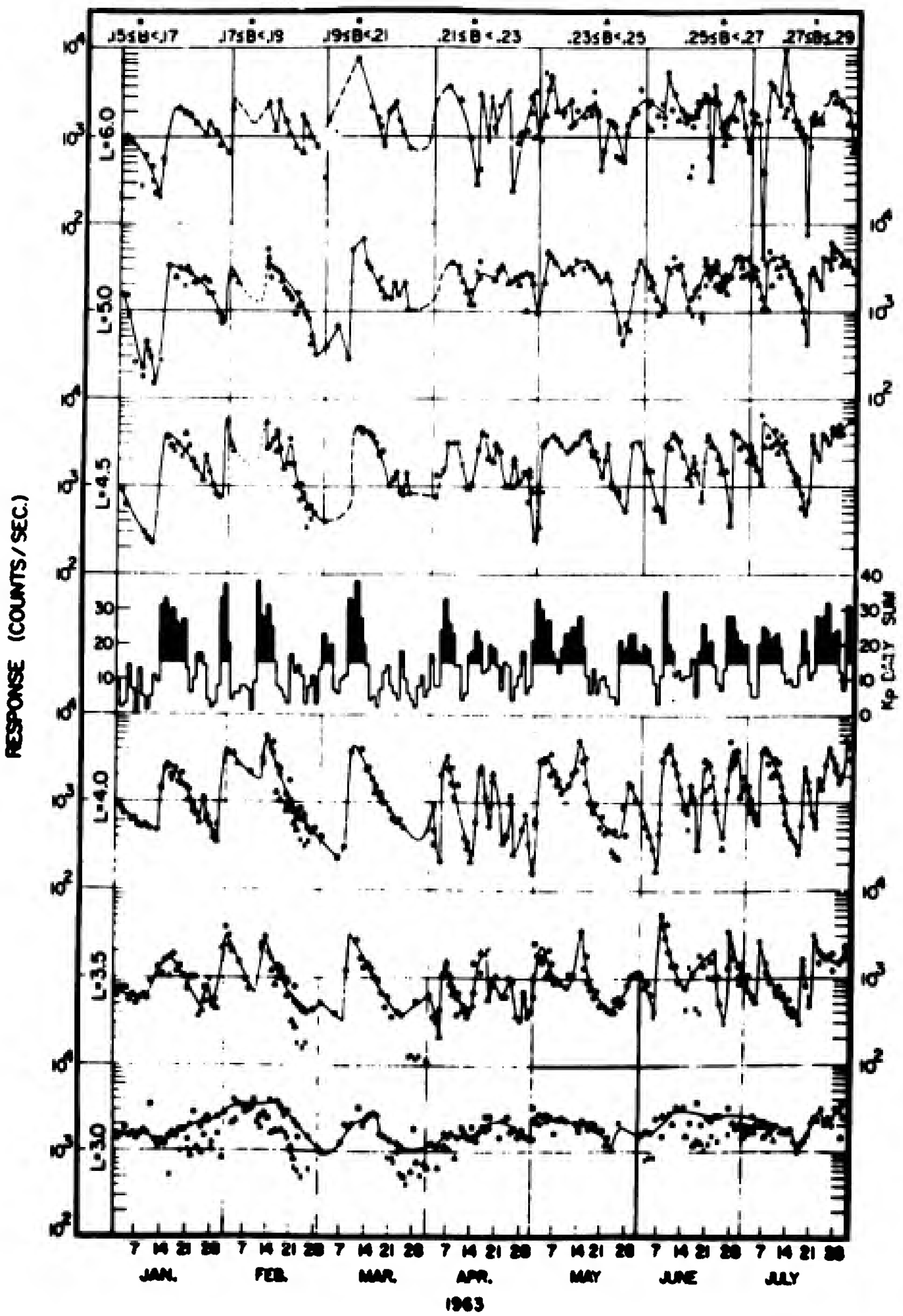


Figure 10. The time variations of the count rates of electrons with $E > 40$ kev on Injun 3 correlated with K_p, taken from Craven,[28] 1966. The L and B values are given.

The horizontal component of the earth's magnetic field decreases during the main phase of magnetic storms and is anti-correlated with K_p. Cahill (29) observed the magnetic field on Explorer 26 during the great magnetic storm of April 17, 1965. He presented strong evidence for the inflation of the inner magnetosphere during the main phase by the temporary injection of large numbers of low energy protons.

C. The Aurora

Eerie greens, blues, and reds are seen in the aurora due to the excitation of atoms and molecules of the atmosphere by incoming electrons and protons. Spectacular photographs taken by Akasofu (30) near Fairbanks, Alaska are shown in figure 11. At the upper left is a quiet diffuse auroral arc and at the top right a similar arc with strong pink light emitted by excited nitrogen molecules. The other four photographs are ribbon-like auroral type active rayed belts.

The positions and movements of the auroral forms were studied by Davis (31). He found that the aurora have maxima near midnight at geomagnetic latitudes from 65 deg to 70 deg. His distributions in geomagnetic latitude at various times during the night are shown in figure 12. These data were taken on 59 nights during 1957-1958.

The energies of the incoming particles that are responsible for the aurora are peaked near 10 kev. The proton energies were first obtained from the doppler shift of the hydrogen light caused by the velocity of the incoming protons. In 1960 an estimate of proton and electron energies was obtained by McIlwain (32) who found that most of the aurora was caused by electrons near 10 kev. Most recently the energy distribution was measured with an electrostatic analyzer on a rocket by Albert (33). His sharp energy distribution peaked at 10 kev is given in figure 13.

Chapman and Ferraro (34) in a series of papers from 1931 to 1933 proposed a detailed model for magnetic storms. It was based on the collisions of particles from the sun with the earth's magnetic field. The distortion of the earth's field was only temporary during the storm. Yet this model is the basis for most of the modern theories of the earth's permanently distorted magnetic field.

Piddington (35), in 1960 suggested that the receding solar gas cloud pulled the magnetic field lines out into the tail. The novel idea of annihilating the magnetic field lines, called merging, was proposed by Dungey (36) in 1961 as a way of introducing energy into the earth's magnetic cavity. This idea was developed and extended in the model of Axford, Petschek, and Siscoe (37). The tangential stresses at the boundary of the magnetic cavity move the magnetic field lines to the rear into the tail. Merging occurs with the interplanetary magnetic field at the nose of the magnetic cavity and in

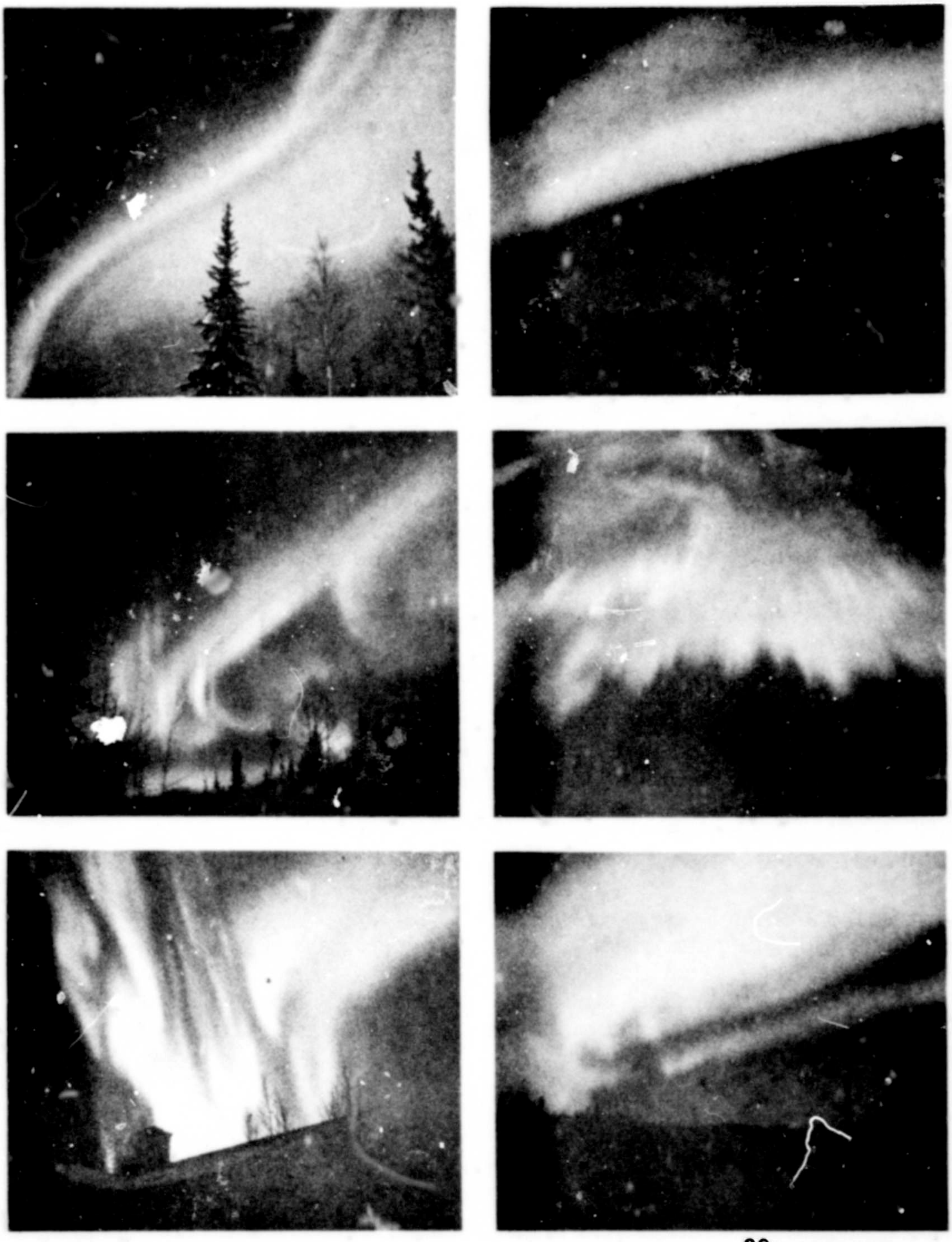


Figure 11. Photographs of the aurora taken from Akasofu,[30] 1965. In the upper left is a photograph of a quiet and diffuse auroral arc. At the top right is a similar arc with pink light from excited nitrogen molecules. The other four are ribbon-like auroral types called active rayed bands.

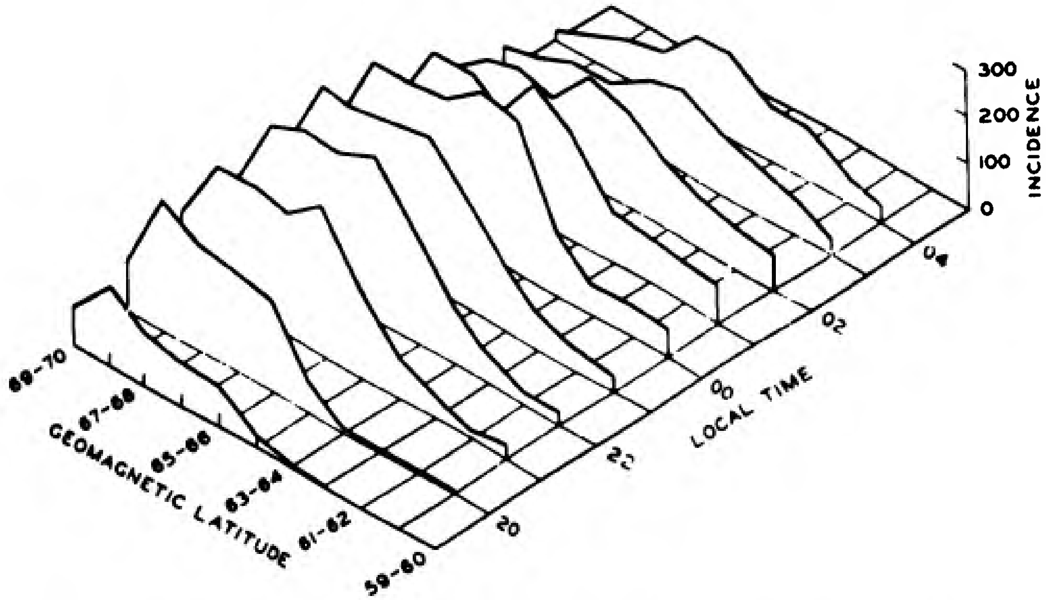


Figure 12. Incidence of aurora versus geomagnetic latitude and local time, taken from Davis,[31] 1962. Data from 59 nights during 1957-1958 were used.

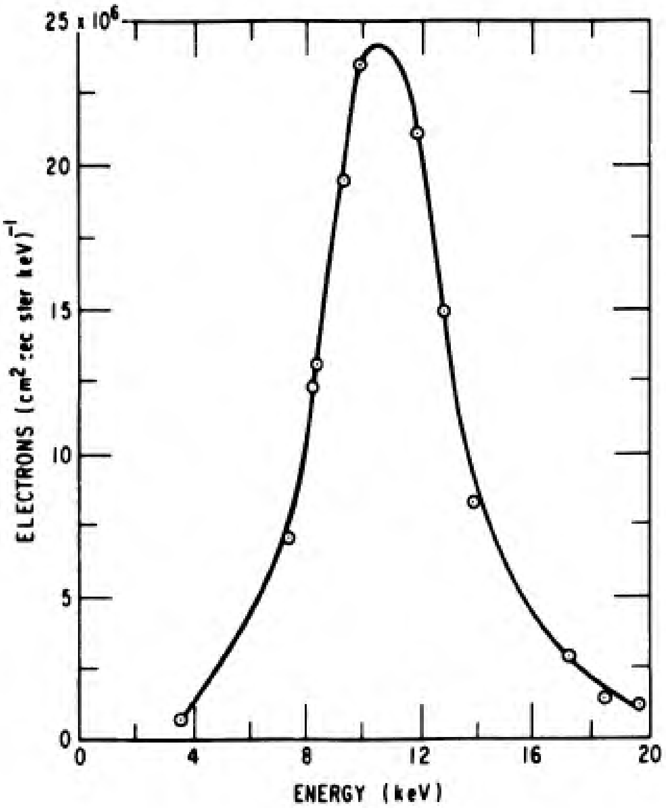


Figure 13. Electron energy distribution measured with an electrostatic spectrometer on a rocket in an aurora. The measurement was at 250 km at Fort Churchill on 16 September 1966. Pitch angles were between 80 and 90 deg. Taken from Albert,[33] 1966.

the tail in the equatorial plane. This annihilation of magnetic field lines is shown in figure 14. A neutral sheet or "wedge" separates the magnetic field lines that are directed toward the earth from those directed away from the earth. The movement of the magnetic field lines toward the merging line, perpendicular to the page, is indicated by the arrows. One magnetic field line moves to the right into interplanetary space while a second closed line moves to the left toward the earth. The closed line is pulled toward the earth and rotates to the sunlit side with the rotation of the earth. It then moves out again to merge with the lines in interplanetary space in the nose of the cavity. The magnetic field in the tail is maintained by the current of charged particles out of the paper in the neutral wedge and the currents into the paper in the magnetic cavity boundaries. A section through the tail in the bottom half of figure 14 gives the directions of the currents.

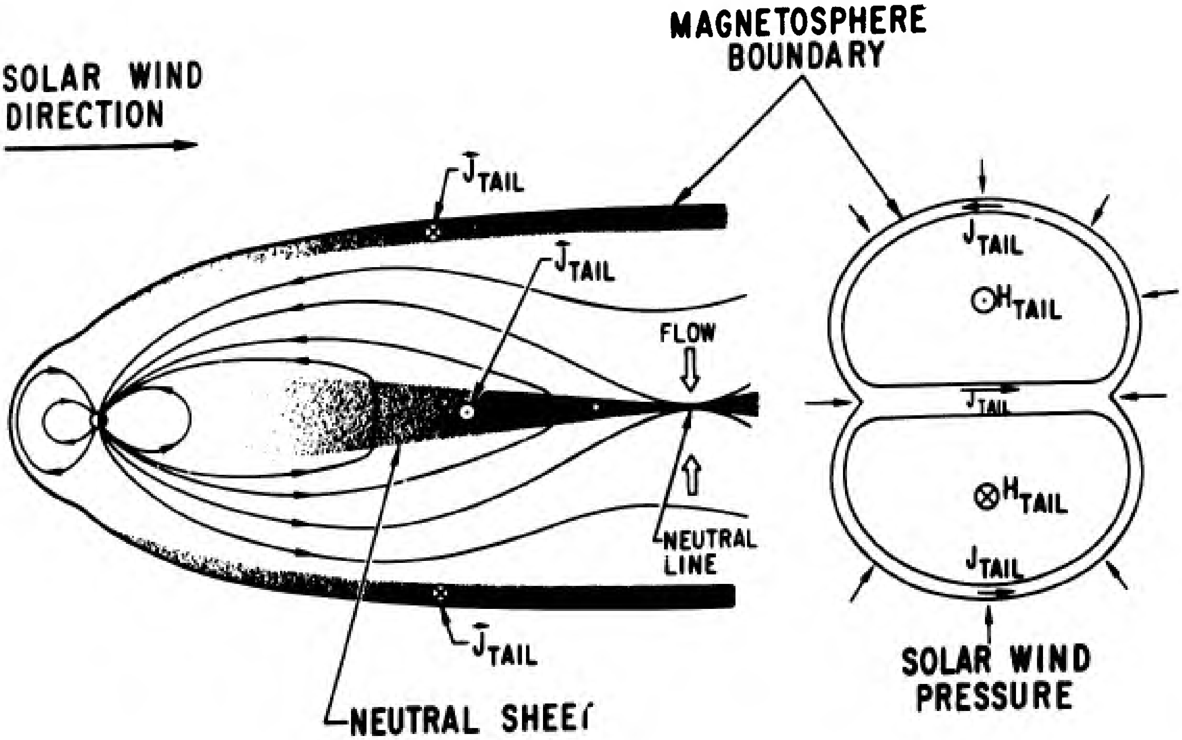


Figure 14. (a) A sketch of the magnetic field lines in the fast merging model taken from Axford, Petschek, and Siscoe,[37] 1965. The neutral sheet or wedge and the magnetic cavity border are shaded. A current out of the paper in the wedge and into the paper in the cavity boundary supports the magnetic field. The magnetic field lines are merged on a neutral line perpendicular to the paper. The arrows show the directions of the magnetic field lines at merging. (b) A cross-section through the tail looking away from the earth. The directions of the magnetic fields and the currents are shown. The arrows normal to the boundary show the solar wind pressure.

Order of magnitude calculations (37) lend credibility to the merging model. The electric field across the tail from dusk to dawn is set up by the annihilation of the magnetic field lines at the neutral line. The induced emf, $\mathcal{E}$, found from Maxwell's fourth equation, is

$$\mathcal{E}\ (\mathrm{eV}) = -\frac{300}{c}\frac{d\Phi}{dt}\ (\mathrm{gauss\ cm^2})$$

$$= -\frac{300}{c}\ BL\, v_B \qquad . \tag{1}$$

Substituting for the length of the merging line across the tail, $L = 40\ R_e$, the velocity of light, c, and for the velocity of the lines toward merging $v_B = 0.1\ v_A$ where v_A is the Alfven velocity,

$$v_A = \frac{B}{\sqrt{4\pi m\ n}} \quad , \tag{2}$$

m is the ion mass in grams. Take B as 20γ and n as 10 ions/cm^3. One finds = 30 Kev. The flow of energy toward the earth is three times the magnetic field energy density just outside the neutral sheet (the 3 comes from the 3 deg of freedom) multiplied by the Alfven velocity,

$$E = \frac{3\ B^2}{8\ \pi}\ v_A \ . \tag{3}$$

This gives $E = 7 \times 10^{-2}$ erg/cm^2-sec and the total energy flux over an area one R_e in height and the width of the tail gives a total energy flux, $E_T = 7 \times 10^{17}$ erg/sec.

This energy flux from merging is enough to supply the total normal energy loss in the aurora estimated to be $1\text{-}4 \times 10^{17}$ erg/sec. The merging energy is about an order of magnitude less than the energy flux in the solar wind of 5×10^{-1} erg/cm^2-sec and the total solar wind energy flux over the nose of the magnetic cavity of 1×10^{19} erg/cm^2-sec.

At times of magnetic storms the energy storage in a temporary magnetic ring may be 10^{18} erg/cm^2-sec. Since the merging energy is proportional to B^3 in Eq. (3), a doubling of the magnetic field in the tail increases the merging energy flux to the earth by a factor of 10.

It is perhaps of interest to compare the energy available from merging to other energy sources. The energy in light from the sun striking the earth is 1×10^6 erg/cm^2-sec or 2×10^{25} erg/sec over the magnetic cavity nose. The energy of rotation of the earth is much higher yet, 2×10^{36} ergs.

Objections (38) were raised to the fast merging theories because the mechanism for dragging the magnetic field lines into the tail at high velocities is not defined. The particle density is so low in the solar wind that the particle-particle collision time is a few years. If the friction at the magnetic field boundary takes place by particle-particle interactions, the merging time must also be a few years. Clearly this is too long if the tail magnetic fields must react to magnetic storms which occur every few days or weeks.

Instead Dessler (39) suggests a magnetic cavity with a very long tail, many sun-earth distances in length. In his model, the merging is very slow and the energy input takes place all along the tail. There is no connection to the field lines of interplanetary space except at the end of the tail. O'Brien (40) modified this model by connecting the neutral sheet to the aurora as shown by the dark cross-hatched region in figure 15. He organized the

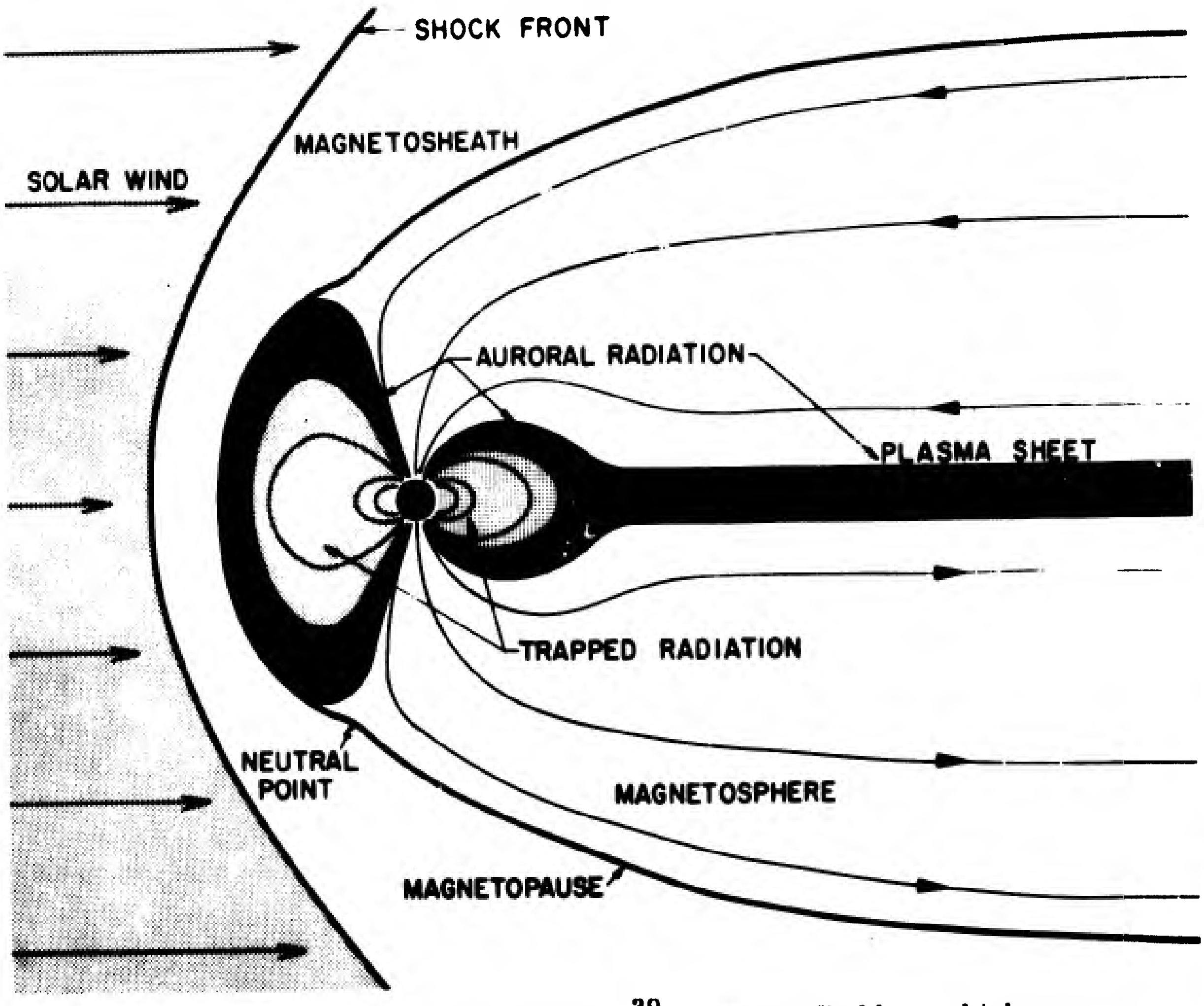


Figure 15. The long tail model of Dessler,[39] 1964 modified by and taken from O'Brien,[40] 1966. The plasma sheet is connected to the auroral regions which extend around the earth to the sunlit side. The trapped radiation region is in closer to the earth.

magnetic and charged particle information into the following regions: The Van Allen geomagnetically trapped radiation region, the auroral region, the magnetosheath region, and the interplanetary space region. He emphasizes the "auroral region," the entire region in the magnetic cavity except for the trapped radiation. The auroral particles, the islands or pulses in the tail, and the spikes at high latitudes at 1,000 km are all associated phenomena which occur in his "auroral region."

A detailed calculation of the motion of auroral particles in an electric and magnetic field model of the magnetic cavity has been carried out by Taylor and Hones (41). The authors used their own magnetic field representation and an electric field deduced from the atmospheric current system that accompanies magnetic storms. They derived potentials as high as 50 kev, that may be used to accelerate charged particles in the magnetic cavity. The surface of the magnetosphere is an equal potential surface since there is no interconnection with interplanetary lines of force. Their electric fields prohibit entry of solar wind protons into the tail but permit entry and acceleration of solar wind electrons on the evening side. Among their results, they find a definite latitude boundary between auroral electrons and protons. The auroral protons enter the earth's atmosphere at the lower latitudes.

V. CONCLUSIONS

The description of the experiments which have measured the magnetic and charged particle properties of the earth's magnetic cavity have been described. The magnetic storms and aurora and their time and space variations were discussed. The major theories to explain the experiments were presented.

The primary observations that can be explained by a fast merging magnetic field model such as that of Axford, Petschek, and Siscoe are now reviewed. The solar wind bombards the earth's magnetic field. The viscous forces on the boundary, unspecified, drag the magnetic field lines away from the boundary and create the long tail. The merging of magnetic field lines in the tail transforms the magnetic field energy into kinetic energy of the electrons and the protons. The closed magnetic field lines rotate with the earth to the sunlit side where they merge again with the interplanetary magnetic field lines. The continuous injection into the magnetic cavity of new magnetic field lines from interplanetary space with attached solar wind particles is a continuous source of replenishment of particles for the neutral wedge. Currents in the neutral wedge return through the boundary of the magnetic cavity to form current loops that furnish the magnetic fields in the tail.

The electron islands, spikes of pulses in the tail are electrons which were accelerated in the neutral sheet by the electric potential set up by the merging of the magnetic field lines. They are in transit toward or away from the trapped radiation belts. The intensity of these charged particles drops off with their distance away from the neutral sheet which indicates that the neutral sheet is the source of the particles.

The 10 kev electrons in the aurora obtain their energy from the tail potentials. The very sharp peaked energy distributions suggest that they originate from one location in the dusk to dawn neutral line. Electrons are observed on the day side because the lines connecting to the dawn side of the tail are at a high negative potential while protons are observed on the dusk side because the lines connected to the dusk side are at a high positive potential. This is indicated on the sketch of the magnetic field line configuration of figure 16. In this model the potential is arbitrarily fixed on 0 at the nose of the magnetic cavity on the sun-earth line and is 0 on the meridian plane that passes through the sun-earth line. The potential of the tail at the line of merging is +15 kev on the dusk side and -15 kev on the dawn side. Aurora may also be observed in the day because electrons that are acceler-

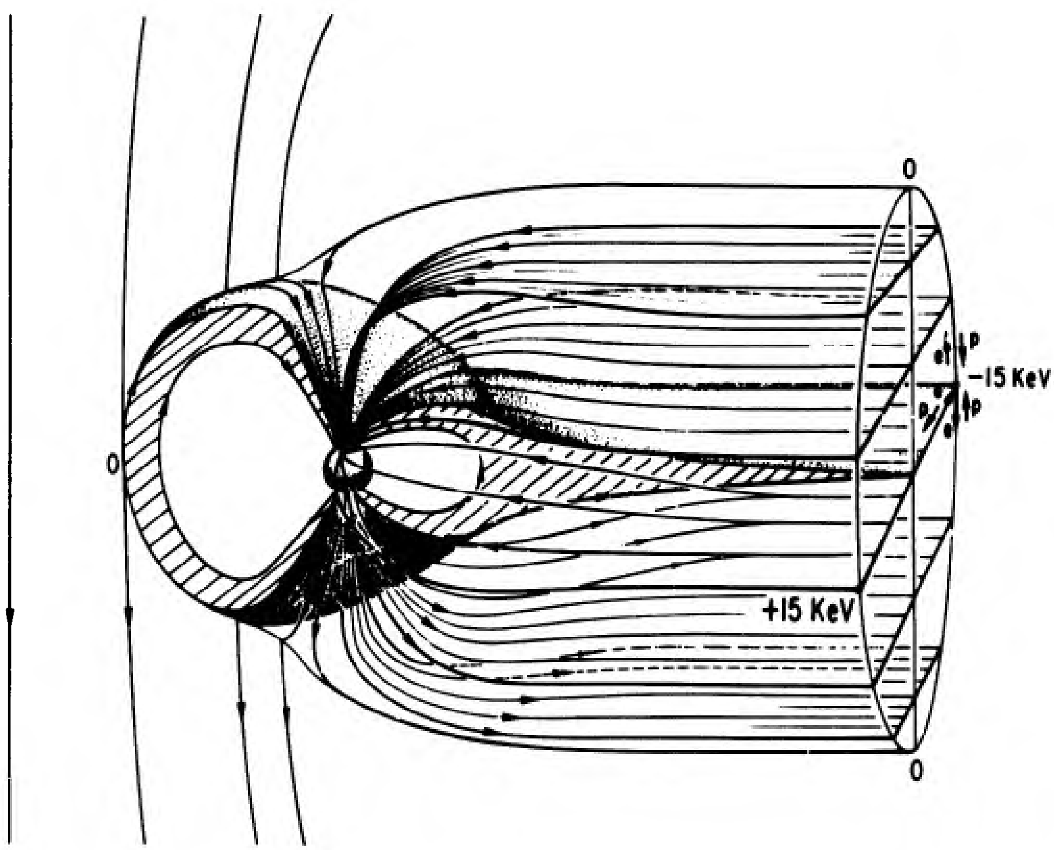


Figure 16. The magnetic field lines in a fast merging model of the magnetic field cavity. The merging occurs on a line from the dusk to dawn side in the tail and with the magnetic field lines in interplanetary space on the nose. Electric potentials are indicated on the surface of the cavity. The directions of motions of the electrons and protons are shown.

ated by the electric potential in the tail are carried around to the day side by the closed magnetic field lines which rotate with the earth. These particles also drift around the earth with a motion of their own.

The main phase of a magnetic storm is observed as a decrease in the magnetic field on the surface of the earth. It is caused by the inflation of the magnetosphere due to a large number of protons temporarily injected by a magnetic storm at L values from 2 to 5. These protons are injected in the dusk quadrant in a non-symmetric way.

A fuzzy boundary exists between the outer edge of the outer electron radiation belt and the auroral region. Magnetic field lines connect the auroral region to the neutral sheet. At times of magnetic storms more magnetic field lines are pulled into the tail. The magnetic field both fore and aft is compressed and the outer boundary of the outer electron radiation belt moves to lower latitudes. Most of the particles injected are immediately lost into the atmosphere and are not trapped except for short periods of time.

Some protons and electrons are trapped, however, and diffuse into the trapped radiation region. This is the source of the low energy protons trapped in the radiation belt. The protons are accelerated to 10 Kev in the tail by the potential set up by the magnetic field merging. They then diffuse across the magnetic field lines by changing energy according to EL^3 = constant while conserving their magnetic moments.

The decrease in cosmic ray intensities, Forbush decreases, occur at times of magnetic storms and during the maximum of the solar cycle. They may be partially explained by the increased magnetic fields due to the increased number of lines in the magnetic cavity, particularly in the magnetic tail.

It was observed that the low energy electrons with $E > 40$ kev in the outer electron radiation belt increase and decrease along with K_p. During these times more new particles are injected into the magnetic cavity along with the greater number of magnetic field lines. The electrons are accelerated up to the energies of observation by the potential created during merging. However, the higher energy electrons with $E > 1.6$ Mev decrease as K_p increases and sometimes return to their initial values when the magnetic field returns to normal. This could be an adiabatic charge in energy while conserving the magnetic moment. Sometimes it takes several weeks for the electron flux to return to normal. In this case, old electrons are probably lost and new ones diffuse inward from the magnetic cavity boundary and gain energy while conserving their magnetic moments.

Qualitatively most of the phenomena of the magnetic cavity, the aurora, magnetic storms and some of the phenomena of the radiation belts can be explained by the theory of fast merging of magnetic field lines. Order of magnitude energy calculations are reasonable. But there are many questions yet to be answered. First, there are no direct measurements of magnetic field line merging. There are no measurements of electric fields that give the calculated accelerating potentials of 30 kev. The mechanism of pulling the magnetic field lines into the tail is not explained. No detailed calculations have been made to show what fraction of the electrons or protons in the solar wind cross the shock front, pass through the magnetosheath and enter the magnetic cavity. No loss mechanisms have been combined with injection calculations to describe equilibrium particle space or energy distributions. No time-dependent Fokker-Planck type equation has been solved to obtain the time distributions of the particles. Until the crucial measurements are made and the detailed calculations are carried out, the theoretical explanations must remain as speculations.

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Particle Populations in Space

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PARTICLE POPULATIONS IN SPACE

C. E. Fichtel and F. B. McDonald

INTRODUCTION

The development of spacecraft and the study of the properties of the primary particles in space have naturally gone together because each depends on the other. Satellites and sounding rockets have provided two powerful new means of examining these fundamental particles outside of the earth's atmosphere and even beyond the magnetosphere. On the other hand, radiation information is needed to ascertain the degree of structural damage it will produce and to determine the radiation hazard for manned space flight. This paper will summarize briefly the present information on the particle populations in space with the aim of giving a picture of the flux, composition, and energy spectra of the various types of radiation, and at the same time indicating how well the properties of the radiation can be explained theoretically. We shall begin with a discussion of galactic cosmic rays, which were discovered first, and then proceed to solar cosmic rays and the Van Allen Belt particles.

GALACTIC COSMIC RAYS

In this section, the cosmic ray component which is accelerated outside of our solar system and which arrives with a kinetic energy >10 Mev/Nuc will be discussed. The copious acceleration of moderate to high energy particles on the sun makes it necessary to designate energetic particles as being either of solar or galactic origin.

The principal features of the galactic cosmic ray are its energy and charge spectra and its modulation with time.

A. Energy and Charge Spectra

The composition and energy spectra of the primary cosmic radiation striking the top of the earth's atmosphere are reasonably well known at the present time (1, 2, 3). Briefly, 85% are hydrogen, 12% helium, approximately 1% are in the carbon, nitrogen, oxygen group and .25% are in the group neon and heavier. In this heavier group, nuclei of all charge up to and including iron ($Z = 26$) have been identified. There is a small but significant flux of lithium, beryllium and boron which is approximately 0.25% of the total flux. High energy electrons constitute 1-3% of the total flux (4, 5). Whether these electrons are of galactic or solar origin is not fully understood at the present time. From the recent results of Explorer XI (6) an upper limit of .1% can be placed on the flux of high energy gamma rays.

A detailed summary of the charge spectrum is given in table I. There are two features of this charge spectrum which should be mentioned. Firstly, the flux of lithium, beryllium, and boron is surprisingly high. If we assume that these elements are extremely rare in the source region - as the Table of Stellar Abundance would have us believe - then these nuclei must be produced by fragmentation of heavier nuclei colliding with interstellar hydrogen nuclei. This, then, gives a measure of the average distance traversed by the galactic cosmic radiation before striking the earth. Using presently available fragmentation parameters (3), this corresponds to a value of 4 gms/cm^2 or implies an average age of the order of 10 (7) years. The other salient feature is the large flux of CNO and $Z \geq 10$. The observed values are 10 times greater than that expected from known Stellar Abundance. At the present time, this is not understood but can perhaps be understood in terms of super-novae origin (7).

Table I Relative abundances of multiply charged nuclei.

WITH A BASE OF 10 FOR OXYGEN

	He	Li, Be, B	C	N	O	F	Ne	11 Z 18
SOLAR COSMIC RAYS	1250	0.2	6	2	10	0.3	1.3	1.4
SUN	?	0.01	6	1	10	0.01	?	1
ORDINARY COSMIC RAYS	360	11	18	8	10	1	3	9

THE UNCERTAINTY IN THE VALUES IN THIS LINE VARIES FROM 15% TO 40%

THE UNCERTAINTY IN THE VALUES IN THIS LINE ARE OF THE ORDER OF A FACTOR OF 2

In the high energy region ($E > 3$ Bev) it has been observed that all charged components have energy spectra of the form

$$J(E) = \frac{K_Z}{(1 + E)^{\gamma}}$$

where J(E) is the flux in particles M^2-sec-sr with kinetic energy $> E$, γ is a constant independent of Z, and K_Z is a function of A. $J(E > 1 \text{ BV})$ is typically 1800 part M^2 sr-sec at solar maximum. In the region .3 - 5 Bev it is observed that all components appear to display the same form of spectra when expressed in terms of rigidity ($R = PA/Z$) where P is the momentum nucleon, A is the mass number, and Z the atomic number of the primary.

Expressed in these terms the differential spectra displays a maximum in the region of 3 BV and is either constant of decreases down to .3 BV. In the region .4 - .7 BV, Vogt (8) has found large increases. Whether these are due to solar or galactic cosmic rays is not known.

B. Modulation of Galactic Cosmic Radiation

It appears reasonable to assume that the flux of cosmic rays incident on the solar system is constant. However, in the vicinity of the earth, large modulations are observed which appear to be controlled by solar activity.

The two most important types of modulation appear to be the 11 year variation and the Forbush or storm type decrease. It was first noted by Forbush that the cosmic ray intensity varied inversely with solar activity over an 11 year cycle (9). Also, Forbush first observed the rapid world-wide decreases in cosmic ray intensity which are associated with some magnetic storms (10), generally following large solar flares. At present the best evidence indicates that the modulation is heliocentric and is controlled by solar activity. The effects on cosmic rays can be summarized as follows (11):

1. The proton and alphas have the same form of differential rigidity spectrum at solar minimum and maintain the same relative form of rigidity spectrum during the solar cycle ($R > 1.0$ BV).

2. The total intensity is decreased by a factor of 2 from solar minimum to solar maximum and the lower energy particles are affected most - but the low energy component is never completely removed.

3. At low energies or rigidities the form of the spectrum changes appears to be the same for the 11 year cycle as for the Forbush decreased that have been observed.

SOLAR COSMIC RAYS

It is now well established that solar cosmic rays arrive at the earth following some major flares in intensities which are orders of magnitude greater than ordinary cosmic rays. The first evidence for these particles came from sea level ion chambers (12, 13); however, these detectors and the neutron monitors developed after them are only able to see those events which have a large high energy component. The development of the riometer (14) in 1956 provided an instrument which is sensitive to the effects of incoming particles in the low energy region, 10 to 100 Mev, and can detect a flux of the order of ten particles (cm^2-sr-sec) or greater in this range. The riometer records showed that during this last solar maximum, there were at least a dozen of these events per year (15).

The most detailed data has come from particle detectors flown on balloons, sounding rockets, and satellites. Balloon borne equipment has provided much valuable information on the intermediate energy interval (16), from approximately 80 to 500 Mev, for protons, and also yielded the first evidence of helium nuclei among the energetic solar particles (17). Sounding rockets with recoverable payloads provide a means of studying these events above the earth's atmosphere with both electronic counters and nuclear emulsion techniques. Proton energy spectra down to a fraction of an Mev (18), and detailed charge composition measurements (19) have been obtained in this manner. Finally, electronic experiments in satellites outside of the Van Allen Belts can give a detailed history of the energy spectrum of an event down to very low energies. However, not until Explorer XII was launched on August 15, 1961 did such a system exist. Previous satellite experiments have provided integral fluxes above some energy, and these results have aided in the study of several events (20).

One of the most striking features of these solar cosmic ray events has been the variation from one event to another. In some events, the flux of protons above 20 Mev has exceeded 10^3 particles cm^2-sr-sec for more than a day (18, 21, 22) and the total energy arriving at the top of the atmosphere of the earth for the whole event has been 10^4 ergs/cm^2-sr, about the same order of magnitude as that for cosmic rays for a year. On the other hand, events which are more than a hundred times smaller than this have been seen (23, 24) and even smaller ones probably occur frequently and are not detected. The energy spectra and its time variation have also shown marked differences from one event to another. For example, at comparable times in the November 12, 1960 and the July 12, 1961 events (22, 25) the integral fluxes above 10 Mev were nearly the same, but above 100 Mev they differed by more than a factor of 300. In some events, the maximum low energy intensity occurred as early as four hours after the flare; whereas in others, it occurs as late as thirty or forty hours after the flare.

In order to show some of the general characteristic of these events, the time variation of the integral flux above 20 Mev, 100 Mev, and 500 Mev are shown for three events (26) in figures 1a, 1b, and 1c. In figure 1d, an imaginary event is shown which is just large enough to include any event ever observed. Particularly complete data exists for the September 28, 1961 events from the work of McDonald and co-workers (27) on Explorer XII. A detailed energy spectrum as a function of time exists for a large portion of the event including the important first hours. Their results show that the flux in any velocity interval rises smoothly to a broad maximum and then decays regularly, the rate of rise being greater for particles of higher energy. Further, this study revealed that although the energy spectrum changed shape throughout the event, it did so smoothly with the result that the energy spectrum was always a smoothly varying function of energy with no very sharp discontinuities at any time.

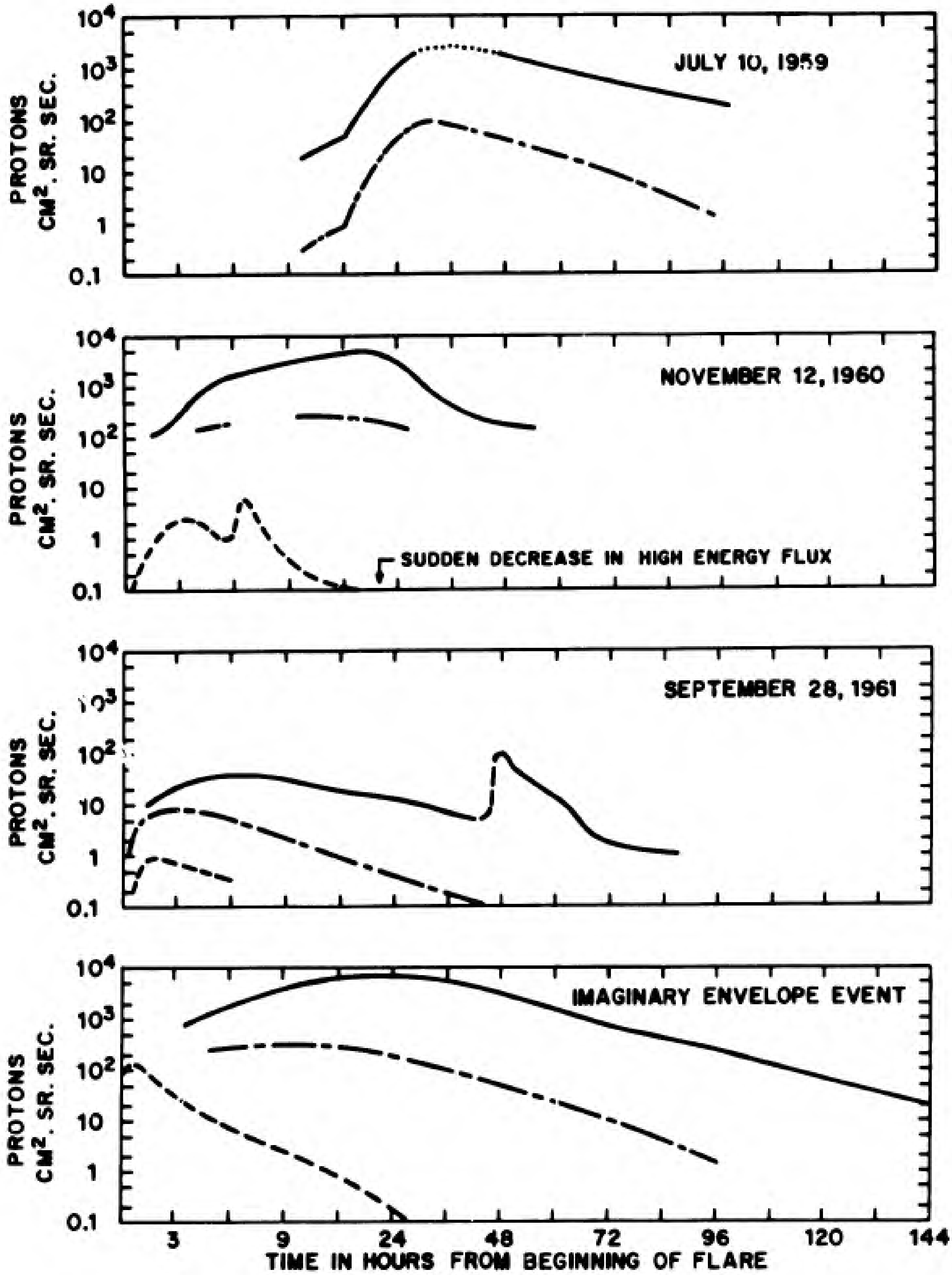

Figure 1. Time variation of the integral flux above 20 Mev (solid curve), 100 Mev (dot and dash curve), and 500 Mev (dashed curve) for three events and an imaginary envelope event which is just large enough to include any event ever observed.

Another interesting result obtained from the Explorer XII results was the direct detection of a large low energy component (27, 28) below about 30 Mev around the time of the sudden commencement of the magnetic storm as shown in figure 1c. This large low energy flux had previously been expected on the basis of sea level riometer data and the predicted association of a plasma wave in space with a sudden commencement, but this was the first direct evidence.

Having briefly discussed the characteristics of the primary component, namely the protons, attention will now be given to the charge composition of the particles in these events. On the basis of the detailed study of three events, there seems to be good evidence that the relative abundances of the various nuclei are nearly the same in each event when compared in the same velocity intervals for energies in the tens of Mev region (19, 22). The proton component is by far the most abundant, with helium nuclei being less abundant by more than an order of magnitude, and the heavier nuclei by at least three orders of magnitude relative to the proton component.

Among the multiply charged component, the helium and medium nuclei (carbon, nitrogen, oxygen, and fluorine) have the same energy spectrum. The energy spectra of the other multiply charged nuclei have not as yet been determined because they are extremely rare; however, it is reasonable to assume that their energy spectra would also be the same, at least up to nuclei with a charge of about sixteen. The relative abundances of these elements in solar cosmic rays is then independent of energy. They are shown in table I, along with those of the sun deduced from spectroscopic evidence for those elements where data exists. It is seen that the two sets of numbers are the same within uncertainties. Although the helium abundance in the sun cannot be determined by spectroscopic means, the relative abundance given in table I for helium in solar cosmic rays is within the rather wide limits set by theoretical models of the sun.

The proton component has been observed to have a very different energy spectrum from the other components, due probably to its different charge to mass ratio. Therefore, the relative abundance of the proton component varies with velocity. For example, in one event the proton to helium ratio varied from about twenty at 40 Mev/nucleon to about three-hundred at 120 Mev/nucleon.

The information obtained on energetic solar particles can now be compared to the composition of galactic cosmic rays. There are at least five important differences between solar cosmic rays and ordinary cosmic rays. Two of these, the different carbon to oxygen ratios and the different light to medium ratios can be attributed to the fact that ordinary cosmic rays have gone through several gm/cm^2 of material wherein the light nuclei are formed by fragmentation, and there is at least an increase in the carbon to oxygen ratio. The other three, the different helium to medium nuclei ratios, the different ratios between the medium nuclei and those in the charge group, $11 \leq$ nuclear charge ≤ 18, and the different proton to medium nuclei ratios, are only enhanced by fragmentation. The helium to medium ratio is five times larger for the accelerated solar particles; the ratio of the medium nuclei to those in the charge group $11 \leq$ nuclear charge ≤ 18 is four times larger for the energetic solar particles; and the proton to medium ratio at galactic cosmic ray injection energies is at least four times larger for solar cosmic rays.

The solar particles that are seen at the earth have already been acted upon by both the acceleration phase at their source and the transit phase, wherein they are modulated by the interplanetary conditions. In the modulation process, the particles are acted upon by the magnetic fields which are believed to have many irregularities which scatter the particles. The interplanetary conditions during an event are further complicated by one or more shock waves, or magnetic bottles, moving outward from the active regions onthe sun. At this time, no explanation exists that will quantitatively predict the development of an event in any particular case; however, some general features of these events do seem to be becoming evident. The fact that the radiation observed near the earth is essentially isotropic, except for early times in some events, indicates that scattering of the particles must be very effective. Further, the rate of increase of the particle flux early in an event is much greater for high energy particles than for low energy ones, in agreement with the general predictions of diffusion theory. Finally, since solar particles are seen for many days after a solar event, the trapping in the inner region of the solar system must be relatively strong.

Turning to the acceleration phase, Parker (29) has shown that within the framework of the present understanding of plasma dynamics, all particle acceleration mechanisms occurring outside of the laboratory are reducible to the Fermi mechanism (30, 31, 32) which is based on random particle collision with magnetic inhomogeneities. Insofar as comparisons can be made, the experimental results seem consistent with a Fermi-type acceleration mechanism.

VAN ALLEN BELTS

The Van Allen belt radiation, unlike cosmic rays, consists of particles trapped in the earth's magnetosphere. These charged particles spiral back and forth along the lines of force of the earth's magnetic field. Present evidence indicates that these particles are predominantly, and perhaps essentially exclusively, protons and electrons. The intensity and energy spectra of these particles vary greatly with the position in the trapped region and even the angle with respect to the magnetic field at any given point. Further, at least at large distances from the earth, several earth radii, rather large fluctuations in intensity are observed. For these reasons, a complete description of the particle properties would have to be long and detailed, and, in many respects, the picture would have to remain incomplete because of the lack of information. Therefore, only the more fundamental known characteristics will be reviewed here. The data on the proton component will be reviewed first and then that of the electrons.

Several satellite experiments (33, 37) including the original work of Van Allen have shown that the protons with energies greater than about 30 Mev are contained in a roughly doughnut-shaped region centered over the geomagnetic equator and extending from approximately 500 kilometers above the earth to about 6000 kilometers. The maximum intensity approaches approximately 2 X 10^3 protons cm^2-sr-sec in the heart of this region. Detailed energy spectra are available at several points in this region from the experiments of Freden and White (38, 39) and others (40) in one region and Naugle and Kniffen in another. The energy spectra deduced from their work are shown in figure 2. In addition to these studies, there is additional information on the very low energy proton component. Bame et al (42) saw integral fluxes above 1 Mev of from 0.3 X 10^5 part cm^2-sr-sec, depending upon the position, but within two earth radii, and an energy spectrum from

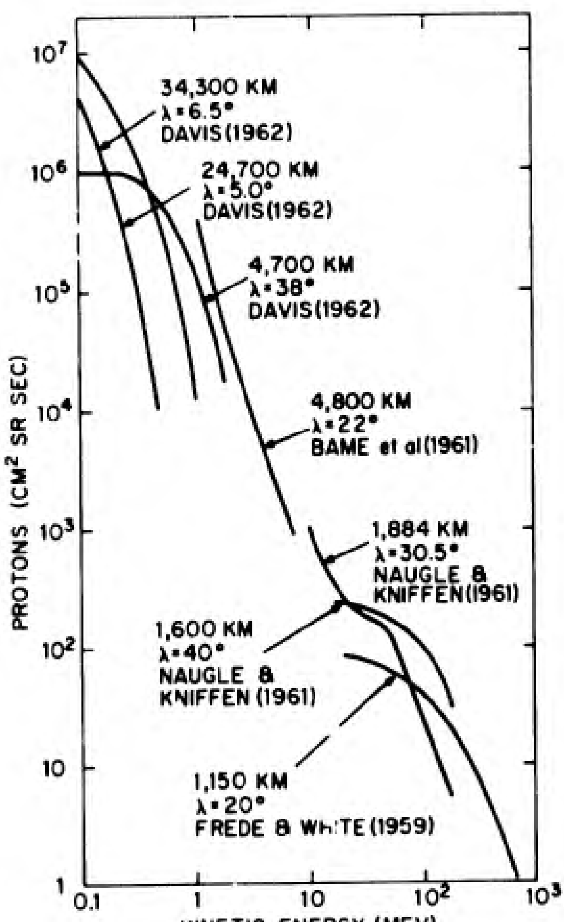

Figure 2. Proton energy spectra at different points in the Van Allen Belts as measured by several experimentalists.

2.7 to 7 Mev that has approximately the same slope as that observed by Naugle and Kniffen at high energies. Davis et al (43) see integral fluxes above 0.1 Mev in excess of 10^6 protons cm^2-sr-sec at about 6 earth radii. The spectrum is again very steep and the flux is below 10^4 protons/ cm^2-sr-sec above 0.5 Mev at this large distance from the earth. These spectra are also shown in figure 2. Finally, Freeman (44) has detected a very intense flux of particles at altitudes from 900 to 1000 Km. If these particles are assumed to be protons and reasonable assumptions are made about their energies, the results would indicate a proton flux above 0.1 Mev in excess of 10^8 protons (cm^2-sr-sec).

Much of the existing knowledge on the electron population of the Van Allen Belts comes from the same satellite experiments referred to earlier (33-38, 45, 48). The flux of electrons with energies greater than 200 Kev is known to reach a maximum at about four earth radii, and the electron component is observed to extend out to about fifteen earth radii at the equator. There is considerable controversy over the absolute flux values and the shape of the energy spectrum due to the difficulty of interpreting the experimental data; however, the most recent estimates (47) give a flux of 5 X 10^6 electrons cm^2-sr-sec above 600 Kev in the region of highest intensity and 5 X 10^8 electrons cm^2-sr-sec above the 40 Kev.

There has been considerable speculation concerning the origin and history of the particles in the Van Allen Belts. Hess (47), Kellogg (48), Lenchek (40), Singer (50), Vernov et al (51) and others have considered the possibility of albedo neutron decay, where the neutrons are secondaries from the interactions of galactic and solar cosmic rays in the atmosphere. There is reasonably good agreement between the flux and energy spectra of the proton component in the inner part of the belt above about 10 Mev, but there are apparently many serious disagreements, the most serious involves the flux and energy spectrum of the electrons. In order to explain the properties of the electron component, several theories related to either direct injection or local acceleration by high-frequency electromagnetic fields (52) have been suggested. However, as yet, a detailed quantitative explanation has not been obtained.

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World-Wide Aeromedical Evacuation and Recent Developments

Brigadier General Harold F. Funsch

General Funsch is Command Surgeon, Military Airlift Command. The professional and medical-administrative policy of nine hospitals and dispensaries, and the operation of the world-wide aeromedical evacuation system of the Military Airlift Command are under his supervision. General Funsch received his M. D. degree from St. Louis University School of Medicine. After serving an internship in St. Louis and a residency (OB-Gyn) in Omaha, Nebraska, he entered on active duty as attending physician at Fort Omaha in 1940. He later served in assignments with the Air Transport Command, Air Training Command, and Fifth Air Force, in the United States and overseas, before being assigned to his present position. General Funsch is the author of numerous professional and medical managerial publications.

WORLD-WIDE AEROMEDICAL EVACUATION AND RECENT DEVELOPMENTS

Brigadier General Harold F. Funsch, USAF, MC

Although the underlying concept and the techniques of aeromedical evacuation have been known and applied for many years, the combination of hostile action in Vietnam and modern jet aircraft has brought this rapid method of patient handling into a new and clearer perspective. We see, in this era, the culmination of long years of effort -- years during which the broad potential of the aeromedical medium was clearly recognized, but in which the inherent limitations of available equipment militated against its realization.

During the final half of 1965, with combat activity in Vietnam intensifying, we found ourselves evacuating a high percentage of patients to the United States by air.

For the first time in history, patients were reaching hospitals of definitive care, 8,000 miles from the combat zone, within a few days after being wounded. For the most part, these patients were stabilized before beginning the long leg of their journey. All varieties of illnesses and injuries were airlifted; and in no case was air transportation contraindicated once stabilization had been achieved.

The operation of a world-wide patient airlift system poses a host of complex problems, many of which have been resolved by U. S. Air Force medical personnel dedicated to making it work. To accomplish the mission successfully, specialized medical equipment has been devised by the medical crews themselves, and then tested by the USAF School of Aerospace Medicine before being sent out for further evaluation in the field.

Medical personnel must be specially trained and prepositioned at points where it is anticipated they will be needed. Estimates of casualties and anticipated diseases (exotic and otherwise) must be made -- and airlift provided to meet these estimates. And, of course, in addition to all of these considerations, patients from other areas than the Far East must also be evacuated to and within the United States.

The logistics of aeromedical evacuation are bound up with and compatible with a wartime environment, since airlift aircraft in that environment are flying high priority cargo and personnel forward to the combat zone. Since the return airlift capacity is only partially utilized, a good portion of it becomes available for patient movement.

There are a number of cogent reasons for airlifting patients to the United States from any theater as a matter of course. Chief among the arguments are:

(1) There is a very positive contribution to the morale of the fighting man in the knowledge that, if he is wounded, the advantages of modern therapy and surgery near his home will be available to him within a short time.

(2) Medical non-effective time is curtailed by affording the casualty the most modern medical facilities, rather than less optimum treatment in the field.

(3) The scarce resource of specialists can be conserved, and more efficiently utilized, by concentrating them -- and by permitting them to practice in an ideal environment where modern equipment and paramedical personnel are available to them.

(4) The forward medical facilities are enabled to maintain a low census, and thus are better prepared to handle influxes of casualties.

(5) The combat commander is relieved of the responsibility and the tremendous logistical burden of non-combatant patients, thereby being freed to devote his entire attention and energy to the conduct of the war.

(6) Aeromedical evacuation makes economical use of returning aircraft which would otherwise not be fully utilized in this "retrograde" phase of the airlift mission.

With a modern fleet of jet aircraft, and properly trained medical personnel, the need for large overseas hospitals is being greatly diminished. The following pages, after a brief history of the medium, will outline the techniques, procedures and methodology of today's military aeromedical evacuation.

HISTORY

The art and science of aeromedical evacuation have evolved as a byproduct of the gigantic strides in both aviation and medicine. From its austere and humble beginnings as a military operation in 1910 (1), its progress has been a measure of sound concepts and effective practices which are now being applied every day around the world.

Applications pioneered by the U.S. Army Air Corps, and subsequently by the U.S. Air Force, have led to the fruition of a highly organized system and an exceedingly specialized technique. Between 1943 and 1947, the Army Air Corps moved approximately 1,360,000 patients -- with only 46 deaths in flight (2). A particular case described by Grant (3) exemplifies the spirit of aeromedical evacuation and its unique wedding of the aeronautical and medical sciences.

In June 1944, in an isolated and rugged section of western China, a young officer was stricken with bulbar poliomyelitis. Artificial respiration was administered for 14 days, during which an airstrip was hacked out of the wilderness and a crude respirator was built. He was then flown out in a small plane, with the pilot dodging mountains and storms -- while using one hand to operate the lever of the respirator. A twin-engine C-47 subsequently flew the patient over the "Hump" of the Himalayas to a medical center equipped with an "Iron Lung."

The patient recovered.

Since 1949, Department of Defense policy has dictated use of aerial transportation for the sick and wounded wherever practicable. This includes aeromedical transportation of all patients between various government hospitals, as well as -- on occasion -- civilian facilities in which members of the Armed Forces and their dependents may be temporarily hospitalized. In unusual cases, civilians may be transported, on a life-saving basis, with approval from Air Force headquarters.

Through December 1966, something over three-quarters of a million patients -- more than 807,000 -- had been transported over both domestic and international routes. No patient has ever been lost as a result of aircraft accident.

Specifically trained teams conduct aeromedical evacuation operations wherever Americans are serving their country. A vast global network provides a safe and rapid transport link, directly connecting even the most isolated military outpost with more than 350 government hospitals.

Civilian applications of aeromedical technology, although lacking the impetus and resources of the military, have been considerable. Commercial airlines have developed rules for travelers with medical disorders. Guidelines for use by physicians, in evaluating whether their private patients should travel by air, have appeared from time to time (4-7). An excellent review of the principles of aeromedical evacuation, with emphasis on the civilian aspects, appears in Harry G. Armstrong's classic compendium "Aerospace Medicine." Major General Armstrong, a former Surgeon General of the Air Force, pioneered many of the early advances in aviation medicine. Significant contributions originating at the USAF School of Aerospace Medicine have constructed a firm base for the sciences of aeromedical evacuation (8-11).

OPERATIONAL CONCEPTS OF AEROMEDICAL EVACUATION

The aeromedical evacuation system of the U.S. Air Force is organized into three major operational subsystems types:

(1) Intra-theater. This type of system operates wholly within an overseas theater or combat zone. It is organized, staffed, equipped, and oriented toward combat support. Patient movement is effected within and from combat zones in the specific theater of operations. The Air Force operates two such systems, one in Europe and one in the Western Pacific area. Since the Korean War and until recently, these operations have been typified by peacetime evacuation missions of ailing servicemen and their family members. The onset of American involvement in the hostilities in Southeast Asia has occasioned a smooth transition to the primary combat support mission. Intra-theater aeromedical evacuation utilizes propeller-driven cargo and troop carrier aircraft, and is the responsibility of the theater or combat zone command. Forward aeromedical evacuation by means of helicopter is provided by the Army and Marine Corps within their combat zones. Twin engine aircraft as well as four engine C-130s -- all with short takeoff and landing ability -- augment patient movement to control patient staging and treatment facilities.

(2) Inter-theater. This long range system operates between the patient staging facilities of overseas aerial ports and the continental United States. It is a global network operated by the Air Force Military Airlift Command (MAC). One major system serves the Far East/Pacific area, the other Europe and its environs. The advent of jet transports has led to the replacement of slower four engine propeller aircraft, and has helped to revolutionize the inter-theater aeromedical evacuation system. Since 1950, more than 251,000 patients, including sick family members, have been carried by this overseas service. Since the cessation of hostilities in Korea, regular schedules have been maintained across both oceans. The patients involved have had medical and surgical conditions much the same as those found under civilian conditions. More recently, however, the Far East/Pacific system (a part of the MAC Twenty-Second Air Force) has undergone a striking change in both the number of patients moved and the nature of their conditions. During the ten years prior to 1965, this system moved an average of about 4,200 patients annually, approximately one-third of which were litter cases. Since January of 1966, however, these figures have increased to an average of 1,773 patients monthly, more than one-half of which are litter cases.

(3) Domestic. The domestic system is also a MAC responsibility; it services the numerous government hospitals within the U.S. with scheduled trunkline and feeder flights. The domestic aeromedical evacuation system covers the continental United States and near off-shore areas (Alaska; Newfoundland and Labrador; Bermuda; Puerto Rico; the Canal Zone; and Guantanamo Bay, Cuba). Since 1950, more than half a million patients have been moved by this system. It also responds to special and emergency requests, including civilian patient movement to special treatment centers (burns, respiratory failure, etc.). Pending acquisition of a suitable short-haul jet transport, this will continue to be a non-jet operation. In times of unusual

need, the long range jets have been called upon for this service. Air Force Reserve and Air National Guard units serve as a back-up during times of national disaster or hostilities.

REQUIREMENTS FOR AEROMEDICAL EVACUATION

(1) Communication and Coordination. If the inherent medical and logistical advantages of aeromedical evacuation are to be exploited to their fullest potential, effective communication, coordination and control are essential. All available media of communications are utilized to insure the optimum intermeshing of: requirements for patient movement; aircraft availability and efficiency of utilization; and hospital resources. Coordination with aircraft control elements is vital in order to insure rapid transit of the patient from point of origin to ultimate destination. The Aeromedical Evacuation Control Center (AECC) is the nerve center of the system (fig. 1). This center maintains contact with medical treatment facilities originating and receiving patients, and coordinates all matters of patient air transport with all participating or interested agencies. The AECC determines aircraft space requirements; coordinates these with aircraft allocation and operational agencies; maintains patient movement and aircraft capability records; supervises the ground handling and loading of patients; and, where multiple stops are to be made, determines aircraft itineraries to insure proper patient onload and offload sequence.

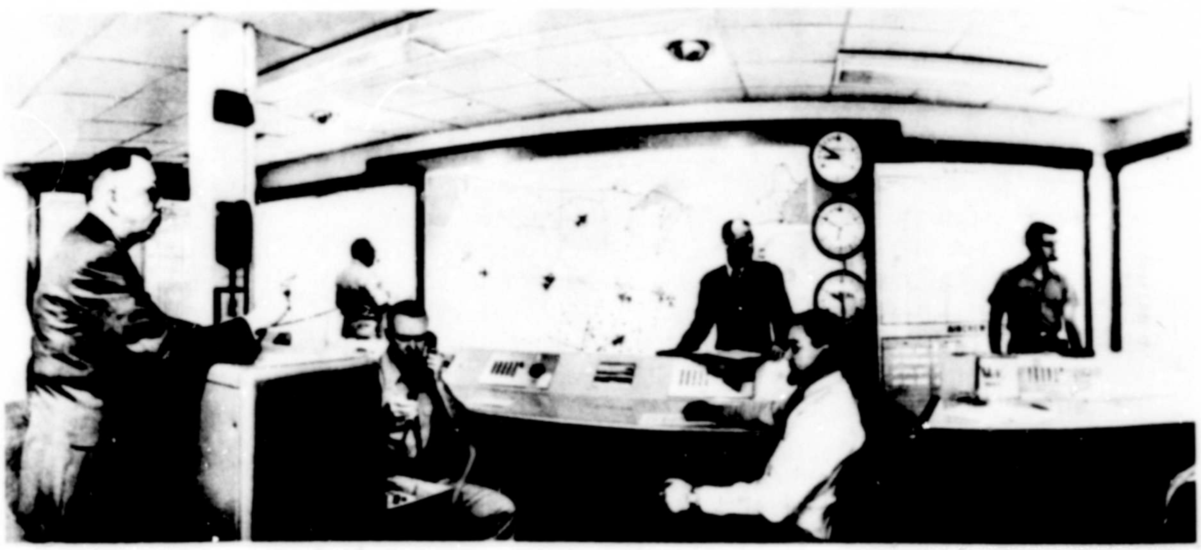

Figure 1

An example of command control facilities, and the concomitant procedures, is found in the 375th Aeromedical Airlift Wing, which is responsible for operating the domestic system. Both the wing headquarters and the Central Aeromedical Evacuation Control Center are located at Scott Air

Force Base, Illinois. The domestic system airlifts Armed Forces patients to and between over 600 medical facilities serviced by air operations into and out of more than 400 airfields. The key to successful performance of this mission is continuing knowledge, in the Central AECC, of three factors:

1. Current workload in terms of patients to be transported.

2. Status of assets with which to satisfy the workload.

3. Method of satisfying workload and progress.

Four large write-in visual displays provide up-to-date information on these key factors. They consist of:

1. Patient Status Boards.

   a. Patient Holding in CSU (Casualty Staging Units).

   b. Patients Originating in Area.

2. Aircraft and Crew Status Board.

3. Mission Management Board.

4. Map of U. S. showing current geographical coverage by aeromedical evacuation missions being processed on the Mission Management Board.

Again, it must be emphasized that the accumulation and maintenance of current information on patients, aircraft, crews and mission accomplishment demands an efficient system of communications. An exclusive-use telephone network connects the Central AECC with its seven subordinate AECCs (as shown in fig. 1). Two digit direct dialing connects any pair of stations; any number of stations from three to all may be connected for conference calls by two-digit direct dial to the central switchboard. Patients are routed to specific destinations by centralized medical regulating offices which monitor bed and specialty availability both within and outside the United States.

(2) Casualty Staging and In-Transit Aeromedical Evacuation Facilities. A patient or casualty staging unit, usually located at an aerial port or in a combat zone, provides facilities for the reception, feeding, medical care, screening and administrative processing of patients. In-transit aeromedical evacuation facilities are usually incorporated within base hospitals, and physicians are available for patient care. The use of such facilities serves a number of purposes: reception and accumulation of patients for more effective utilization of airlift; rerouting, re-evaluation, triage and stabilization of seriously ill patients; and a haven in the event of prohibitive weather

or operational difficulties which might prevent flight. Patient staging units arrange for special ambulances, ramps, flightline air conditioning and other services.

(3) Aircraft. By virtue of its design, almost any aircraft capable of carrying cargo is potentially adaptable to aeromedical evacuation. Not all of them -- particularly the older type transports, the short-haul aircraft and the helicopters -- are pressurized; nor do they all offer the relatively luxurious convenience of the larger piston and jet airplanes. With a few exceptions, they provide for vertically suspended, adjustable litter supports; airline type seats for ambulatory patients (which face to the rear as a safety feature); adequate lighting, heating and ventilation; and latrines and wash basins. Electrical connections for powered equipment (e.g. suction), non-skid flooring surface, galleys, and luggage and supply storage facilities are important. Oxygen is available in various systems. Ease in loading and deplaning of patients is given considerable attention in transport design and utilization. Some of the aircraft can be loaded only to a door high above the ground, which imposes a requirement for ramp equipment. Riggings for isolation or modesty curtains are provided. The basic litter supports themselves also serve as infusion stands.

Moving patients in the domestic system requires four distinct types of mission: (1) trunk line; (2) inter-area; (3) area feeder; and (4) offshore.

On the trunk line missions, covering relatively long distance routes, C-118 (Douglas DC-6 type) aircraft are employed; the medical crew consists of two nurses and three medical technicians.

The inter-area mission is normally utilized to pick up and deliver patients who stop between two major patient terminals. The area feeder, on the other hand, originates and terminates at the same station -- moving patients to and from hospitals in the surrounding area. Both the inter-area and area feeder missions are carried out by C-131 (Convair 240) aircraft with a medical crew of one nurse and two medical technicians.

The offshore mission is, at present, being handled by augmentation from the Air National Guard, using both C-121 (Lockheed Constellation) and C-97 (Boeing stratocruiser) aircraft. Each carries a crew of two nurses and three medical technicians. Such a route structure makes it possible for the Air Force to provide normal service in the overseas ports at McGuire Air Force Base, New Jersey and Travis Air Force Base California, on a twice-a-week basis -- and the same frequency to most major hospitals. The offshore routes operate on a bi-weekly basis. With the recent increase in patient loads to Travis growing out of the Southeast Asia conflict, additional trunk line missions have been necessary. When the influx to this aerial port has been greater than the capability of the domestic system to absorb, route extensions of jet aircraft from the Southeast Asia area have been made to major domestic patient treatment areas.

In intertheater operations, jet aircraft are used. The introduction in 1961 of the C-135 (an early cargo version of the Boeing 707) marked the greatest forward step in aeromedical evacuation since the advent of cabin pressurization. Flying above most inclement weather at better than 450 knots (520 m.p.h.), boasting a tremendous range, and being readily convertible from cargo/passenger to aeromedical evacuation configuration, the C-135 revealed a new horizon in aeromedical evacuation concept and technology.

In mid-1965, the Lockheed C-141 Starlifter succeeded the C-135 as the major MAC long-range transport. The C-141 is a high speed, long range, high swept-wing aircraft powered by four turbofan engines. It is 145 feet in length, with a wing span of 160 feet. Its spacious cargo compartment can be equipped to carry more than 150 troops, or up to 80 litters in rows of three and four tiers each (fig. 2). In the latter configuration, there is space for up to 16 attendants. Various combinations of litters and seats for ambu-

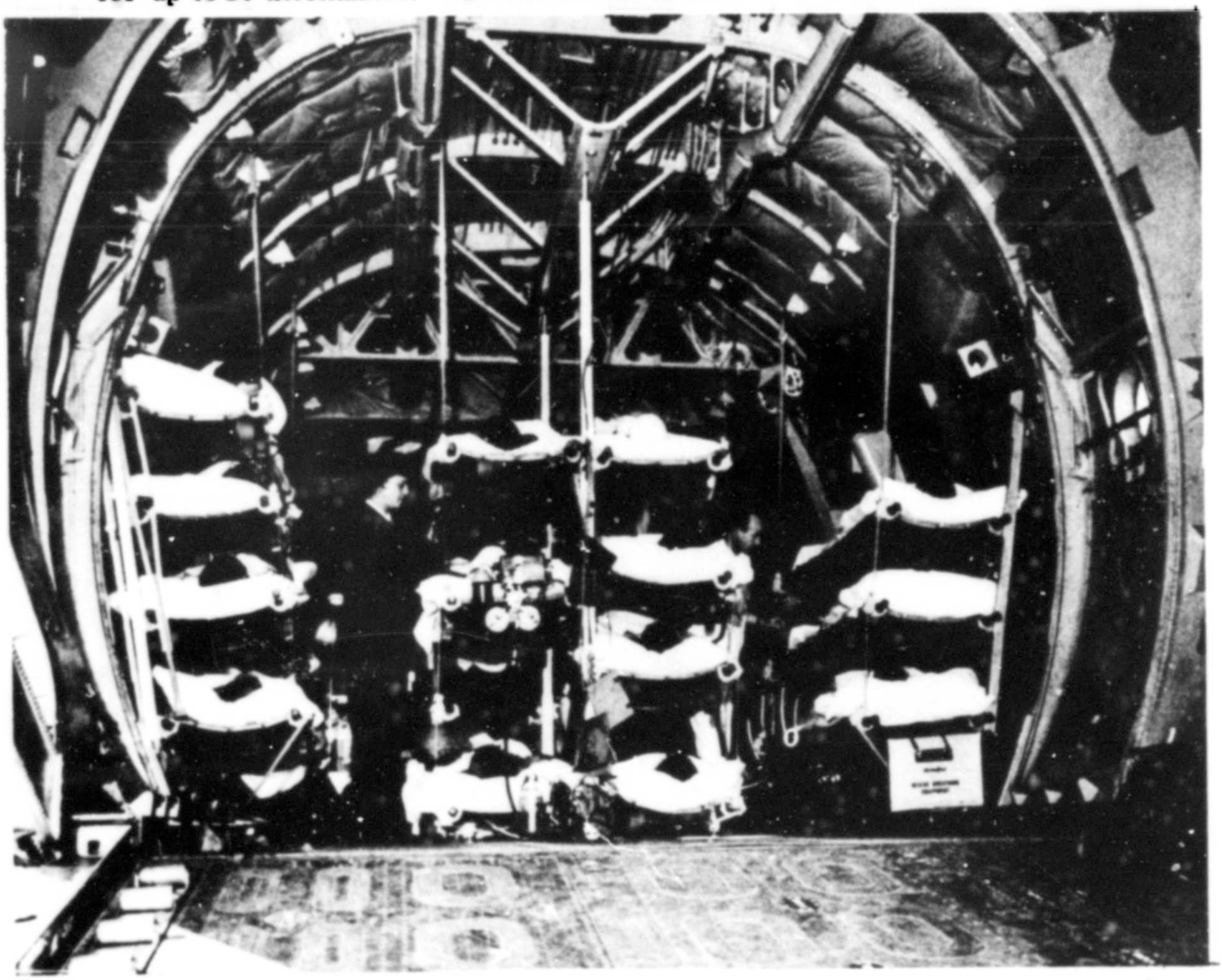

Figure 2

latory patients are also possible, the usual configuration being 42 litters and 42 seats. Average cruise speed is 420 knots (485 m.p.h.) at an average cruising altitude of 33,000 feet. With an 80-litter load, the non-stop range is 5,000 nautical miles (5,750 statute miles). The time required to convert from cargo to patient mode is less than three hours.

It should be emphasized that the C-141 is a multi-mission aircraft, capable of transporting troops of more than 50,000 pounds of cargo overseas and then returning in the aeromedical evacuation mode.

Crew and patients on the C-141 have separate oxygen systems; the latter is capable of supplying 80 litter patients with continuous flow oxygen for nine hours at 25,000 feet cabin altitude. The flow can be manually activated or starts automatically at 12,500 feet cabin altitude. Some of the O_2 distribution lines are permanently installed, while others can be attached with the litter stanchions. Two regulator panels are available for the therapeutic oxygen system. The masks used are of the plastic throw-away type, with quick-disconnect fittings.

Two identical and parallel air conditioning systems control the environment within the aircraft. Temperature control is achieved through ceiling and floor heating; cabin temperatures are comfortable. Inflight humidity ranges between 3 and 25%, a distinctly suboptimal level which must be taken into account in the case of tracheostomized patients. Interior noise levels, although high in relation to airline criteria, conform to military standards and are not dangerous to the patients.

The aircraft is designed to operate with a normal cabin pressure differential of 8.2 psi and a maximum of 8.6. Thus, the pressurization system is capable of maintaining sea level cabin pressure until the aircraft reaches a true altitude of 21,000 feet. At 33,000 feet -- the normal cruising altitude -- an equivalent cabin altitude of 5,500 feet or less is maintained. If circumstances should require, it is possible to maintain sea level equivalent altitude up to as high as the 31,000 foot flight level. At the 40,000 foot level, a cabin altitude of 8,000 feet or less can be achieved. No instance of loss of cabin pressurization has been reported in the C-141, and only one instance is on record for the predecessor C-135 aircraft.

A palletized comfort station is located in the forward end of the cargo compartment. This modular unit contains two flush-type latrines, washbasins, and well-equipped galley facilities. The requisite electrical and waste removal provisions for the comfort pallet are a permanent part of the aircraft installations. Baggage storage is also palletized.

As to emergency provisions, five to six 20-man life rafts are carried, and an individual specially-designed life vest is supplied for each patient. Three escape hatches are provided in the cargo/patient compartment.

Petal-type rear-end doors with self-contained ramp simplify patient loading directly from ambulances. Side paratroop doors may also be utilized for boarding ambulatory cases (fig. 3).

Figure 3

(4) Special Equipment and Supplies. The requirement for reduced weight and bulk inherent in the air transport mode has led to many innovations and adaptations in equipment. Electrical equipment, for example, had to be made compatible with the aircraft electrical supply system, and designed to prevent interference with navigation and communications systems. Back-up systems are available for the more critical items of equipment. Lightweight Carmody aspirator and Globe or Handy combination resuscitator sets are used. The Ambu respirator bag, with masks and pedal-operated suction, is usually available. Standard incubators are employed for premature infants.

On smaller aircraft, oxygen is carried in small portable, lightweight low-pressure "therapeutic kits," with simple continuous-flow regulator. There are replenishable from the aircraft's central O_2 reservoir. Larger aircraft carry the conventional large green high-pressure tanks in a special harness with the bubbler type humidifier. Troop oxygen outlets abound in all troop carrier transports. The jets provide for emergency oxygen in the event of cabin depressurization. In the C-141, a liquid oxygen system provides for the greater quantities required by larger patient loads on 9-10 hour transoceanic flights. The oxygen may be administered by any of the conventional methods.

Folding litters with lightweight aluminum or wooden parallel frames allow for easy portability and security. Foam mattresses and head rests provide a measure of comfort. The space between tiered litters is adjustable, and litter straps are mandatory. Riggings are such that Stryker frames can be securely carried. A special Collins traction apparatus (12) is used for spinal injuries; this is a portable device for maintaining constant traction, by means of an adjustable spring, even during aircraft maneuvers or turbulence.

When a full body type respirator is indicated, the lightweight (200 lb) respirator developed by the USAF School of Aerospace Medicine (SAM) may be used (fig. 4). This SAM lung, powered by aircraft current inflight and

Figure 4

by special battery power packs between bedside and aircraft, and equipped with a back-up motor and manual control lever, has enjoyed a most distinguished career in the poliomyelitis era. Wilson's fine studies (10), and the work of the SAM special polio movement teams around the globe have written a particularly stirring segment of the history of Air Force medicine. During the 12 years from January 1955 to January 1967, 532 polio patients requiring respiratory assistance were transported safely and without mortality.

Emerson pleural drainage pumps or simple closed water seal drainage bottles are used when pneumothorax cases required movement.

More recently, with the development of intermitten positive-pressure respirators, the Air Force has employed the small eight-pound Bird respirator to help move patients requiring partial or complete respiratory assistance. This machine may be driven by air or oxygen. A special litter mount, (conceived by Captain Donald F. Sweeney and Staff, USAF Hospital Travis, and developed and produced by the Bird Corporation, Palm Springs, California) utilizing two small D-type O_2 cylinders, has been developed for inflight use as well as in transporting patients to and from the aircraft (fig. 5). Each cylinder contains a one-hour oxygen supply. The cylinders may be exchanged without interrupting respirator operation, and connections on the regulator provide for attachment to larger or more centralized O_2 sources. Total weight of respirator, mount and cylinders is 35 pounds; lighter weight cylinders are also available. Ease of operation, and economy of space, weight and equipment, have been dramatic. Aeromedical evacuation crews receive special training with the respirator, and a flight surgeon or anesthesiologist accompanies patients with respiratory paralysis or failure.

One of the problems encountered in transporting tracheostomized patients has been the drying of mucosal surfaces and thickening of tracheal secretions. These phenomena have proved troublesome in spite of special attention. In the C-141, the ventilation system produces a relative humidity between 3 and 25%, depending upon specific location in the aircraft. To counteract this, studies have been initiated on the use of the "artificial nose" (13), an aluminum foil head-and-moisture exchanger which acts as a self-humidifying device (fig. 6).

Most of the items for inflight patient care are disposable, just as their counterparts on a modern hospital ward might be. Plastic bags are used for drainage and colostomies. The aeromedical evacuation aircraft is, in the truest sense, a general ward -- with a variety of patients requiring varied medications, observations, nutrition, fluids, sedation, and provisions for excretions and comfort. The flight is equipped with supplies and dressings; the flight nurse's kit is a miniaturized pharmacy. Injectables come in pre-packaged disposable units. Special medications, including intravenous fluids, are carried as required.

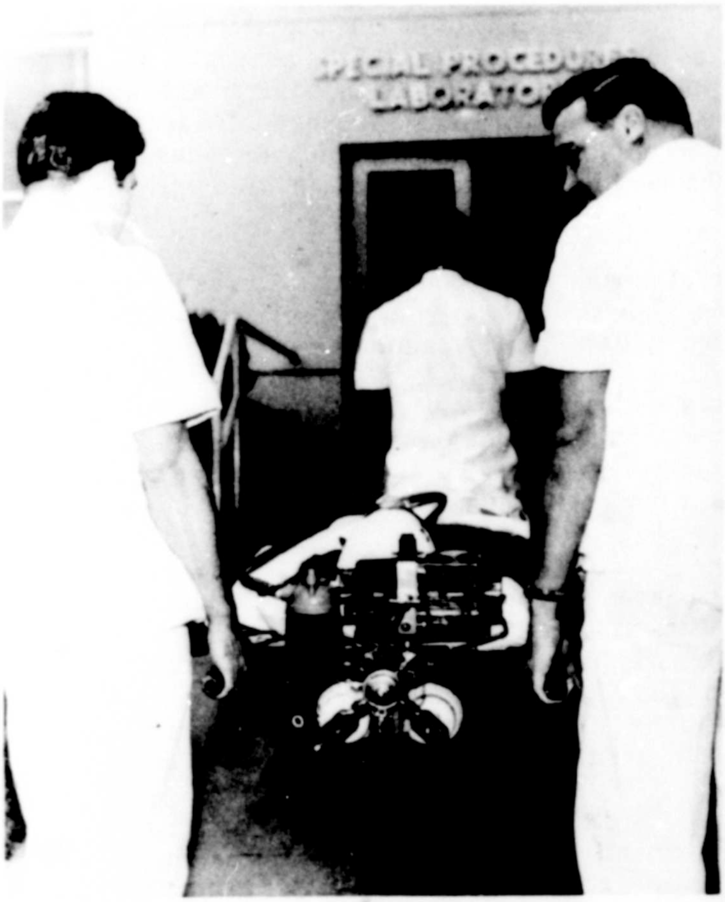

Figure 5

Figure 6

As in the more conventional hospital on the ground, however, wards and equipment are only as good as the personnel who serve them.

(5) Medical Crews. The Military Airlift Command acts in accordance with a fundamental aeromedical evacuation thesis: "Patients are not cargo; patients are not passengers; patients are patients." Thus, everything humanly possible is done to personalize the care, observation and treatment of the patient, both inflight and at in-transit facilities. The flight medical crew is, without question, the vital keystone of the entire aeromedical evacuation concept. The crew may vary from a single aeromedical technician, alone with his severely injured passenger in a helicopter under fire in the forward combat areas, to a sophisticated team in a large jet; either way, the objective and the motivation are identical: care of the patient.

The flight nurse represents the ultimate elite in the Air Force Nurse Corps. Specially and painstakingly selected, the prospective flight nurse -- although already a registered nurse -- undergoes an intensive six-week course in aeromedical evacuation at the USAF School of Aerospace Medicine, Brooks Air Force Base, Texas. The subject matter ranges over a broad spectrum -- from aviation physiology, pharmacology, advanced first aid and psychiatry to ditching and survival training. All must be physically qualified, and all are required to take physiological training, which includes an altitude chamber flight to 43,000 feet with exposure to "rapid decompression."

The flight nurse carries a great burden of responsibility. As she tends her flying ward of sick and wounded, there is usually no physician immediately available. She must know her patients, her machines and her medicine. She discharges the composite function of RN, stewardess, record keeper and problem solver, capable at all times of anticipating and responding to emergencies. She dispenses her medication on time, even though jet aircraft rapidly traverses numerous time zones. She is decisive, necessarily capable of independent action, a thorough observer and a warm, understanding human being.

On transoceanic flights, two nurses share the workload and maintain their inflight medical records. They also maintain continuous contact with the flight crew to keep informed on possible turbulence or changes of altitude. Patients are constantly being fed or comforted, or having their dressings changed. Oxygen may be required, the infusion may infiltrate. There is little time for relaxation. In truth, medical crews figuratively walk their way around the world.

Assisting the flight nurses are expertly trained aeromedical technicians, whose training is equally discriminating and rigorous. They are graduates of the Medical Technician Course at Gunter Air Force Base, Alabama. They are further trained in the Aeromedical Technician Course at the School of Aerospace Medicine, in a five-week curriculum similar to that of the flight nurses' but less technical.

On certain flights, a flight surgeon or other physician may be added to the crew when one or more particularly ill patients are aboard.

There are thousands of dedicated, hard-working personnel in the United States Air Force Medical Service; no finer compliment can be paid to any of them than to identify him or her as a member of the aeromedical evacuation team.

PATIENT SELECTION FOR AEROMEDICAL EVACUATION

In forward aeromedical evacuation, there is no choice in patient selection. Flying is usually the only possible way to travel. Regardless of the wound or injury, the casualty is flown to a better treatment locale following first aid.

Currently in Southeast Asia, a variety of patients are moved by helicopter and light plane every day. In the forward areas, the flights are of short duration at relatively low altitude -- posing only a limited risk as weighed against the necessity of delivering the patient for further, frequently life-saving, care. Often no medical officer is initially available for medical aid and clearance.

Following the first echelon move, every attempt is made to stabilize the patient's condition. Until the patient reaches an adequate medical facility, there can be little if any selection for aerial movement.

Intra-theater aeromedical aircraft move "stabilized" casualties and other patients within and from the combat zone; medical clearance, at this stage, has already been established. The duration of flight is longer, the loads urgently large and the medical flight teams busier. Aircraft utilized in this phase include the military equivalents of the Hercules turboprop assault aircraft (C-130), the DC-6 (C-118), and the Super Constellation (C-121).

In the chain of patient mobility to larger overseas hospitals and to the United States, patient selection for travel becomes more discriminating, even though -- paradoxically enough -- the aircraft used in this link provide more comfort and more sophisticated equipment. Rigid patient selection is important for the longer duration flights because the aircraft are neither flying operating room suites, blood banks, nor spacious hospital wards complete with on-call physicians.

The factor governing selection for movement outside the combat zone are manifold; they include such considerations as intra-theater and offshore bed availability, medical resources, and military operations. Patients with illnesses or injuries from which they can be readily returned to effectiveness are rarely moved an appreciable distance unless bed capacity is compromised. Those, on the other hand, who require specialized care and hospitalization beyond a period prescribed by the theater commander (presently 60 days), are flown to the United States. This includes patients whose care will be long term, or who are unlikely to be restored to effectiveness, as well as cases requiring ultra-specialized care or elaborate diagnostic procedures.

Intra-theater aeromedical evacuation systems deliver relatively short-term injury and illness categories from casualty staging areas to offshore service hospitals. They also transport the severely wounded, or those afflicted with more chronic and debilitating illnesses, to the large and busy casualty staging unit at Clark Air Base in the Philippines. There the giant jet C-141s stand by for the now "short" over-ocean haul home. Stops may be made at stations along the chain of movement for on - or offloading of patients.

The physiological determinants for patient selection are based upon ascent to higher altitudes. This, of course, is accompanied by a decrease in barometric pressure, resulting in (1) reduced partial pressure of oxygen, which occasions a reduction in the oxygen saturation of arterial blood; and (2) expansion of body gases.

Cabin pressurization in modern aircraft permits flights well above 25,000 feet with cabin levels equivalent to residence at 5,000 to 8,000 feet. However, some patients suffering from anemia or heart or pulmonary disease, who are comfortable at sea level, may develop hypoxic symptoms at even these relatively low cabin altitudes.

Expansion of air in the body cavities is in proportion to the increase in altitude. At 5,000 feet above mean sea level, 1,000 cc of air will expand to 1,200 cc; at 10,000 feet, to 1,500 cc. The presence of air -- intercranially following a skull fracture, or in a pleural cavity, pulmonary cyst, mediastinum, or in an injured eyeball -- can under these circumstances be very dangerous. Expanding intestinal gas may produce pain and threaten wound integrity in the recent post-operative state. Colostomy cases tend to experience increased drainage. In such cases, the flight nurse may request lower altitude missions or, where possible, an increase in cabin pressurization.

It may be seen, then, that while there is no absolute contraindication to aeromedical evacuation, the physiological changes resulting from changes in altitude must be carefully considered in every case. It should also be noted, in this connection, that the U.S. Navy currently has an airborne hyperbaric chamber under study.

The Air Force has developed patient selection policies on the basis of physiological responses to the flight environment, practical experience with millions of air transported patients, and certain general principles. Requirements and policies during periods of military action and in the area of hostilities are necessarily different from those obtaining in peacetime.

Following are a few of the general guidelines referred to above:

Moribund patients apt to die enroute, or those with highly contagious diseases, are not normally transported. Terminal cases may be moved for compassionate reasons. Acute infections of the central nervous system are moved only if adequate medical care is locally unavailable and transfer will be lifesaving. Special care and equipment may be requested enroute.

Mandibular fractures are not moved unless provided with instantly removable or elastic tie-bands. Lacking such provisions, emesis could be catastrophic.

Patients with active pulmonary tuberculosis are routinely transported, with special attention to sputum disposal and the wearing of face masks. Transportation of infectious hepatitis and malarial patients has caused no problem, except that such patients are more prone to airsickness. Special consideration is given when moving patients with pneumothorax, heart failure and chronic pulmonary diseases, including asthma and emphysema. Advanced pregnancy and blood dyscrasias may also necessitate special attention. Several deliveries have occurred during flight in the aeromedical evacuation system, although in general travel during the final month of pregnancy is discouraged.

Intracranial lesions, particularly with increased intracranial pressure; and patients in shock, or with acute and severe trauma; are transported only when adequate medical care is not locally available.

Patients with post-traumatic progressive acute renal failure, and those with hepatitic insufficiency, are poor risks. Again, however, if there is a necessity for transfer, there is no contraindication involved.

Acute burn cases have frequently been moved to burn treatment centers, receiving active treatment enroute. They are generally transported early, between the shock and infection phases, and are kept covered.

Altitude restrictions are applied for penetrating head and eye injuries, severe anemias, pneumothorax, severe emphysema, very recent thoracic and abdominal surgical patients, and known sickle hemoglobinopathies.

Cast changes, where required, are performed at least 24 hours before movement. Bi-valving of newly applied casts is recommended.

Psychiatric patients are specially categorized for movement, and managed accordingly.

As a result of the hostilities in Southeast Asia, patient flow across the Pacific has increased. In general, the foregoing principles and practices have been followed. As medical capability in the overseas areas has improved, patient selection has become more discriminating. Casualties in the postoperative state have been successfully airlifted in pressurized aircraft, after having been stabilized and made comfortable.

To assist in the observation and care of patients in the aeromedical evacuation system, the following classification of patients is followed:

a. Class 1 - Psychiatric Cases

(1) Class 1A - Severe; requiring restraints, sedation and careful observation. Litter.

(2) Class 1B - Moderate to severe; potentially troublesome; requiring sedation. Litter.

(3) Class 1C - Mild; cooperative and requiring relatively little observation. Ambulatory.

(All Class 1 patients are specially positioned within the aircraft for optimum observation)

b. Class 2 - Litter Cases (Non-psychiatric)

(1) Class 2A - Unable to leave litter.

(2) Class 2B - Able to ambulate in emergency.

c. Class 3 - Ambulatory Cases (Non-psychiatric), requiring minor medical attention.

d. Class 4 - Ambulatory Cases (Non-psychiatric), capable of unattended travel; requiring no treatment other than medical surveillance.

This classification system has proved to be most effective in promoting both more selective patient care and more efficient aircraft utilization.

A system of patient movement precedence is also followed, divided into the three categories of "urgent," "priority," and "routine." Under this system, the diagnosis and severity of the patient's condition do not by themselves determine the category to which he is assigned. The governing factor, rather, is the importance of timing of movement in order to save life or provide essential medical care.

Patients who must be moved immediately for emergency treatment, to save life or prevent severe complications of an existing serious illness, are classified Urgent -- and are moved immediately.

Patients requiring prompt medical care, which is not locally available, are classified Priority -- are enplaned within 24 hours, and delivered to a definitive treatment medical facility with the least possible delay.

Other patients are classified as Routine; they are enplaned within 72 hours, and moved on routine or scheduled flights.

Each Aeromedical Airlift squadron keeps an alert crew available at all times to respond to these special requirements, inasmuch as some Priority and almost all Urgent patients require a special mission to satisfy the postulated time criteria. The flight time and medical crew requirements for these special missions are generally predictable over a fairly extended period of time, but such missions consistently create irregular peaks in the workload as viewed over the shorter term.

SCOPE OF AEROMEDICAL ACTIVITY

On the 12th of October, 1965, 13 missions were operated in the domestic aeromedical evacuation system, encompassing a total of 62 departures, 171 patients moved, and 90 hours of flying time. That was a typical day, since the number of patients moved each 24 hours varied at that time between 150 and 350. The number of patients, however, is now on an uptrend because of the influx of medical cases from Southeast Asia.

Despite the increase, every effort is made to limit the number of stops per mission so that pick-up and delivery can be made during the normal working hours of the using medical facilities, and for the convenience of the patient. This is not always possible to achieve -- due to the patient loads and the numerous facilities to be served along some of the evacuation routes. Obviously, full cooperation of the hospitals using the aeromedical evacuation system is absolutely necessary; having patients ready at the time of pick-up, and planning ambulance and bus transportation for them, are essential.

A FLIGHT PROFILE

The inter-theater aeromedical evacuation activities are equally as busy as in the domestic system. Some feel for the complex relationships may be derived by following the planning and procedures required for a typical flight across the Pacific.

In Southeast Asia, a centralized medical regulating office coordinates patient requirements with bed availability within the theater, and alerts the casualty staging unit at the aerial port. Coordination and communication are basic to smooth reception. Among the requirements bearing upon the situation are: flight arrival time; number and type of ambulances; litter bearers; deplaning ramp; air conditioning units; lighting for night arrivals; portable communications systems; and a standby medical officer for triage of patients.

The pre-arrival manifest will include patients' names, diagnoses, travel classifications and destinations. The report might read, as an example, "40-20" -- indicating 40 litters and 20 ambulatories. The number of seriously ill is reported, and the need for special or emergency equipment made known.

At the overseas aerial port, patients from the combat area are rapidly deplaned -- either to the casualty staging unit or to the hospital itself, as determined by the flight surgeon meeting the aircraft. The hospital will receive those requiring special medical observation or intensive care. Patients are refreshed, fed, and treated if necessary. All are seen by the medical staff. Some may be scheduled for surgery or additional studies.

Administrative personnel make appropriate corrections in the records. The Armed Services Medical Regulating Office (ASMRO) in the U. S. is contacted for hospital assignments for those patients approved to cross the Pacific. Customs declarations, passports and other administrative details are attended to. Patients are briefed on the journey ahead, on personal effects, and on their assigned destinations.

When a jet aircraft arrives at the port, it is promptly unloaded and required maintenance is performed. One to three hours are allotted to converting the aircraft to the aeromedical configuration. A flight plan is drawn up. Flight nurses and medical technicians screen both the patients and their records. Physicians' orders are reviewed. Medical records, special diets, medications, supplies and equipment are collected.

Perhaps the best single example of the broad scope of planning, and the magnitude of the capability of the MAC aeromedical evacuation system, was to be found in the recent movement of 56 Vietnamese paraplegics to the United States aboard a single aircraft. Among the items requested for the flight were litters, mattresses, sheets and blankets, pajama tops, pillow cases, plastic urine drainage bags, large syringes and Foley catheters, tubing by the yard, and a supply of indigenous food. This unusual mission was carried out in an almost routine fashion.

Next, a loading plan is prepared, which considers classification, severity of illness, patient comfort, and requirements for observation. Those with heavy casts, or who are apt to require more medical care, are positioned in lower litters or more proximate to the nurses' station. Bulkhead litter stations are preferred for the very ill. Psychiatric patients are carefully located (the use of tranquilizers has greatly eased the problem of transporting agitated patients). A single litter tier, although it may be occupied by only one patient, displaces three rows of triple seats. Patients with spica casts are allotted two litter positions, Stryker frames three. There is always a competition, or trade-off, as between special equipment and patient-carrying capacity.

The patients are fed prior to departing the staging unit or hospital. Casts and dressings are checked. One hour is allotted for departure from the unit, and an additional hour for loading the aircraft. At the plane, a portable air conditioning unit provides comfort until such time as the aircraft's own systems go into operation.

On board, flight plans and ditching assignments are reviewed by both the flight and medical crews. Life vests are made conveniently available for each patient; 20-man life rafts and associated survival gear are strategically located. All loose items and litter riggings are secured, the passengers are briefed -- and the flight departs.

While, as may be seen from the above, preflight preparations are numerous and painstaking, the inflight portion likewise consists of a constant but quiet stream of activity and infinite detail. In the relatively noisy interior of the flying ward, the team pursues duties comparable to those of their ground counterparts -- although admittedly under somewhat more exacting conditions. Limited, concise records of course and treatment are kept. Patient requirements are programmed from a posted nursing care plan. Vital signs are checked. Fluids and hot and cold meals are served. All litter patients receive back care.

At intermediate stops, where time zones differ, Greenwich Mean Time is used to avoid confusion. At these infrequent stations on the journey from Southeast Asia, patients may be delivered to treatment centers, or others brought aboard. Changing climatic conditions may necessitate flight line heating and an exit weather curtain. Patients in coma or requiring tracheostomy care are constantly attended during the stops. The latter requires very special care, as has been pointed out, because of the low cabin humidities and the ready tendency of secretions to inspissate. Colostomy excretions tend to be profuse, requiring frequent plastic bag changes. Infusions tend to run more slowly. Compatible blood is occasionally carried for special cases, but transfusions are rarely administered in flight without a physician in attendance. In pressurized jet aircraft, airsickness and barotitis have been encountered much less frequently.

Refueling, where necessary, is rapid. Red Cross and volunteer workers board with refreshments and comfort items. Fire and rescue crews stand by at all times. Flight schedules are interrupted only by maintenance needs. Should delay for any reason be protracted, the system is prepared for the care of the en route patients.

Flight and medical crews are replaced at major stops; the essence of the movement is continuity of patient care and speedy transport. Hushed and unhurried care is administered even in emergencies. Special equipment stands by, ready for immediate use.

At the aerial port of debarkation in the United States, a well organized reception team rapidly deplanes the patients to the casualty staging unit. Here, prior to transfer to the domestic system, rest, screening and additional care are offered.

The record of the USAF aeromedical evacuation system speaks eloquently for itself: Since 1954, 79,152 cases have been airlifted over the Pacific. Of this number, only thirteen have expired in flight; 78% of which were seriously wounded or burned casualties from Southeast Asia.

Although both the inter-theater and domestic systems are operated by MAC, as Air Force command, the patients in hospital clothing are indistinguishable as to whether they are Army, Navy, Air Force or Marine

Corps. In fact, regardless of the service to which they belong, all are tendered the same painstaking, personalized care which they have so richly earned -- and so patiently deserve.

SUMMARY

Long and extensive experience has demonstrated that any patient capable of being moved can be transported by air.

Aerial movement has played a key role in improving survival rates of the wounded. Rapid, safe movement of casualties to field hospitals, and thence to larger medical centers, has made prompt specialized care possible. Strategic and domestic aeromedical evacuation capabilities have placed the large and splendid military medical centers in the United States within 24 hours of actual flying time from any combat zone. During his transportation, the patient is kept under continuous medical surveillance. He is carefully screened at the casualty staging centers of both the aerial ports of embarkation and debarkation. He receives medication and ancillary care in flight. Special equipment is utilized for cases requiring suction, oxygen, respiratory assistance, traction and the like.

The outstanding record in movement of patients by aeromedical evacuation teams is due in large part to extremely careful preparation for flight. This is then consistently followed by continuous careful treatment during en route transportation, and all along the way to the final destination of the patient.

As a result, the prompt return of a seriously injured serviceman to a hospital close to his home is not only medically effective, but psychologically - is a tremendous adjuvant to morale, both for the patient and for his family.

Second, early and safe evacuation of patients reduces the strain on the overseas medical facilities in the field, thereby increasing their potential for managing casualty surges.

And finally, aeromedical evacuation permits the conservation and centralization of the large but by no means unlimited resources of military medicine, limiting the requirement for constructing additional expensive fixed medical facilities overseas, with their concomitant enormous requirement for logistical support.

The concept and the techniques of this miracle of medical movement have, as stated at the onset, been known and applied for many years. The basic difference today is that the modern jet aircraft has provided the aeromedical evacuation system of the Military Airlift Command the necessary additional speed, range and capacity to respond to any requirement for swift mass transportation of casualties on a truly global scale.

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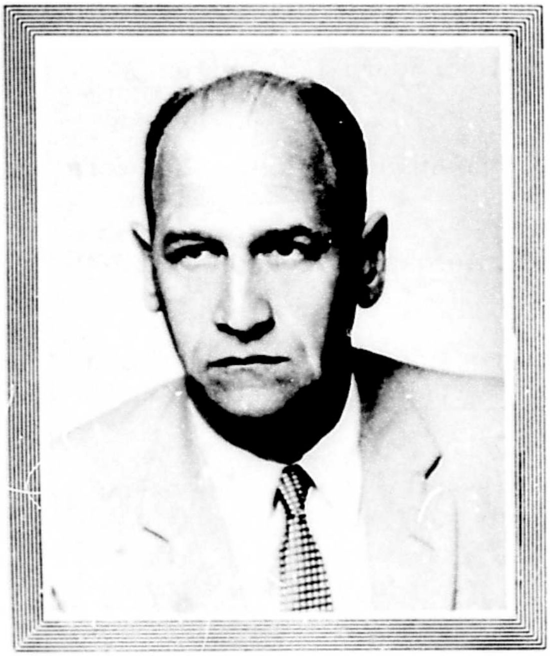
Information Processing Aspects of Bionics



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INFORMATION PROCESSING ASPECTS OF BIONICS

Hans L. Ostreicher, Ph. D.

I. INTRODUCTION

So far the lectures in this series and, in fact, the entire traditional contributions of the life sciences to aeronautics, astronautics, or any other technological area, have been devoted to the protection of man and to the enhancement of his abilities. The contributions of bionics to technology are of a different kind: it is not concerned at all with protection; its goal is, rather, the discovery and formalization of principles found in living organisms, and the application of these principles toward the design of a better technology.

Bionics is concerned with the derivation of technological knowledge from living organisms. By studying how living systems perform technologically important functions, bionics takes advantage of millions of years of evolution of living systems during which they adapted themselves for optimum survival. While nature has done pretty well in many areas, one of the outstanding successes of evolution is the information processing capability of living systems, as exemplified by the "intelligent" behavior of living organisms, and the study of sophisticated information handling techniques is, therefore, one of the principal areas of bionics research. Examples of these superior capabilities are: pattern recognition, concept formation, prediction, optimum decision making, learning and self-adaptive control. Information processing does not exhaust bionics by any means, and in many other areas as, for instance, the structure of materials, conversion of energy, optimum mechanical propulsion, and boundary layer control, highly useful knowledge can be gained from the study of living organisms. However, because of the great importance of information handling for modern technology and the great superiority of some living information processors, the topic of this lecture is devoted to the information processing aspects of bionics.

II. COMPARISON OF NATURAL AND TECHNOLOGICAL INFORMATION PROCESSING SYSTEMS

Let us begin with an assessment of information processing capabilities of living organisms and machines. In order to make such a comparison it is convenient to divide an information processing system, whether living organism or machine (fig. 1) into four stages: (1) The signal reception, where the information enters the system and is converted into a form appropriate for the further stages. (In biological terms: the receptor organs). (2) The preprocessing stage, where certain not too complex routine operations are performed with the incoming signals (biology: peripheral structures). Biological as well as technological systems have found it very useful

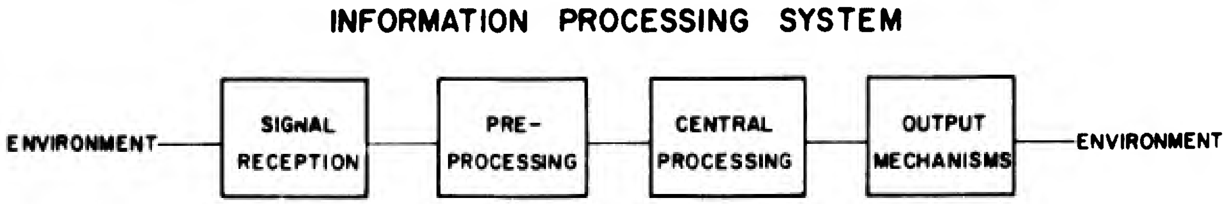


Figure 1

to relieve both the central processor and the communication channels to it by compressing the information content of the incoming signals right at the entrance. (3) The central information processing stage (biology: higher nervous centers). (4) Output mechanisms which convert the internal code into appropriate action and enable the system to interact with its environment (biology: muscles and glands). In table I, some of the functions performed by the four stages are listed.

Table I

RECEPTION	PREPROCESSING	CENTRAL PROCESSING	EFFECTOR MECHANISMS
ENERGY CONVERSION	FILTERING (PROPERTY FILTERING)	LEARNING	CONTROL OF MECHANICAL MOTION
CRUDE FILTERING	SCALING	PROBLEM SOLVING	CONTROL OF ELECTRICAL SYSTEMS
CODING	EDITING	OPTIMUM DECISION MAKING	CONTROL OF CHEMICAL SYSTEMS
DIGITIZING	RECODING	PATTERN RECOGNITION	
	AVERAGING	CONCEPT FORMATION	
	NOISE SUPPRESSION	NAVIGATION	
	CROSS CORRELATION	ASSOCIATIVE MEMORY	
	SHARPENING		
	INFORMATION COMPRESSION AND SELECTION		

Although there is, of course, considerable interaction and feedback among these stages and although the dividing lines among the assignment of particular functions to preprocessing or central processing might be subject to argument, this breakdown gives a useful basic framework for further discussion.

A. Signal Reception

The initial stage of any information processing system, the sensor, deals with the raw information, the external signal. The basic function of a sensor is to receive physical stimuli of the external environment and to encode it in a form appropriate for further processing in the rest of the system.

What do we expect from an ideal sensor? Certainly it should contain all the information which is important for the performance of certain functions and for the achievement of specified goals (in biological systems this goal is ultimately always survival of the species). Surely, the sensor should receive as much "pertinent" information as possible. But, because it is for the later stages of the system to make the usually difficult decision which information in a particular situation is pertinent and which is irrelevent or even confusing, we will judge the sensor primarily according to the accuracy and amount of information it receives. Although the feedback to the receiver from the later stages, filtering less important information, is of great interest (1), it belongs to a later stage and is left out of consideration now. There are, of course, in addition to the accuracy, other factors to be considered, such as weight, compactness, power consumption, etc. Table II shows data characterizing the eye as a receptor. It is tempting to compare these figures with those of a TV camera and an ordinary movie camera, but it must be realized that this comparison would not be fair: The cameras have been designed to match the human eye and an effort to increase the resolution of a TV camera beyond that of the human eye would not make sense. The comparison must, therefore, be made with the limits of technological receptors sensitive to electromagnetic radiation (photosensitive cells and tubes).

The results of table II show that all performance specifications of the eye, however remarkable they are, can be met and surpassed by technological photoreceptors; but at the price of bulkiness, weight, great cost, and

Table II

OPTICAL SIGNAL RECEPTION

		HUMAN
STIMULUS		ELECTRO MAGNETIC RADIATION
SPECTRAL RANGE ($m\mu$)		400 – 750
THRESHOLD (ERG)		10^{-12} (~ 5 QUANTA)
RESOLUTION	INTENSITY $\left(\frac{\Delta I}{I}\right)$	$10^{-2} - 10^{6}$
	TIME (SEC.)	$10^{-1} - 5 \cdot 10^{-2}$
	SPACE (MIN)	$10^{-1} - 10^{0}$
	WAVELENGTH $\Delta\lambda$ ($m\mu$)	1 – 2
CHANNEL CAPACITY (PERIPHERAL)		10^{6} BITS/SEC
NUMBER OF RECEPTORS		$\sim 10^{8}$
PACKING DENSITY (CM^2)		$\sim 10^{7}$
PREPROCESSING		RETINA REDUCTION OF FIBERS
WEIGHT		~5 g
VOLUME		5 CM^3

sometimes low stability and low reliability.

For the reception of acoustic energy, table III gives a comparison of capabilities of the ear and microphones. Just as the eye has reached the ultimate sensitivity in some spectral ranges (sensitivity to a few quanta), it should be noted that the threshold of the ear around 1000 Hz is only slightly above the level of the thermal noise in air and that an increase in sensitivity of the ear would make this noise audible - a very questionable advantage for a living organism.

Table III

ACOUSTIC SIGNAL RECEPTION

		MAN	ANIMAL	MICROPHONE + AMPLIFIER
STIMULUS		PRESSURE VARIATION		
FREQUENCY RANGE (CPS)		15-20000	100-130,000 (DOLPHIN) 30 - 100,000 (BAT) 1000-150,000 (SOME INSECTS)	$0 - 10^{5}$
INTENSITY RANGE DYNE / CM^2		$\sim 10^{-4} - 10^{3}$		ABOVE $\sim 10^{-4}$
RESOLUTION	TIME (SEC)	$\sim 10^{-1}$		$\sim 10^{-5}$
	INTENSITY $\left(\frac{\delta E}{E}\right)$	$\sim 10^{-1}$		$\sim 10^{-4}$ V / DYNE / CM^2
	FREQUENCY	2 - 40 CPS		$\sim 10^{-2}$ %
CHANNEL CAPACITY (PERIPHERAL)		$\sim 10^{4}$ BITS / SEC		
NUMBER OF RECEPTORS		$\sim 10^{4}$		
PACKING DENSITY OF RECEPTORS (CM^2)		$\sim 10^{6}$		
PREPROCESSING		MIDDLE EAR (TRANSFORMER), COCHLEA AND PERIPHERAL NETWORKS		
WEIGHT		$\sim 10^{0}$ g		$\sim 10^{2}$ g
VOLUME		$\sim 10^{0}$ CM^3		$\sim 10^{0}$ CM^3

There are many more interesting receptors in living organisms like chemical sensors, receptors sensitive to electric fields (particularly in fishes), polarized light, wind speed, hydroscopic deflection, hydrostatic pressure, etc., which usually show great reliability and versatility.

Table IV compares the information transmission characteristics of the more important senses in man (2). It is to be noted, however, that the figures for the information capacity hold only for the peripheral receptor organ and decrease sharply as the signals progress toward conscious perception.

Table IV

PERIPHERAL INFORMATION TRANSMISSION
BY HUMAN SENSORY RECEPTORS

	NUMBER OF RECEPTOR CELLS	NERVE FIBER	INFORMATIVE CAPACITY
EYE	$2 \cdot 10^8$	$2 \cdot 10^6$	$3 \cdot 10^6$ BITS/SEC
EAR	$3 \cdot 10^4$	$2 \cdot 10^4$	$3 \cdot 10^4$ BITS/SEC
TASTE	$\sim 10^7$	$2 \cdot 10^3$	
SMELL	$\sim 10^7$	$2 \cdot 10^3$	
TOUCH	$5 \cdot 10^5$	$\sim 10^6$	LOW
PAIN	$3 \cdot 10^6$	$\sim 10^6$	
HEAT	$\sim 10^4$	$\sim 10^6$	
COLD	$\sim 10^5$	$\sim 10^6$	

B. Preprocessing

Preprocessing, i.e., performing simple routine data processing operations at or near the sensor achieves two goals: (1) It relieves congestion of the communication channel to the central processor and (2) it saves capacity at the central processor for more sophisticated operations. Examples of operations performed by biological systems at the peripheral (preprocessing) level are: filtering (Fourier type analysis, but also more complex "property" filtering), scaling, signal sharpening, adaptation, enhancement of signal to noise ratio and many more.

The most refined and best understood examples of biological preprocessors are the middle and inner ear (cochlea) for the auditory channel (3) and the retina for the visual system (4).

The auditory system performs the preprocessing partly by mechanical and partly by electrical means. The retinas of the frog (3) and the pigeon (6) have recently been shown to perform a remarkable "property filtering" by utilizing ganglion cells which fire only under relatively complex outside stimuli, related to danger or food.

Figures 2 and 3 show the simplified anatomy of a pigeon eye and the schematic of an actual hardware model (7) using the same circuits to detect a moving edge. The same model (7) recognizes also verticle straight edges, horizontal straight edges, motion in a particular direction, convex edges

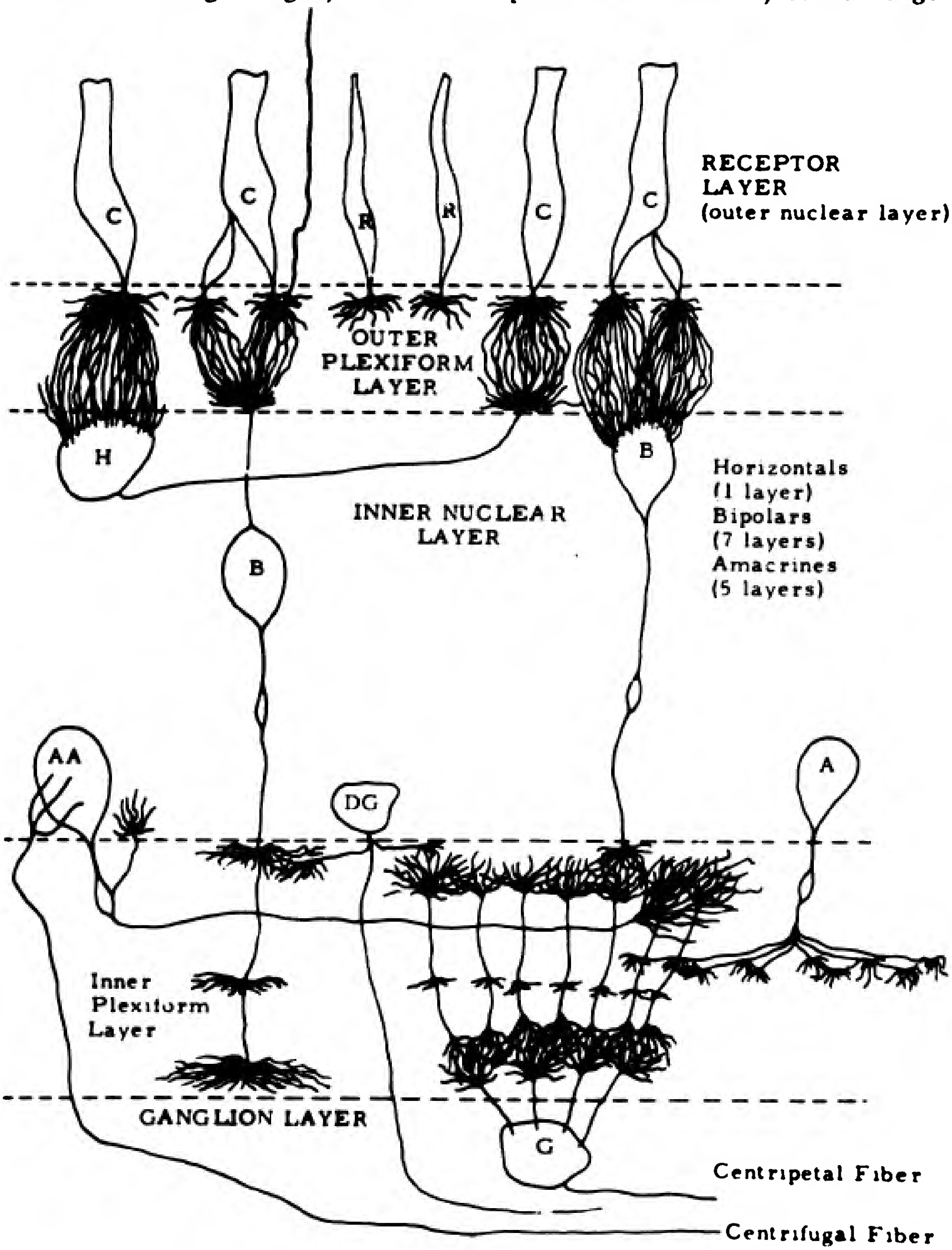
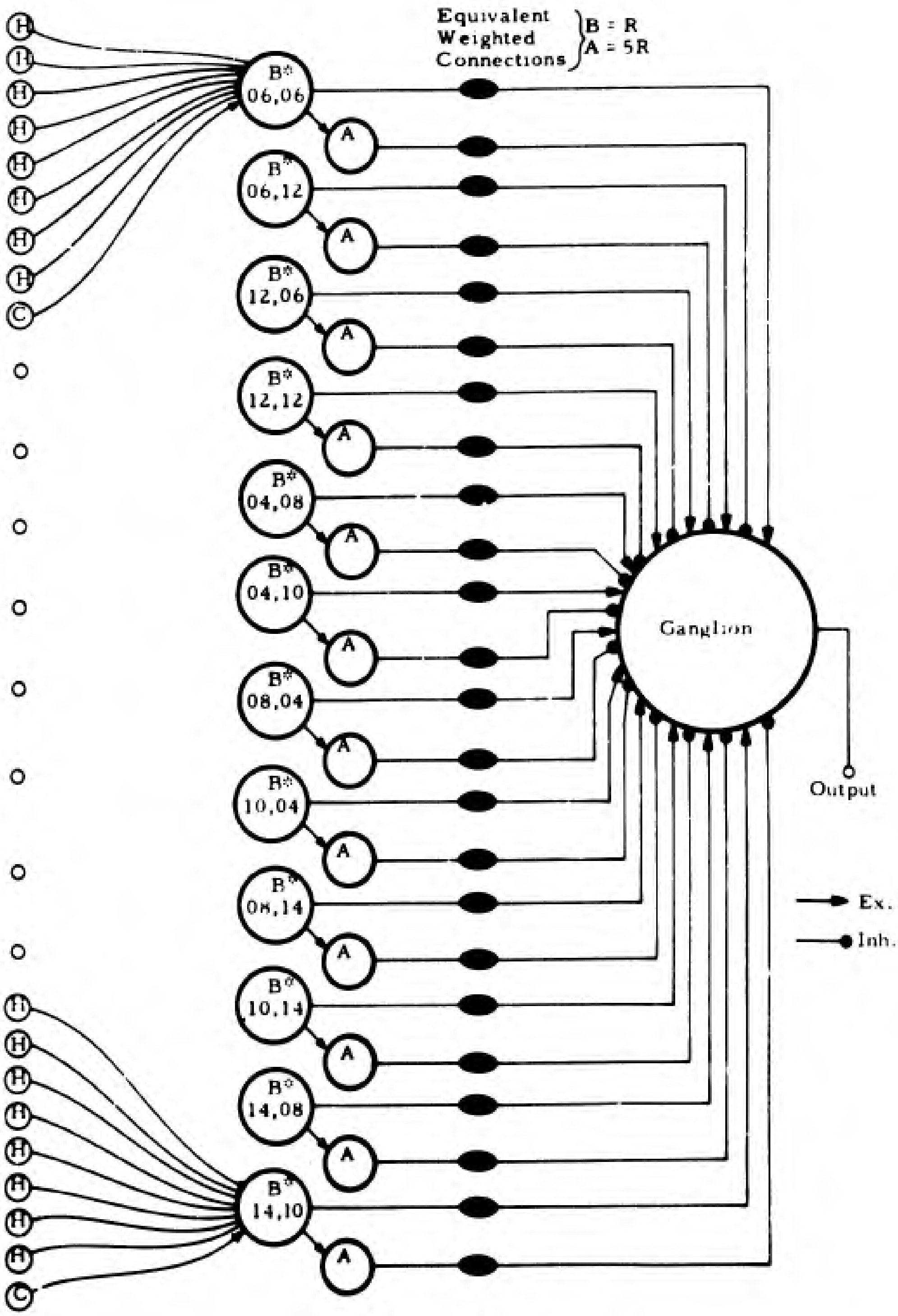


Figure 2 Simplified Diagram of Avian Retinal Anatomy



Moving Spot or Edge Detector

Figure 3

and luminosity. Figures 4 and 5 show the human cochlea and an electronic analog model (8). This model is being used as preprocessor for speech-sound recognition and speech compression (9) because the output channels of the model provide important parameters for speech processing.

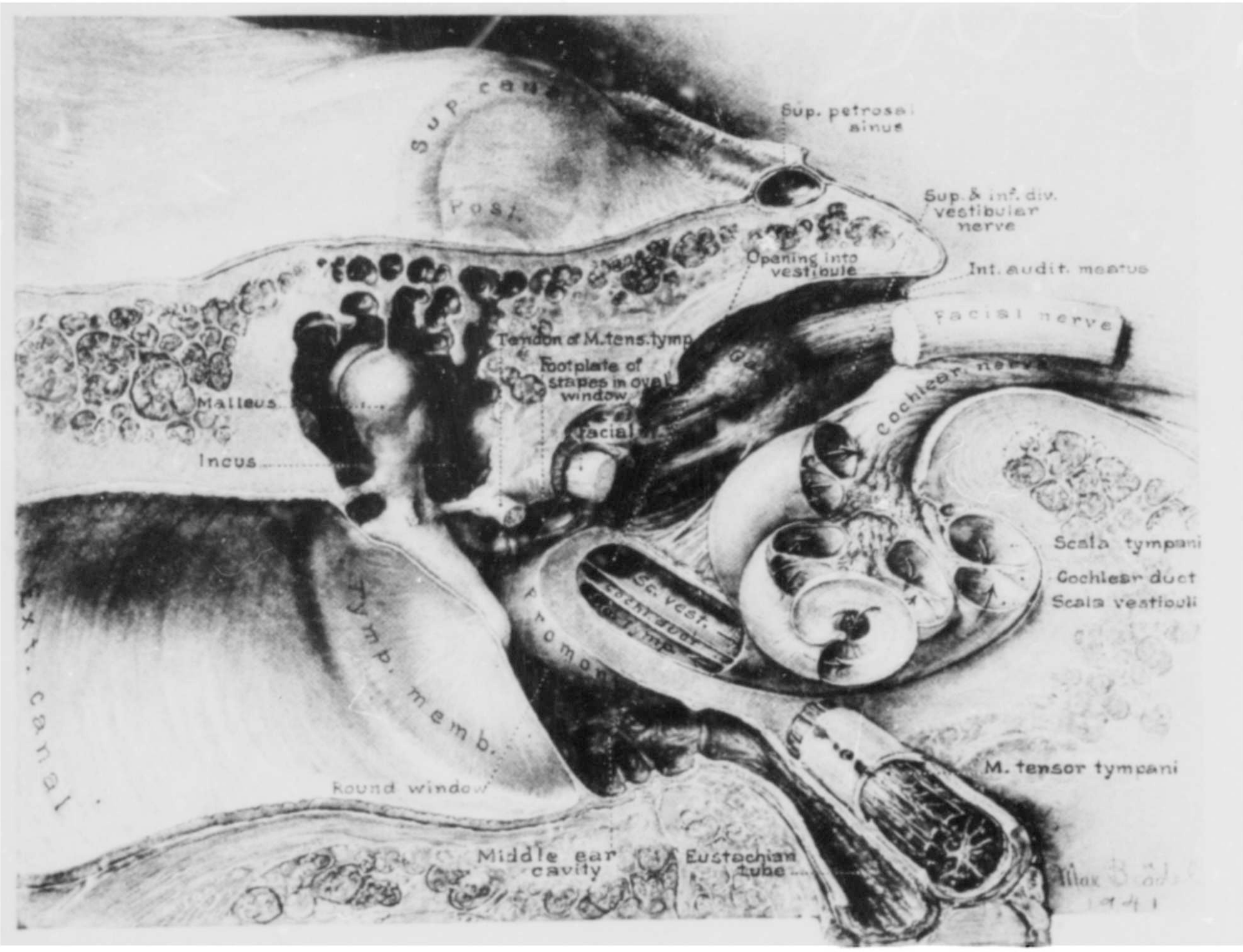


Figure 4. Anatomy of the Middle and Inner Ear.

C. Central Processing

The central processing stage is responsible for the transformation of incoming information into desirable responses. This stage, which is the basis for intelligent behavior, is the most difficult to understand, but offers the greatest challenge to the model builder.

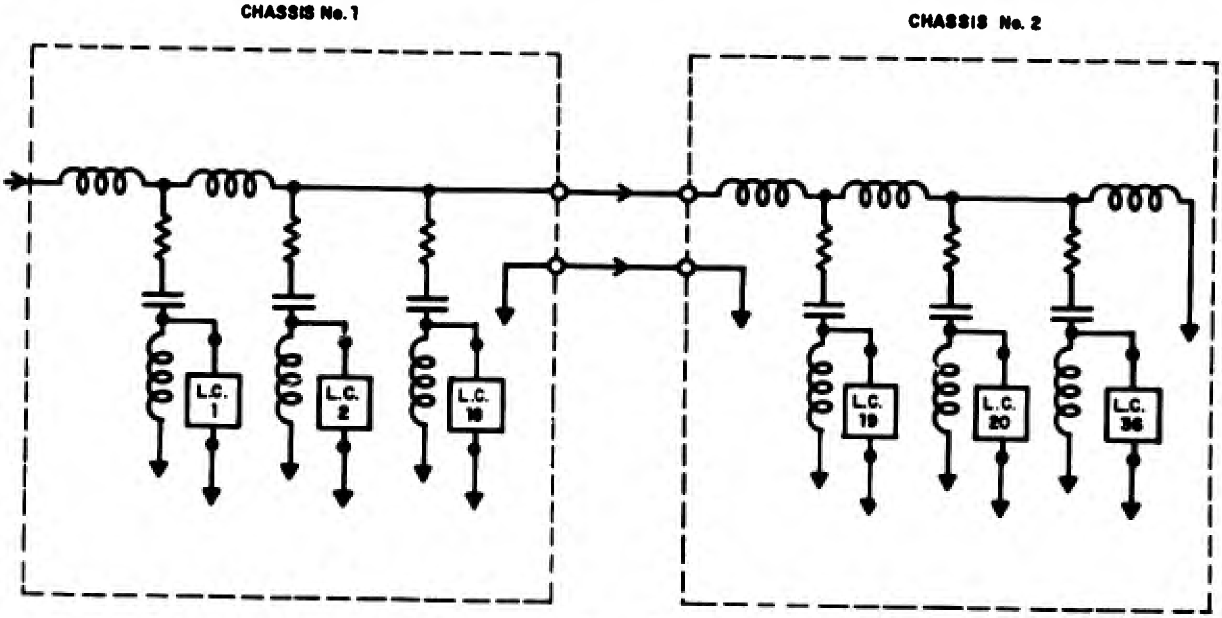


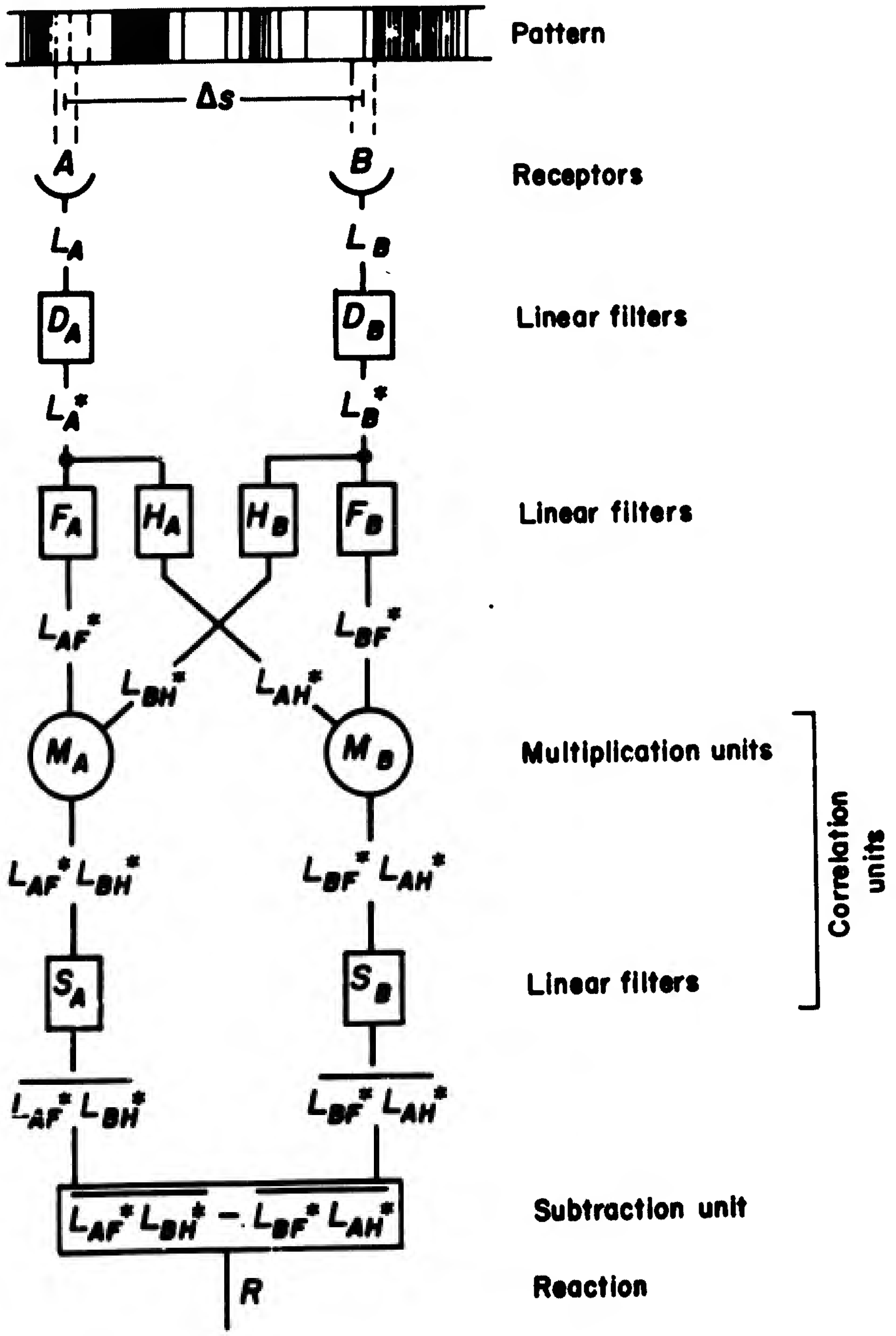
Figure 5 ANALOG COCHLEA

Although the central, integrative processes in biological systems are in general poorly understood, several important principles have been clarified in recent years and models for "intelligent" behavior have been built or simulated by computer programs.

Let me first mention two simpler examples of biological central processors: (1) the well known navigation method of bats (10) which compares favorably with radar or sonar, and (2) the not so well known principle of measuring the ground speed by certain beetles in flight (11). The development of this latter method, based on calculating the auto-correlation function and illustrated by figure 6, into a technologically useful ground speed meter is under way.

For the simulation of the more complex functions of the central processing stage we have on the one hand, conventional large scale general purpose computers with their high accuracy and high programming flexibility, but time consuming sequential operation, and on the other hand, a relatively new breed of unconventional automata developed for the purpose of simulating "intelligent" behavior and built more or less in analogy of biological systems.

Table V shows a comparison of characteristic parameters for the best developed biological information processor (human brain) and a large conventional general purpose digital computer, which is presently in use.



NEURAL NETWORK OF A SPECIAL BEETLE PERFORMING AUTOCORRELATION

Figure 6

Table V

COMPARISON OF INFORMATION PROCESSING SYSTEM

	BIOLOGICAL SYSTEM (HUMAN BRAIN)	COMPUTER (7090)
MODE OF OPERATION	PARALLEL OPERATION, DIGITAL, ANALOG	SEQUENTIAL OPERATION, DIGITAL
INPUT, OUTPUT	$\sim$ 25 BITS/SEC	$\sim 10^{6}$ BITS/SEC
MEMORY: A. CAPACITY	$10^{13}-10^{20}$ BITS	$\sim 10^{6}$ (HIGH SPEED)
B. TYPE	ASSOCIATIVE	ADDRESS
TIME FOR ONE ELEMENTARY OPERATION	$10^{-2}-10^{-1}$ SEC.	$10^{-6}-10^{-5}$
BASIC COMPONENT: A. SIZE	$10^{-8}-10^{-5}$ CM^{3}	$10^{-2}-10^{0}$ CM^{3}
B. NUMBER	$\sim 10^{10}$	$\sim 10^{5}$
C. PACKING DENSITY	$\sim 10^{7}$ CM^{-3}	10^{-1} CM^{-3}
DEVELOPMENT TIME	$\sim 10^{9}$ YEARS	$\sim$50 YEARS
WEIGHT	$\sim 10^{0}$ LBS	$\sim 10^{3}$ LBS

Among the unconventional automata (12-22) which have been proposed for "intelligent" tasks, only few exist as actual hardware models, while the majority is simulated on general purpose computers in order to test the power of the principles.

Three areas to which considerable effort has been devoted and where practical applications are being made or can be expected within the near future, are: pattern recognition, design of learning machines, and speech recognition.

<u>Pattern recognition</u> is a powerful method of information compression and reduction which has evolved in all higher animals enabling them to order and categorize the vast stream of data continuously received through the receptor organs. From an abstract point of view, pattern recognition is nothing but the categorization of signals into classes reducing greatly the number of signals which must be processed. Various models for such pattern recognition machines have been proposed.

Devices capable of recognizing "low complexity" patterns as, for instance, the recognition of printed characters and numerals (reading machines) (23) or of other simple visual patterns (applicable for reconnaisance) are under development and sometimes even in practical use. Principles primarily used in these new developments are: parallel operation, classification based on weighted conditional probability, cross-correlation with a fixed set of functions and various iterative, algorithmic procedures; principles which are theorized to be used by the central nervous system. "High complexity" problems like the recognition of faces or signatures have, so far, found no satisfactory solution. One reason for the lack of success is the fact that present-day machines are too simple to abstract and handle the large number of parameters involved in these and many similar problems encountered in daily life.

Learning Machines. The principle of learning, that is, the capability of a system to change its response to a stimulus depending on the "favorable" or "unfavorable" reaction of the environment to an initial response, promises to become a powerful principle in the design of control systems. Figure 7 illustrates one of several principles which have been proposed for the design of "learning networks." The feedback from the environment to the initial response changes the structure of the system, causing a different response the next time the same stimulus appears. The principle of learning is used in a flight control system (26, 27) which is in an advanced stage of development. Another important application of learning machines is

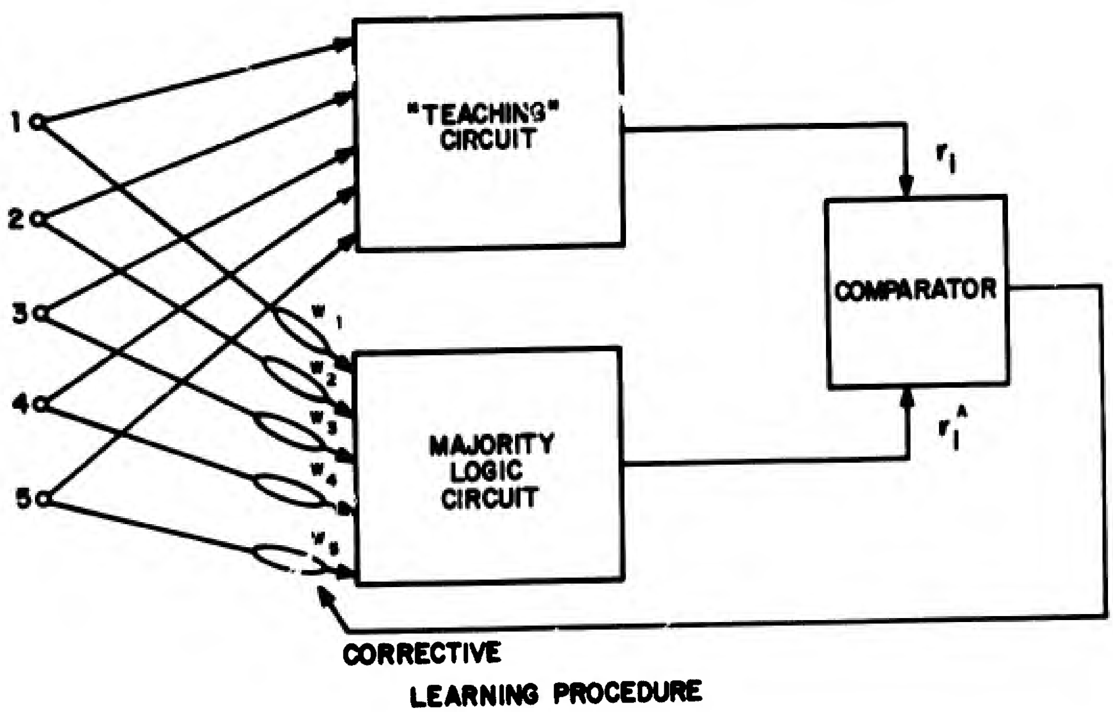


Figure 7

their coupling with pattern recognition devices, which produces a flexible machine which does not only recognize the fixed patterns for which the machine was designed, but can be "trained" to recognize a great variety of patterns.

Speech Recognition. The recognition of spoken words of the English (or any other) language for a wide variety of speakers is a problem of great practical importance and has been attacked by a number of research groups. The main problem for efficient speech recognition consists in the derivation of a set of parameters which characterizes the word, but suppresses most of the other information contained in the acoustic signal.

One of the efforts (9) which has been particularly successful in bandwidth compression of speech is based on the electronic analog cochlea which was described earlier. The same method also shows great promise for success in the recognition of speech.

Speech recognition research has presently reached the point where machines have been designed which are successful in the recognition of a limited, not too complex, vocabulary (5-50 words) spoken by a group of speakers with the same dialect.

D. Output Mechanisms

The last and final stage of an information processing system is the interaction with its environment. Living organisms interact with the outside world primarily by motions of their bodies, which are activated by muscles. The translation of decisions made by the central processing stage into motions of a mechanical system is certainly a problem where much can be learned from biological organisms. Not much work has been done in this area because more or less conventional electromechanical transducers can in many cases be used as output devices, although much cruder and clumsier ones than those used by organisms.

As mentioned previously, the peripheral information capacity decreases sharply at the conscious level of the central processing stage (to less than 100 bits/sec.). An estimate of the information contained in the output mechanism shows again a strong increase, due to genetic and learned "programs" stored in the effector stage. Figure 8 shows this interesting information processing principle, with numbers characteristic for the human nervous system.

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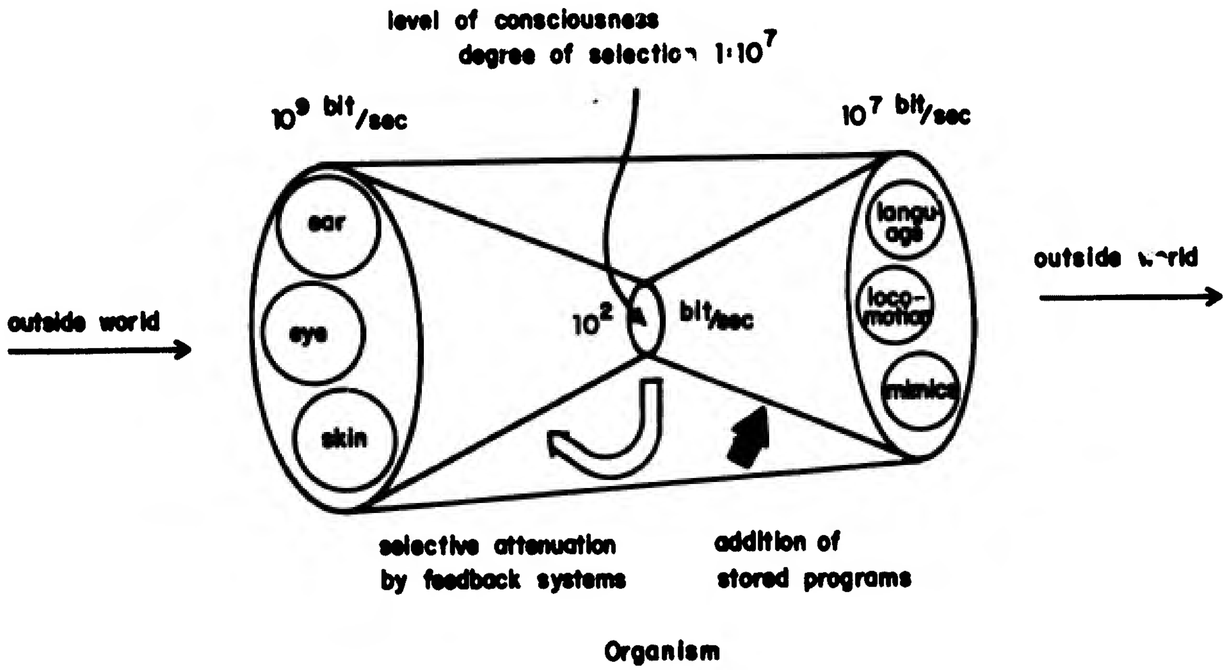

FLOW OF INFORMATION

Figure 8

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Manned Propulsion Devices and their Application on Earth and in Space

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MANNED PROPULSION DEVICES AND THEIR APPLICATION ON EARTH AND IN SPACE

Leonard M. Seale, Ph.D., and Jerome E. Emerson

INTRODUCTION

A review of aviation history indicates a continuous series of attempts, on the part of man, to fly with systems in which the man himself provided either, or both, the power for flight and the means of stabilizing flight. As a matter of fact, the period of time extending some thousands of years, from early Chinese flight attempts to the late 1800's, was characterized by approaches to flying that used man's abilities as the focal point of the design approach.

With the rapid development of the science of aeronautics after the turn of the 20th century, however, the trend in aviation shifted from "man centered" flying to "machine centered" flying. That is, the man was no longer considered to be either a source of power for flight or the primary means of providing system stability; rather he was placed in a powered machine which was designed to be aerodynamically stable. As a consequence of these developments in aeronautics the pilot, while still essential to successful flight, was not the focal point around which aviation technology developed.

In the mid-50's, however, primarily as a consequence of the rapid development of aircraft technology during and following World War II and the increased developments in rocket engine technology, a renewed interest in "man centered" personal mobility systems developed. Serious efforts were initiated in three different modes of personal flight: flying platforms, one-man helicopters, and earth and space operational rocket powered propulsion systems. The general conclusion reached through these studies was that personal flight with small relatively simple systems was feasible. However, an unresolved technical area was that of system stabilization and control. The reason that system stabilization and control appeared to be the critical problem area was that in this class of system, the man's mass accounted for a large percentage of the total flight weight of the system and, therefore, any movement of the man within the system resulted in considerable c.g. shifts and hence significantly interacted with system stability and control. Some design approaches attempted to minimize this effect; others proposed using the c. g. shift as the primary means of control in flight.

This paper is directed at reviewing the work on personal propulsion systems for earth and space applications which has been completed in the last decade. Primary emphasis will be placed on earth mobility systems, man-machine integration and the problems associated with vehicle stabilization and control. Some extrapolations from the data collected on earth systems to similar systems operating over the surface of the moon are presented. In addition, a brief discussion of the application of the control techniques developed for the earth system to earth orbital systems is presented.

EARTH PERSONAL PROPULSION DEVICES

Areas of Application

Table I presents a partial listing of missions which could be accomplished or supported by an earth based individual propulsion device. In reality, the range of potential application is limited primarily by one's imagination and the practical considerations of mission worth versus cost. The potential of individual propulsion devices at this point in time can be compared to the status of the helicopter during World War II. The real impetus to helicopter development occurred in the Korean conflict when the craft gained importance as a medical evacuation system. Following this initial operational demonstration of the helicopter, applications of its capabilities to a wide range of other mission requirements became readily apparent. In a similar manner, it is felt that the individual propulsion device will find applications in a wide range of missions once an initial operational application has been demonstrated.

TABLE I

POTENTIAL MISSION AREAS FOR
INDIVIDUAL PROPULSION DEVICE APPLICATION

CIVILIAN

1. Rescue
2. Forestry Service
3. Police Control
4. Transportation into inaccessible terrain
5. Emergency medical assistance

MILITARY

1. Wire laying
2. Liaison
3. Amphibious Assault
4. Passage over barriers
5. Clandestine operations
6. Forward observers
7. Reconnaissance

System Concepts

Three different types of individual propulsion devices have been extensively studied for application on earth.

(1) One-Man Helicopters - Considerable effort was expended in the late 1950's on small one-man helicopters for civilian and military use. The results of flight tests by the Hiller Corporation (1) and the Rotor-Craft Corporation (2), to name only two such programs, indicated system feasibility.

(2) Flying Platforms - Based largely on the efforts of Zimmerman, Hill and Kennedy (3) at Langley Aeronautical Laboratory of NASA, considerable analyses and flight tests were completed on a device on which the operator stood or sat and which was propelled by a rocket engine or propeller mounted on the bottom of the platform (4, 5). Control of the system was accomplished by kinesthetic means; i.e., shifting of the body c.g. relative to the thrust vector. In general, the results of these studies indicated concept feasibility, although stabilization and control problems were encountered.

(3) Rocket Lift Devices - The Aerojet-General Corporation and the Bell Aerosystems Company both initiated efforts in design and analysis of rocket powered lift devices in the mid-1950's. In general, the early studies indicated concept feasibility although high system sensitivities and resulting control problems were encountered.

For reasons that are not completely understood by the authors, effort on the one-man helicopters and flying platforms was essentially curtailed in the late 1950's, whereas the efforts on rocket lift devices continued and increased in depth and scope. In retrospect, it appears that the following two reasons were of primary importance in determining this trend:

(1) The rocket lift device was inherently smaller, was back-mounted and, as such, portable and easily transported on the ground. This fact was operationally attractive from a military point of view.

(2) The flight tests results of the flying platform studies indicated limitations in control power of the high mass and inertia system. The lack of control power was essentially apparent in cross-wind situations and during translation maneuvers (4). An increase in the control power would have required the incorporation of control surfaces and/or stability augmentation.

The remainder of the earth propulsion device discussion is devoted to a summarization of the work completed on rocket lift devices.

Early Bell Aerosystems Company Studies

Studies of a rocket powered propulsion device were first initiated at the Bell Aerosystems Company in 1953 by Wendell F. Moore when he completed his first conceptual design of a rocket powered individual propulsion device. These early efforts culminated in late 1957 were the first tethered test of a rocket powered propulsion device. The purposes of these initial tests were to obtain basic data on system stability, determine optimum location of the nozzles and the best position for application of the lift force to the operator's body.

To accomplish these objectives the nitrogen gas test rig, shown in operation in figure 1, was fabricated of steel tubing with two underarm stirrups to lift the operator. The rig incorporated two downward pointing rocket nozzles extending laterally from a shoulder harness. Thrust was provided by high pressure nitrogen supplied from an external source through a flexible hose to a plenum which divided the gas flow equally to two nozzles located laterally outboard from the man's body.

Figure 1

The system briefly described above was relatively crude and its limitations made it difficult to separate problems of system stability from problems induced by test rig and flight system coupling. For example, the flex hose would sometimes restrain the freedom of movement of the rig, the nozzles could be mismatched in thrust, and the operator could only attempt to control in one plane, pitch, by fixed arm pieces attached to the tubing to permit rotation of the rig about the shoulderline. Nevertheless, it was the most important tool available for testing the concept feasibility and system stability and control.

The approach which was taken in investigating system control was essentially empirical in nature since mathematical models describing flight dynamics were not as yet developed. As a result of a large number of test flights on the rig, numerous changes in flight control technique and system operating characteristics were incorporated on a trial-and-error basis. The general conclusions reached through approximately three years of testing with the nitrogen test rig were:

(1) Pitch plane control, which was accomplished by rotating the thrusters in the X-Z plane appeared to present no appreciable design or stabilization and control problems.

(2) Uncontrolled lateral oscillations required termination of numerous flights. While it was difficult to specify whether the cause of these oscillations could be attributed to the control system or the problems associated with the tether rig, a question of the controllability of the system without some type of stability augmentation was raised. For this reason, an analytical study of the lateral stability of the system was initiated.

(3) Wide individual differences in the ability of operators to fly the test rig were noted.

Aerojet - General Corporation Study

One of the first analytical studies of the feasibility of a rocket powered personnel propulsion device, presented in the open literature, was conducted in late 1959 by the Aerojet-General Corporation under contract to the United States Army Transportation Research and Engineering Command (6). The study was directed at determining the analytical feasibility of a rocket powered lift device for improving the mobility of the individual soldier. The major conclusions reached during this study were:

(1) Configurations employing the operator sitting or standing on a platform with the engine mounted beneath the system c.g., or with the system mounted on his back were feasible from a stability point of view. The primary mode of control was kinesthetic; i.e., the operator shifted his c.g. around the point of application of thrust to effect attitude and translation control. The standing platform configuration was inherently more stable than the sitting platform configuration, mainly, because of the increased moment of inertia with the operator standing resulted in lower angular accelerations with a given shift in c.g. location.

(2) The back-mounted system, with the thrust applied above the c.g., was determined to be the configuration which could be most naturally controlled by the operator and offered the significant operational advantage of portability over the platform configurations.

(3) Vehicle attitude in roll and pitch should be achieved by a combination of kinesthetic control (movement of the c.g. around the thrust vector by shifting body position) and thrust vector control (rotating the thrust vector around the c.g.). Yaw control should be provided by deflecting the thrust vector of the rocket engine(s).

The results of the Aerojet-General Study, coupled with the results of the Bell nitrogen rig testing and associated analytical studies, provided the basis for further investigation of the rocket powered propulsion device concept.

Demonstration of the Feasibility Unit

In August 1960, the U. S. Army Transportation, Research and Engineering Command awarded Bell a contract to demonstrate the feasibility of manned free flight for military operations by a rocket powered propulsion device. The design approach followed by Bell was guided principally by the results of the early tests in the nitrogen powered test rig and the stability and control analyses conducted by the Aerojet-General Corporation.

The feasibility unit configuration presented in figure 2 was designed around available off-the-shelf hardware. Lift was provided by a 300-lb thrust hydrogen peroxide gas generator located behind the pilot's neck. Insulated tubing carried the rocket exhaust gases to the nozzles located outboard of the pilot. The system was mounted to a fiberglass corset molded to fit the operator's body and lift was applied primarily by lift rings which fit under the operator's arms.

The final system design evolved through numerous design - tethered test tryouts-design iterations (37-39). Fifty-six tethered flights were flown during the program, serving the dual purpose of design verification and operator training. The significant design conclusions reached during the program between the time of the first feasibility unit and the present operational configuration, as related to the general problem of vehicle stability and control, are discussed below.

Originally, the feasibility unit was designed with two rocket nozzles gimballed such that they could, by means of a control stick mounted on the left forward arm, be rotated to produce pitch, roll and yaw control moments. This design had resulted from stability and control analyses which were prompted by the results of earlier flights on the nitrogen gas rig in which pitch and forward translation control was satisfactory but lateral translation and rolling motions were, in general, difficult to control. However, as the tethered flights progressed, it was found that the response of the SRLD was extremely sensitive to the gimballed thrusters and, therefore, the gimballed nozzle assembly was locked in both the pitch and roll directions, the pivot behind the back of the neck was changed to permit lateral (roll) and fore-aft

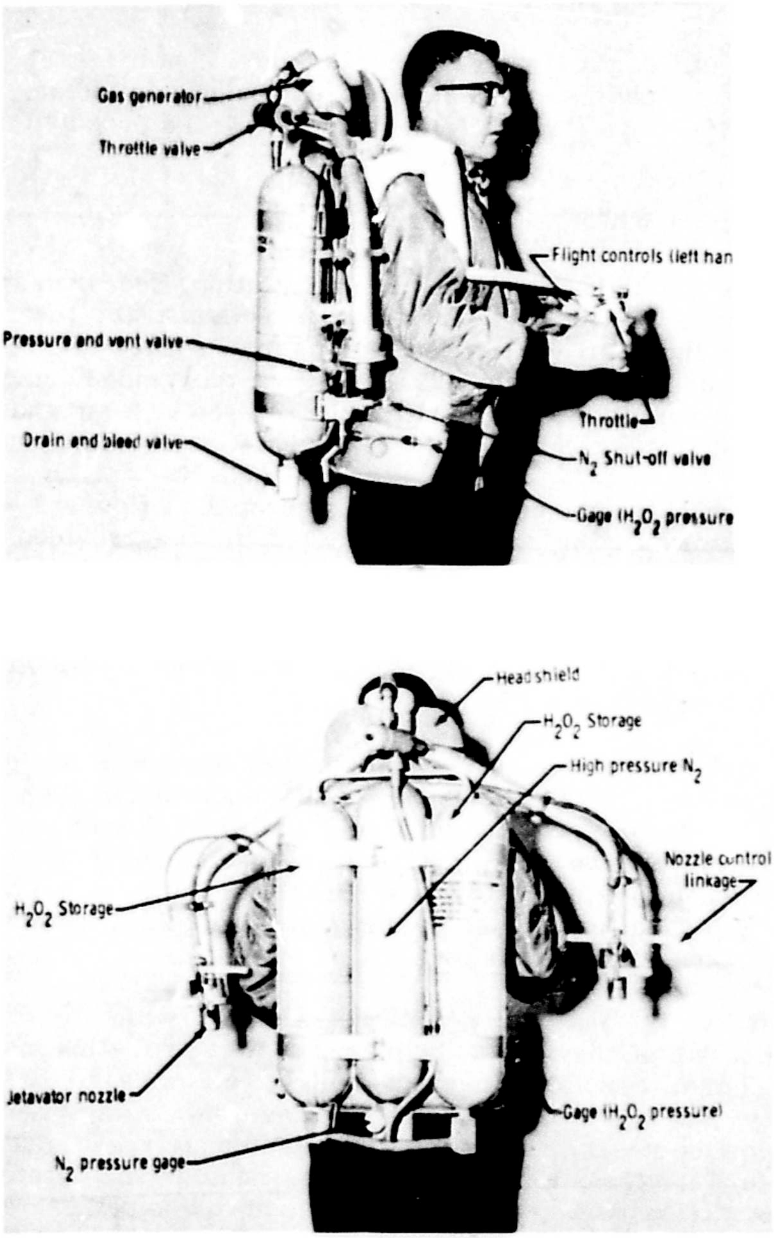


Figure 2. Feasibility Unit of Small Rocket Lift Device.

(pitch) control of the nozzles by vertical and rotary movement of the handles and jetavators were incorporated in the exhaust stream at the nozzle exit plane for yaw control. These changes resulted in a significant improvement in control.

The methods whereby the pilot presently controls attitude during flight are presented in figure 3. Pitch up and down moments are generated as depicted in figure 3a by depressing or raising the control lever arms such that the thrust direction is behind or ahead of the c.g. Such movements result in a proportional acceleration control system with a control power equal to approximately 30 deg/sec^2 per degree of lever arm deflection.

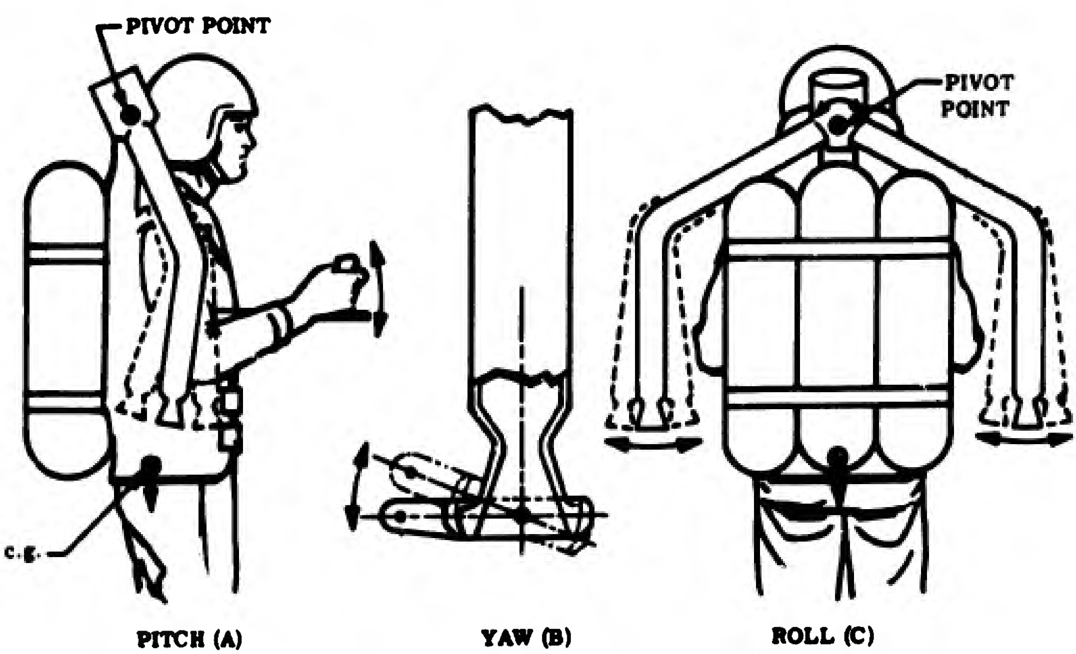


Figure 3. SRLD Control Methods.

Yaw is controlled by means of jetavators mounted on the exhaust nozzles as shown in figure 3b, such as to deflect the exhaust stream fore and aft. Control of the jetavator position is accomplished by a hand controller attached at the end of the left lever arm with a control power of approximately 50 deg/sec^2 per degree of controller rotation.

Roll is controlled as shown in figure 3c. This case is similar to that of pitch, except that the operator moves the lever arms laterally rather than raising or lowering them. Again, this is a proportional acceleration command system with a control power of approximately 40 deg/sec^2 per degree of control arm deflection.

The present throttle control is provided by a rotary hand grip located on the right arm rest. Originally, the throttle control was a squeeze type, mounted in an inverted position at the same point. However, early in the test program, difficulties were encountered in modulating thrust sufficiently to control vertical displacement. Computer studies incorporating an analog simulation of the throttle control were initiated which resulted in establishing the present design and proving its superiority over that previously used.

Another problem area, related to system stabilization and control, which was discovered during the flight test program and subsequently substantiated by analyses was that of the tightness of the couple between the pilot and the propulsion device. The addition of an abdominal support plate to the propulsion device restraint system significantly improved system controllability.

On April 20, 1961, after 36 tethered flights with the feasibility system, Harold Graham, a Bell rocket test engineer, successfully completed the first free flight of the system. This 13-second flight was flown at an average altitude of approximately 18 inches, at a velocity of approximately eight miles per hour and covered 112 feet (eight feet less than the first powered flight of the Wright Brothers).

In the approximately six years since the initial flight, an additional 2900 flights have been completed under a wide range of operational conditions, including flights at velocities estimated to be in excess of 60 mph and distances of over 800 feet. The accomplishments have demonstrated the performances and maneuverability potential of earth operational personal propulsion devices.

The feasibility system, as described above, with a flight duration of approximately 21 seconds, obviously has limited operational application. In order to turn the system into one which meets meaningful mission performance requirements, Bell is presently under contract to the U. S. Army and the Advanced Research Projects Agency for the exploratory development of a new backpack unit which is expected to result in substantial increases in both flying capability and performance. This new system will utilize a small turbojet powerplant mounted inertially on the back of a corset assembly around the operator's lower back or hips. Engine exhaust is channelled equally through two downward pointing nozzles. Along with substantial increases in altitude and range the new system will incorporate improvements in the throttle mechanism and system directional control, consistent with the needs of longer duration flight, and will also incorporate a more effective fuel supply warning system.

Dynamic Analyses

From the beginning of the tethered flight tests to the present attempts have been made to understand the flight dynamics of the small rocket lift device. The initial efforts were directed at the problem of lateral stability and at the development of a man-machine model which represented actual flight in a manner which enabled analog computer studies of the system. While these studies provided valuable assistance in system design, they were considered inadequate from the point of view of, first, describing the actual mechanics of flight and, second, understanding the mechanisms whereby controlled flights was accomplished. The following discussion presents the results of two recent attempts at mathematical descriptions of the system. It is important to note that these two models, as all of the analytical models of the system which have been generated to date, rely heavily on the pilot's inputs regarding how closely the modeled system "feels" like the actual flight system. Until quantitative flight data correlating control inputs and man-machine response are available, such data must provide the primary inputs for development of an analytical model of the system in flight.

Before initiating discussion of the derivation of the mathematical models, a description of the steps involved in a simple translational maneuver are presented in order to afford a deeper understanding of how control is achieved. In actual flight, the operator must be able to synchronize pitch, yaw and roll angles, and at the same time control his altitude by commanding the proper thrust level. Thus, the translation maneuver is made up of five steps:

(1) The operator applies thrust sufficient to lift off the ground and stabilize himself in altitude.

(2) To accelerate forward, he pitches over sufficiently to allow the horizontal component of the thrust vector to accelerate him in the direction he wishes to travel. While pitched over, he may be required to increase his thrust level to compensate for the loss of lift.

(3) Upon reaching what appears to be his desired velocity, the operator pitches back to near zero and proceeds forward at a constant velocity. Some small pitch angle will always be required to overcome aerodynamic drag.

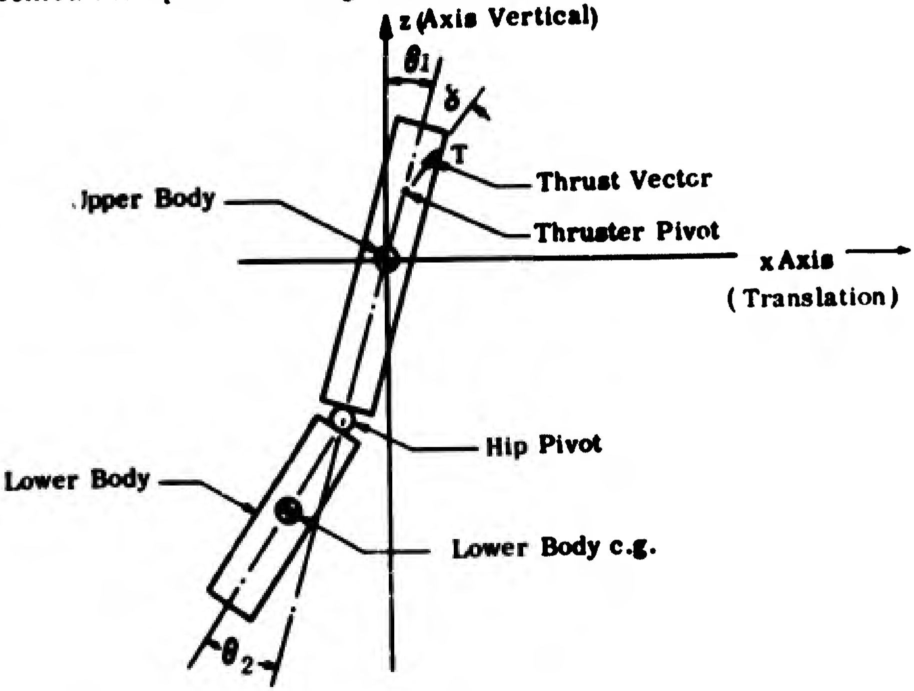
(4) In order to reduce his ground speed to zero, the reverse of step (2) is followed. The operator pitches back such that the thruster is pointed down and forward, thus decelerating him. The maneuver is coordinated with the desired touchdown point so that forward speed is reduced to zero as the desired location is reached.

(5) Setdown is accomplished by reducing thrust to establish the proper descent speed.

While the maneuver is in progress, the pilot will find that he must use roll to control his lateral motion just as he uses pitch to control his forward motion. In the simple translational maneuver described above, zero lateral motion will be allowed; however, in other cases, combinations of pitch and translation, roll and side translation, and yaw control to maintain the proper heading can be used to produce coordinated turns and, in general, enable the operator to fly to virtually any position he desires.

Two-Body Model

The first attempt at developing a mathematical model of the man-machine system in the fore-aft pitching and translation mode took place early in 1963 approximately two years following the first successful free flight (7). The model (fig. 4) utilized a two-body system. The upper mass represented the operator's upper body and attached SRLD. The lower mass represented the operator's legs and feet. The two bodies were assumed to



T Thrust

δ = Thrustor angular displacement with respect to upper body

θ_1 = Angular displacement of upper body with respect to material

θ_2 = Angular displacement of lower body from the upper body

K = Torsional spring constant acting at the pilot's hips

D = Damping exerted at the hips

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

be connected with a torsional hip spring with damping constants. The equations of motion were written for six degrees of freedom representing pitch, translation and vertical motions of both upper and lower bodies. The equations were then programmed on a PACE 231-R computer and a simulation study directed at system control investigations was initiated.

The subject, a trained Bell SRLD pilot, was provided with visual displays of the upper body pitch angle (θ_1), range, altitude and horizontal velocity information. His upper body pitch angle (θ_1) was displayed on an oscilloscope while velocity and altitude versus range were plotted for his viewing by means of a two-pen X-Y plotter. Inputs of throttle setting and thrust vector angle, δ, relative to the upper body attitude were inserted into the simulation by means of the SRLD mockup shown in figure 5. The rig was equipped with a linear pot to pick off signals proportional to thrust vector inclination, achieved by tilting the rig forward and backward. A rotary pot was also provided to pick off a signal proportional to throttle position. The simulated throttle was operated by rotary motion of the right hand consistent with the then current SRLD throttle mechanism.

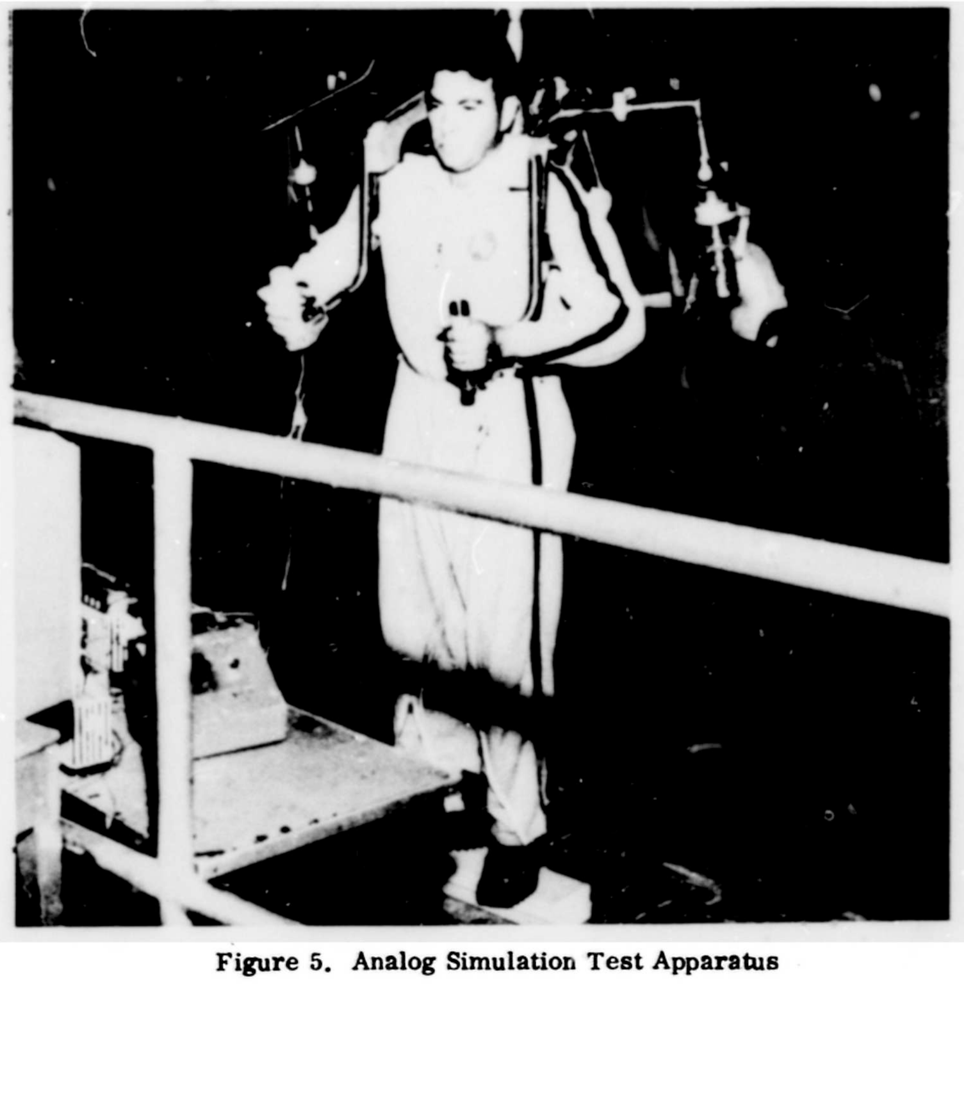


Figure 5. Analog Simulation Test Apparatus

The first attempts at flying the simulation were not satisfactory as the subject experienced problems in developing the proper throttle and δ (deflection) inputs for adequate control. The upper body attitude continuously oscillated through wide angles and, when the amplitude exceeded the limits of the displays, the operator would lose control completely. Conversations with the SRLD pilots indicated that they flew the actual belt by tilting the thrust vector through the δ angle and did not experience any problems with control of the pitching moments which, based on physical data of the man-machine system, would be generated. Also, flight test information from the SRLD did not indicate either oscillatory body pitching motions or the development of large upper body pitch angles during horizontal translation flights. Thus, it was reasoned that some trimming action by the pilot was resulting in the cancellation of pitching moments which were causing difficulties with attitude control in the simulated SRLD. Since it was not obvious at that point in our studies what the action was, it could not be incorporated into the simulation. Therefore, a number of different approaches for compensating for its "reasoned" presence were investigated. First, a simple experiment was conducted in which the pilot flew simulated translation flights with the pitch attitude (θ_1) fixed at zero. The operators commented that the simulation behaved more like the actual system, and the measured flight performance indicated considerably enhanced controllability. However, fixing the attitude degree of freedom to zero was not thought to be the best solution to approximating in the simulation the "reasoned" trimming action of the SRLD operator.

It was concluded that a corrective term, $\Delta\delta$, accounting for the missing portion of the operator's control action should be devised and subtracted from δ, such that overall the difficulty in flying the SRLD and the simulation could be made equivalent. After a study of flight test movies and further discussions with the pilots, it was decided that the corrective term

$$\Delta\delta = \theta_1 + K\dot{\theta}_1$$

would meet most of the above requirements. K was chosen so that the attitude damping of the composite two mass body would be about 0.7.

When this term was introduced into the simulation, system control significantly improved; however, the means whereby the pilot actually flew the system were still not fully explained. It appeared, at that point in time, that the operators were controlling the system in either one of the following two ways:

(1) By Kinesthetic Control - During flight, pitch (and roll) trim of the SRLD is obtained by altering the position of the lower body in order to stay "balanced"; i.e. by providing the proper damping moments to control pitch rate, and to maintain the effective thrust vector

through the body c.g. when the desired pitch angle is achieved. It was concluded, at this time, that if in fact the operator controls the system in this manner, he is moving his c.g. relative to his thrust vector as the primary means of control.

(2) Thrust Vector Control - During flight, the pilot receives sufficient visual (position and motion cues) and dynamic (acceleration) cues such that he is able to control his thrust vector with respect to the total system c.g. If the operator controls in this mode the thrust vector is moved around the c.g. as the primary means of control.

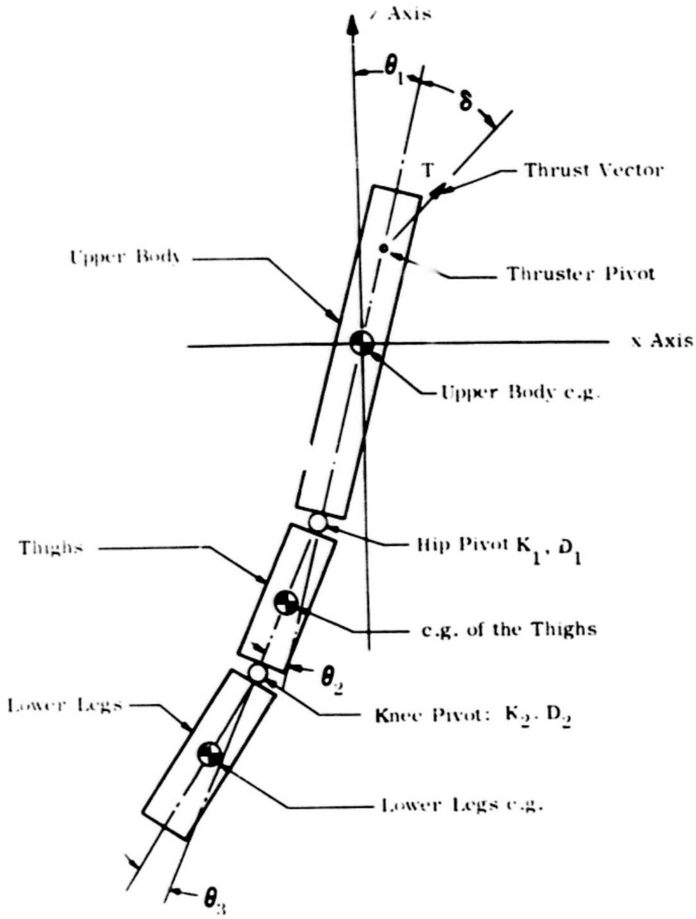
Three-Body Model

A frame by frame analysis of a number of flight films of the first rocket belt pilot was made to determine whether the pilot uses kinesthetic or thrust vector control in flying the SRLD. The analysis indicated that the primary means of pitch control employed by this operator was to "kick his heels" to produce a momentary pitchover moment for forward acceleration. For this reason, it was concluded that the next analytical efforts should be directed at improving the mathematical model to incorporate more fully kinesthetic control but yet make it sufficiently versatile so as to be able to study thrust vectoring control as well.

A diagram of the model used in this new attempt at simulating the system is given in figure 6. The body was assumed divided into three parts as shown. Torsional springs are indicated by K_1 and K_2 connecting the upper and middle bodies and the damping coefficients are given by D_1 and D_2, respectively. The equations of motion were written for the pitch plane degrees of freedom. Using the physical characteristics of the operator and the SRLD the equations of motion were programmed on the PACE-231R computer. The control rig used in these studies was the same as that described previously in the two-body simulation discussion.

Studies were then initiated in an attempt to improve on Neil's (7) original expression designed to compensate for the infidelity of the simulator control action. With regard to kinesthetic control aspects, further investigation of flight films indicated pronounced body motion and general weight shifting of the novice operator. However, the pilots contended that body motion was not being used for control, and that as they gained experience on their own training programs, they learned to overcome this flexibility. On this basis, therefore, an expression for kinesthetic control was not devised. Spring terms in the equations of motion were substantially eliminated and damping constants, made low enough to permit body flexibility but high enough to damp any body oscillations, were inserted into the equations of motion.

A series of open loop analog computer runs was then completed with



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

Figure 6. Three Body Model of the SRLD Man-Machine System

thrust equal to weight and a command input, δ, of one degree for each of three conditions: one-body, in which no body flexure was permitted; two-body, in which angular motion at the hip was permitted; and three-body, where hip and knee action both were allowed. Investigation of the data from the resulting runs indicated not only small differences in response between the three conditions measured in terms of upper body pitch angle θ_1 and translational acceleration, but also demonstrated system stability for each of the mathematical system analogs. These results supported the conclusion that system response is relatively independent of body flexibility. Therefore, mathematical models involving two or more moving parts of the body are not required unless deliberate kinesthetic control is being attempted by the operator.

Shortly after completion of the above open loop tests, the first flights of the SRLD in the Pogo and Chair configurations presented in figure 7 were made. Since the system structure restrained the pilot and made the system, in fact, a one-body system, it became clear that kinesthetic control, either consciously or unconsciously employed, is not used as the primary means of system control. In fact, since the pilots found the Pogo configuration slightly easier to fly than the back-mounted system, it was concluded that body flexure has a small detrimental effect on control rather than functioning as the primary means of control.

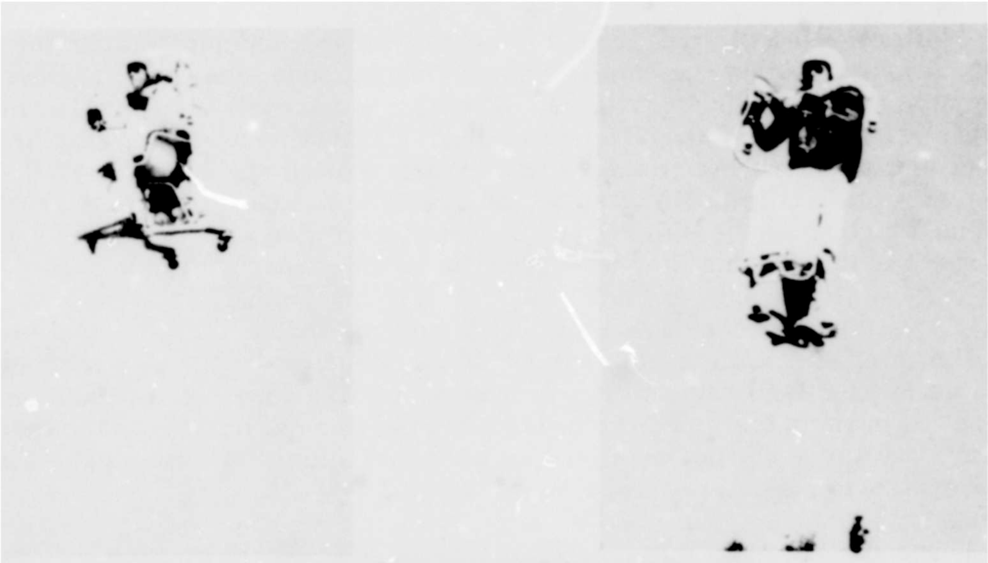


Figure 7. SRLD in Flying Chair Configuration.

Studies were then concentrated on analyzing the pilot's control actions, assuming that they were using thrust vectoring techniques. This overall action, as it is now understood, is qualitatively presented in figure 8 to describe the pilot's inputs and control cues used throughout the flight trajectory.

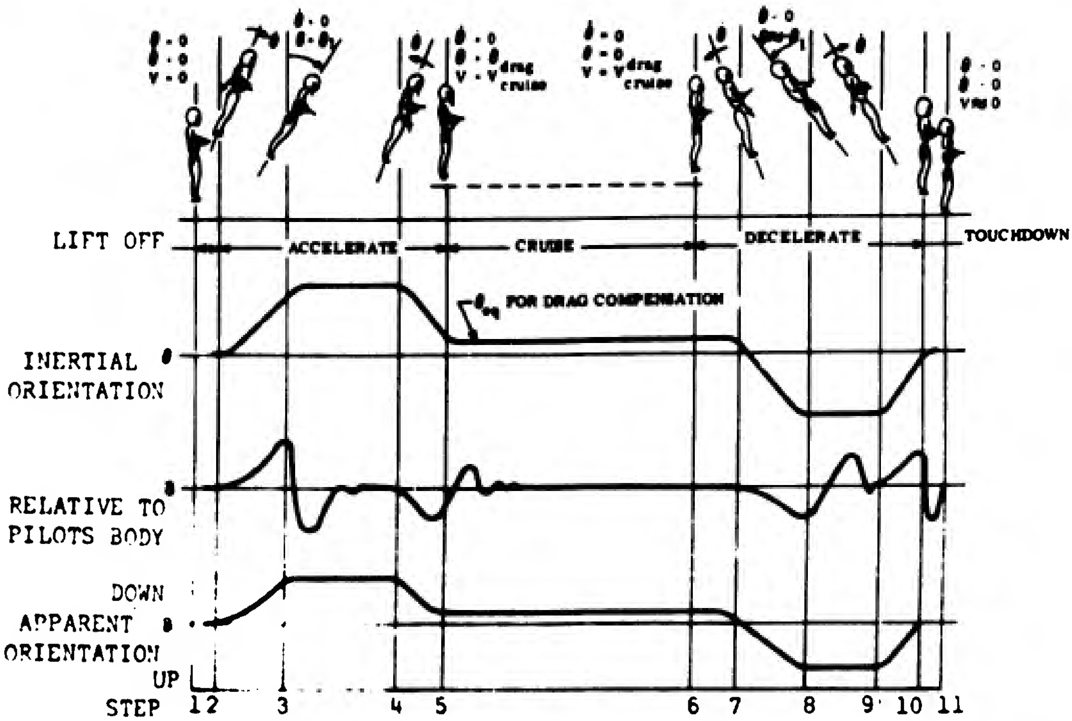


Figure 8. Representative System Response in Pitch to Controller Input.

After lifting off the ground (Step 1 of fig. 8) and modulating thrust to maintain a smoothly ascending or hovering altitude, the pilot, to develop a forward cruising speed will pull down on the thrust arm, deflecting the thrusters back (Step 2). This develops a moment about the cg pitching him over and accelerating him forward. When a pitch angle is achieved which the pilot is satisfied with (Step 3), he returns the lever arm to neutral (Step 4), at which time, he stabilizes the thrust vector at an angle constant with respect to the ground (Step 5) rather than with respect to his body.

As a consequence, the pilot/SRLD with the thrust vector oriented inertially at an attachment point above the system cg becomes a dynamically stable system with oscillatory motions much like those of a pendulum. As a result of their training, the pilots are able to actually vector the thrust to damp out any resulting oscillations and fly a highly precise flight through the cruise and deceleration portions (Steps 7-11) of flight.

One of the most intriguing aspects of the control problem is that the SRLD pilots are not fully aware of the mechanism of inertially orienting the thrust vector, but rather, acquire the ability during their tethered training flights. Their claim of "holding the thrust vector angle, δ, constant with respect to their body axis" makes it necessary to modify the equations of motion to compensate for the lack of motion cues in the fixed base simulation.

Because of the ability of the pilot to stabilize his thrust vector inertially, Neil's original expression appears to be correct for stabilizing at any given orientation. However, when compared with the rocket belt operator's in-flight performance, we found that the inertial pitch angle that the pilots employed to accelerate or decelerate were much larger than the angles they deflected the thruster arms. As a result, translational acceleration was extremely low. Therefore, to give the simulation a faster translational response without disrupting the stabilizing effect in pitch, a third item was added to the expression for $\Delta \delta$; namely, $K_\delta \delta_c$. With this expression, the pilot, by means of small angles of thruster lever arm deflection could cause pitch angles sufficiently large to accelerate the simulated SRLD at a rate compatible with the actual flight. Thus, the input from the simulation rig was modified as follows:

$$\delta = K_\delta \quad \delta_c \quad - \quad \theta_1 \quad - \quad 0.7 \, \dot{\theta}_1$$

Subsequent testing on the simulation rig established a rather surprising high value of 6.67 for K_δ. When this valve was introduced into the simulation, substantially improved results in translational control were obtained.

Closed loop simulation tests were then conducted in which pilots were requested to fly simulated missions of approximately 500 feet with both a rigid body and a three-body model represented in the computer. No distinguishable differences in quantitative system performance or in "pilot response" to the simulation were observed, supporting the connection that the pilots in fact fly the system as a single body with thrust vector control as the primary mode.

CONCLUSIONS

The SRLD, the chair and the Pogo flights have demonstrated that manned propulsion systems of these types are easy to handle and practical to fly. The analyses of the mechanics of system control have been based primarily on correlating flight observations with mathematical models programmed on a fixed base simulator. The results of these studies indicate that these vehicles are flown by means of thrust vector control rather than by a shifting of body weight. Analog simulation studies have indicated that system stability and response is relatively independent of body flexibility so long as deliberate kinesthetic control is not being attempted. Flight experience in flying the SRLD with body flexure, compared with the Pogo and Chair flights, in which the body is held rigid, appears to support this conclusion.

From the studies, it was also concluded that pilots, in their thrust vector mode of control, stabilize their lifting thrust vector inertially rather than with respect to their body axes. As a result, the entire system acts more as a stable, damped pendulum, thus accounting for the ease in flying the real vehicle and the difficulty encountered in fixed base simulation. The feedback loops used in the attempt to account for these simulation differences, appear to be reasonably correct.

It is believed that the above conclusions are, for the most part, valid; however, for a complete verification and to provide a quantitative evaluation of system control action, a program of instrumented flight is necessary in which time histories of body motion control arm deflections, pitch angles, translational accelerations, etc. could be obtained for a series of standard flight maneuvers. Correlation of these with corresponding outputs from the mathematical models would then establish the validity of the control laws postulated, as well as the system gains used in these laws. Such an experimental program was initiated in late 1961 but was curtailed before any usable flight data was derived due to the unavailability to flight hardware and technical problems with an airborne TM system designed to transmit performance and physiological data (8).

LUNAR PERSONAL PROPULSION DEVICES

Areas of Application

Numerous detailed studies of missions which could be primarily accomplished, or supported, by personal propulsion devices on the surface of the moon (or planets) have been completed in recent years (9-14). In general, the application areas may be categorized as follows:

Surface Exploration Sorties - The initial lunar landings involve numerous short excursions from the LM for general scientific observations, collection of lunar rock samples and gross measurements of the physical characteristics of the lunar surface. While these tasks can be accomplished by the walking astronaut, the availability of a personal propulsion device would considerably enhance the radius of exploration and reduce the total extravehicular time required.

Surface Emplacement of Scientific Instrumentation - Instruments such as the Apollo Lunar Scientific Experiment Package (ALSEP) could be readily emplaced at distances from the LM vehicle considerably in excess of those which could be attained by walking. The increased mobility provided by a personal propulsion device would enable a greater range of selection of monitoring sites and, in addition, a greater number of separate sites could be monitored.

Transportation Into Inaccessible Areas - Deep crater and lunar rille exploration is of considerable interest for both lunar surface study and atmospheric sampling. The accessibility of these locations to a walking astronaut or one riding in a surface contact vehicle is limited.

Remote Sensing - A personal propulsion device offers considerable potential for remote sensing across the complete electromagnetic spectrum, with photography being particularly useful. This sensing provides direct scientific information and provides reconnaissance information to guide subsequent exploration activity.

Surveying/Mapping - A propulsion device can be utilized for quick and accurate surveying/mapping of exploration sites which are out of the line of sight of the LM.

Rescue Missions - Lunar propulsion devices can be utilized in conjunction with surface contact vehicles as a means of return to the LM or surface shelter in the event that the surface vehicle malfunctions. In addition, it is feasible to employ a simple propulsion unit with sufficient ΔV aboard, to escape from the lunar gravitational field, inject the astronaut into lunar orbit and rendezvous with a parent spacecraft (12).

While the selection of a lunar flying device over surface locomotion systems is not straightforward, there appears to be such a wide range of potential applications that detailed studies of such systems in specific required missions should be continued and expanded.

System Concepts

The lunar propulsion device concepts which have been studied can be categorized into three main types. The first type includes those vehicles which are controlled by shifting of body weight; i.e., kinesthetic control. The second group includes all vehicles which have stability augmented control systems, while the third type includes those vehicles controlled by the thrust vectoring control process as described for the SRLD.

(1) Kinesthetic Control - The only published work known to the authors involving lunar vehicles which are kinesthetically controlled is that completed by Sanford of North American Aviation, Inc. (15). The flying platform design which he studied placed the propulsion system below the platform on which the operator was standing. Control was accomplished by the operator shifting his weight to create pitching and rolling moments in the same manner as was utilized in the early studies of earth operational flying platforms. Preliminary test results obtained from a flying platform test bed indicated that kinesthetic control was adequate.

(2) Stability Augmented Systems - Vehicles, operating at longer ranges, higher altitudes and capable of carrying different types of payloads, in general require automatic stabilization for attitude control. Studies of vehicles in this category have been conducted both at Hamilton Standard (16) under sponsorship of the Manned Spacecraft

Center and at Bell Aerosystems Company (9, 10) under sponsorship of Marshall Space Flight Center. The studies at Hamilton Standard included both platform and body mounted units with attitude control, in each case, being commanded by a three degree of freedom joy stick. Attitude control was achieved by means of orthogonally mounted thrusters, capable of applying moments on command about the vehicles x, y, and z axes. Results of simulator studies performed with an operator in the loop, indicated that it was impossible to fly accurately and land safely without an automatic attitude stabilization system. The studies at Bell also involved vehicle designs employing orthogonally mounted attitude control thrusters with on-off attitude commands generated by means of a three-degree-of-freedom sidearm controller. Simulation study results were in general consistent with those of Hamilton Standard; that is, some form of automatic stabilization and control was deemed necessary to insure satisfactory vehicle control in all modes of flight.

(3) Thrust Vectoring - The lunar backpack design, patterned after the earth version of the SRLD, and the lunar Pogo, also patterned in design after its earth counterpart, represent the two known vehicles of the thrust vectoring type that have been studies for lunar locomotion. As in the earth case, studies have shown that such vehicles represent simple reliable designs which can be easily controlled over a variety of different flight profiles.

The remainder of this section of the paper is limited to a discussion of the application of the rocket lift device concept employing thrust vector control to lunar surface mobility.

Rocket Lift Device Concept Application to Lunar Operations

The design requirements and operating characteristics of a rocket lift device system (fig. 9) for lunar surface employment are expected to differ in several aspects from that of a similar vehicle on earth. The major contributing factors are discussed below.

Operator Full Pressure Suit Effects

The major influence on system control introduced by the operators full pressure suit is a stiffening effect such that less body flexibility will be presented during flight. As shown previously, body flexibility has only a small disrupting influence on the stability of the system; therefore, restraint on body motion should have some small stabilizing effect on the vehicle flight characteristics. However, one potential detrimental effect which has not been fully investigated to date is the possibility of an inadvertent coupling between the natural frequency of the operator flexing at the hip

Figure 9. Artists Concept of a Back-Mounted Lunar Propulsion Device.

and knee as a multiple body system, and the control system. Preliminary studies have indicated only small differences in control characteristics due to increasing hip spring constants. A second effect also may arise from the suit stiffness if it inhibits the relatively high frequency operator response and arm motion necessary for controlling the direction of the thrust vector. This problem will be the subject of studies to be conducted at NASA Langley Research Center with a Bell lunar Pogo flying on the 1/6 gravity simulator (17).

Figure 10 presents altitude and velocity profiles of four simulated earth flights of the SRLD, under four variations in the operator's effective hip spring and damping characteristics. In order to provide an exaggerated example of the effects of the hip spring constant and damping on the system stability and control, the damping term was set to zero for two of these flights. Although this effect would be impossible to accomplish physically, these flights were performed to illustrate the effects of extreme parameter values. Curves (a) and (b) represent missions in which the upper and lower body members are connected by a stiff torsional hip spring ($K \approx 200$ ft-lb/rad). Curve (a), which oscillates continuously in forward velocity, illustrates the effect of no damping about the hip pivot. Curve (b) illustrates the improved flying characteristics, in velocity and altitude control, which are produced by the addition of damping about the hip pivot. The dashed curves

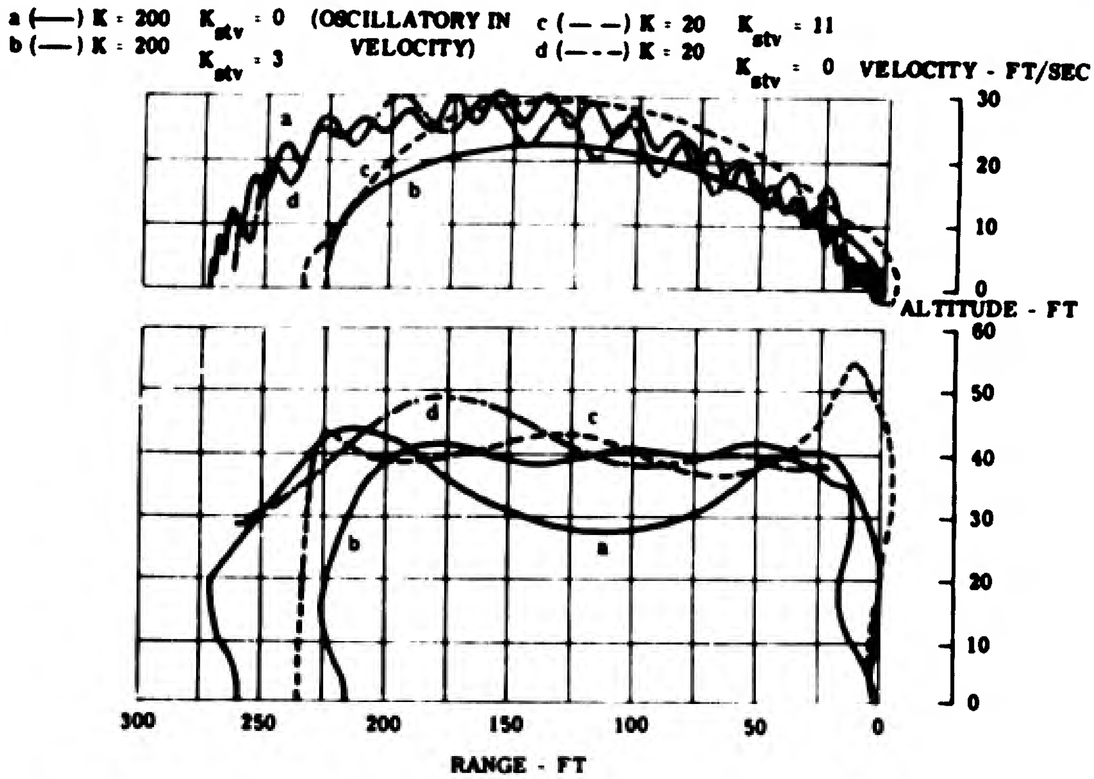


Figure 10. Simulated Earth Flights Demonstrating The Effect of Torsional Spring and Damping Parameters

(c) are for a flight with a 20 ft-lb/rad torsional spring constant and with damping provided between the upper and lower bodies. The other curves (d), oscillatory in velocity, illustrate a typical flight in which the hip damping is removed. Again, the absence of damping results in greater altitude deviation. As mentioned previously, such flights could not actually be flown because the operator would lose control at or shortly after liftoff, if his natural damping were removed. These simulated flights do, however, demonstrate the effect of the operator hip joint characteristics on system controllability. Because of the similarity of results between curves (c), with low spring constant and damping, and (b), high spring constant and damping, it can be concluded that as long as sufficient damping is present, flight characteristics are not affected by the spring constant at the hip. Thus, the presence of an increased spring constant due to a pressurized suit should not have a substantial effect, either in stabilizing or destabilizing the lift device if sufficient damping is available to quickly dissipate upsetting disturbances.

Aerodynamic Drag Effects

The absence of an appreciable atmosphere on the lunar surface will eliminate the requirement for drag compensation during flight. The fact that the pilots are sensitive to drag was clearly demonstrated by a series of simulation runs in which drag effects were not subtracted from the simulated force of acceleration along x. In these tests, the rocket operators demonstrated a marked tendency to accelerate more than decelerate, thus leading to small residual velocities which were unaccountable by the pilots. When the following correction was incorporated into the simulation, however, by subtracting F_D along x, more representative flight profiles were obtained:

Force of drag, $F_D = 1/2\, A \rho \;\; \dot{x}^2\, C_D$

A = area of man = 10 ft^2
ρ = density at sea level
$\dot{x}$ = forward velocity
C_D = drag coefficient for a man traveling upright to the wind = 1.0

From these results, it is apparent that the operators learn to compensate for drag effects in their flight control of the SRLD. Based upon the ability of the operators to adjust to a wide variety of significant system performance changes, however, we do not anticipate any control problems as a consequence of a reduction of atmospheric drag.

Mass and Inertia Effects

The lunar vehicle systems are expected to have larger masses and inertias, compared with their corresponding earth designs, and as a result control powers and accelerations are expected to be considerably lower. Although it is expected that these changes will improve system controllability, the total effect cannot be assessed until they are combined with the effects of flying with the reduced thrust required to operate under 1/6 gravity. These effects are discussed further in the following section.

Reduced Gravity Effects

The 1/6g field present on the moon requires a corresponding reduction in the system thrust. This, together with a general increase in the system mass and inertia, reduces attitude control powers, translational accelerations, and corresponding system response. Simulations and other analyses conducted to date have shown that these reductions result in a general improvement in the controllability of the lunar systems. However, it has also been found that the slower responses, especially in translation, limit ground speed thereby requiring greater transit times. This results, in turn, in a corresponding lowering of the efficiency of flight since the total time during which lift must be provided is increased. This effect is illustrated in figure 11, which was plotted from data obtained from the two-body simulation

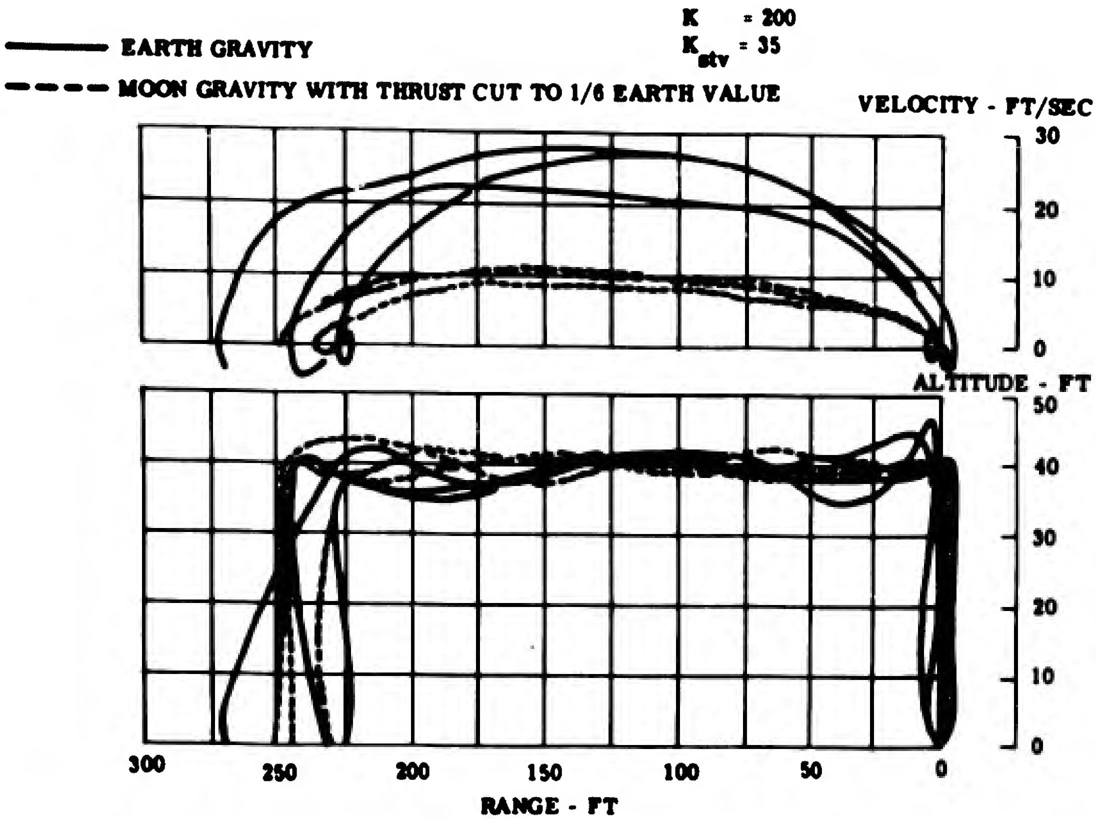


Figure 11. Simulated Flights of Present SLRD Configuratic.i K = 200

studies described previously. For these runs, the initial thrust-to-weight ratio was 1.2. In each of the simulated flights the fligh: task paralleled that of the earth flights; i. e., the operator was required to lift off and stabilize; pitch over and develop a forward velocity; translate forward, holding altitude constant; pitch back and reduce velocity to zero, holding altitude constant; and touch down.

From an examination of the curves, it can be seen that the maximum velocity attained in lunar flight was less than half that developed during earth flights. In flying the simulation, it was also found that after a brief training period to become familiar with the reduced control powers, flight in the lunar environment was somewhat easier. This can be seen in figure 11 by noting that the dispersions in the touchdown point are generally less for lunar flights.

Because of the longer flight times, due to a reduction in acceleration, it was felt that more efficient flight might be obtained if the thrust to weight ratio was increased from 1.2 to 2.0. After a short training program, which served to familiarize the operator with the new control tasks, the technique found to gain the greatest distance was to pitch over immediately at takeoff, accelerate forward, and upward at the same time, throttling back to maintain constant altitude once the desired altitude was reached. Results of flights performed using this technique showed a marked increase in flight efficiency. This is illustrated in figure 12 in which the characteristic velocity, ΔV, is plotted versus range. The main reason for the increase in efficiency was as expected; the higher accelerations made it possible to develop higher velocities, thus shorter transit times. In addition, the higher thrusts also increased the system control torques, giving it attitude response and control characteristics more like that of the earth lift device. As a result, overall vehicle control, although more efficient from a ΔV standpoint, was more difficult to handle from an attitude control standpoint.

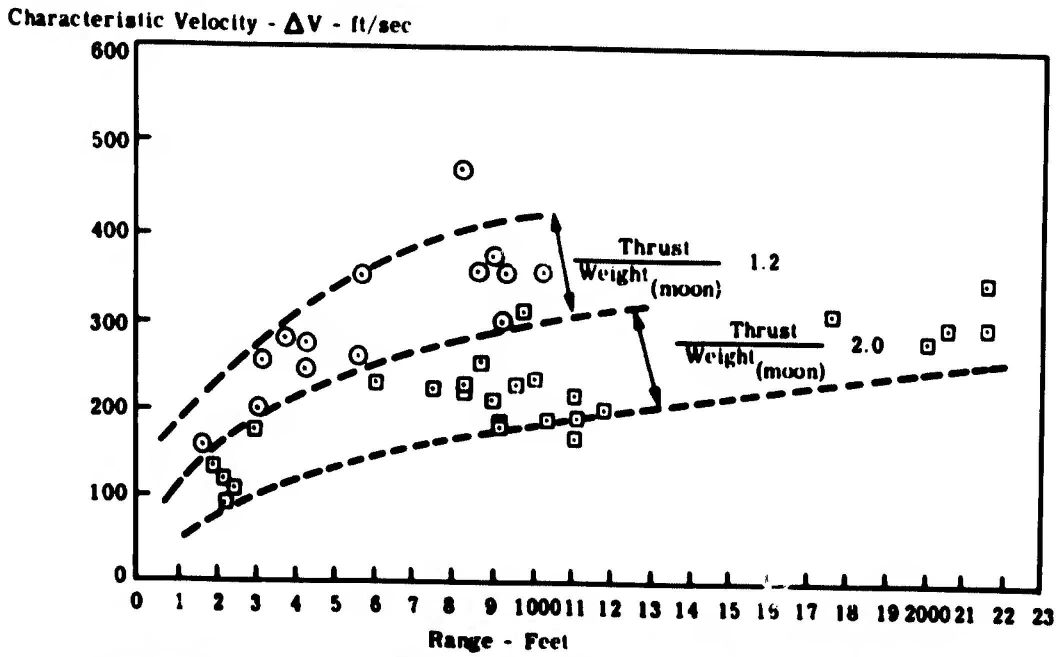


Figure 12. ΔV As a Function of T/W and Range of Flight With a Small Rocket Lift Device

CONCLUSIONS

The results of the analytical and simulation studies conducted to date have clearly demonstrated the feasibility of the Small Rocket Lift Device Concept for lunar surface operations. It is important to note, however, that a back mounted system is characterized by the following two limitations when considered for operational employment on the moon:

(1) The mounting and fastening of the system to the full pressure suit will be a difficult process due to the stiffness of the suit joints. A system in which the operator could stand or sit would considerably improve this situation.

(2) The system volume will be large and difficult to package on the operator in a back mounted system if the ΔV provided to the opera-

tor, and the system payload carrying capabilities, are to be compatible with the mission requirements as currently defined. In addition, the location of the (PLSS) portable life support system on the astronaut's back aggravates the packaging of a system mounted on the operator.

As indicated earlier, it is possible to employ the thrust vectoring control principle to the stand-on Pogo or flying Chair configurations, provided that the point of thrust application is above the total vehicle c. g. Two studies are currently under way at Bell in this general area. One program involves the fabrication of a Pogo configuration of the rocket lift device, similar to that depicted in figure 7, with thrust levels compatible with the 1/6 g environment (17). This device will be flown on the NASA Langley Research Center 1/6 g moving base simulator for the purposes of investigating system control. The second program is directed at fabricating a flexible research simulator designed for investigating lunar extravehicular propulsion concepts and associated human factors problems under realistic moving base flight conditions (19). This device, known as the One-Man Propulsion Research Apparatus (OMPRA), will be installed in the rendezvous and docking simulator at Langley Research Center in the spring of 1967. The employment of these simulators in research studies later this year will provide additional system design and control data under more realistic lunar flight conditions.

ORBITAL PERSONAL PROPULSION DEVICES

Areas of Application

Investigations of earth orbital missions, completed in recent years, have indicated a wide range of missions which can be supported by personal propulsion devices (20-23, 27). Table II lists a number of the major missions which have been identified. In general, these missions should be considered support missions, in that the personal propulsion device is employed to support one or more activities required of the parent spacecraft.

TABLE II

POTENTIAL EARTH ORBITAL MISSIONS FOR A MANNED MANEUVERING DEVICE

Emergency Rescue Operations
Erection of Large Space Structures
Personnel and Cargo Transfer
Antenna Calibration and Mapping
Experiment Monitoring
Experiment Package Retrieval
Space Maintenance
Support to Space Telescopes
Propellant Transfer Monitoring

It should be emphasized that the determination of whether extravehicular operational (EVO) support is required, or not, to support a parent spacecraft mission is not a simple task. This point was developed in a recent paper published by Seale and Economou (20) in which they outlined the following steps as essential to determining whether EVO support is required, or is mission and cost effective:

(1) Analyze the potential operational missions and ascertain where EVO support is uniquely required or where the employment of such support may trade off favorably with other techniques of mission accomplishment.

(2) Determine the kind of EVO support, i. e. manned or unmanned, which best accomplishes the mission objectives and, once a selection is made, select the optimum system approach for accomplishing the necessary support.

(3) Following the initial selection of the EVO support technique, it is necessary to determine the total collection of support equipment required to accomplish the EVO mission.

(4) Following the completion of these tasks, a second iteration of the process should be completed to determine if the selected EVO approach still trades off favorably with other modes of support mission accomplishment, in those cases where unique EVO requirements have not been defined.

Only if the studies, such as briefly described above, clearly indicate a unique requirement for manned EVO, or a favorable mission and cost tradeoff over other techniques for mission accomplishment, should the use of personal propulsion devices be incorporated into the operational mission planning.

<u>System Concepts</u>

Manned orbital propulsion devices may be categorized into two general classes: stability augmented systems and thrust vectoring systems. The reader is referred to the summary of such systems recently published by Willoughby, Garnett and Parker (24) for more detailed descriptions and a comparison of the various design approaches which have been investigated.

<u>Stability Augmented Systems</u>

Numerous orbital maneuvering systems employing varying degrees of stability augmentation have been investigated in recent years. All of these systems have in common the design approach of balancing orthogonally positioned thrusters around the system c.g. Attitude control is typically accomplished through a rate command system which utilizes rate gyro feedback in each axis differenced with astronaut rate commands to form an attitude rate error signal. Translational control is effected in an acceleration command mode through thruster on-off commands.

The following discussion briefly summarizes the major design concepts which have been investigated:

(1) USAF Modular Maneuvering Unit - This system, which was designed for incorporation into the Gemini Program as Experiment D-12, is a five-degree-of-freedom system employing a hydrogen peroxide propulsion system controlled through a rate command system (25) capable of a single one-hour mission.

(2) Astronaut Maneuvering Unit - Mission analysis studies have indicated the requirements for advanced manned maneuvering units incorporating six-degree-of-freedom control, propellants with higher specific impulse, longer duration environmental control systems and recharging capability (21, 26, 27).

(3) Space Shuttles or Work Platforms - Numerous mission and preliminary design studies of vehicles on which the astronaut rides have been completed (28-30). These systems have been considered for missions which require a large ΔV, involve orbital transfer of sizable payloads and include the requirements for in-space assembly and maintenance.

(4) Dual Maneuvering Unit - A mission and cost effectiveness and preliminary design study of a system which can be used either in manned or unmanned modes of operation is currently being conducted under the sponsorship of the USAF Aero Propulsion Laboratory (23). In the manned mode, the system would operate in a manner very similar to an AMU. However, for missions which do not require a manned operator, the vehicle could be remotely flown under the control of the astronaut located in the parent spacecraft.

In general, systems such as described above have been studied for relatively long range missions, missions requiring extended durations with high maneuvering ΔV, missions requiring precise attitude control and/or stationkeeping and for transporting payloads which comprise a major portion of the total system mass.

Thrust Vectoring Systems

Maneuvering devices employing the principle of thrust vectoring, as was the case in the earth and lunar operating environments, do not include stability augmentation. The major design concepts investigated to date are briefly summarized below.

(1) Hand Held Maneuvering Units - Numerous concepts for such systems have been studied in recent years. The initial investigation known to the authors was conducted by Simons and Gardner of the Air Force Aerospace Medical Division (31). Three models of a gas powered device were fabricated and tested on air bearing platforms and during Keplerian trajectories in the C-131B aircraft. Clark and Blechschmidt (32) fabricated a prototype "power cane" thrusting device which incorporated two thrusters. Tests of the device in a tether apparatus resulted in positive conclusions relative to the application of a similar system in orbit. Another variation of the hand held thruster system, utilizing thrusters located on operator's hands was recently investigated by Hanff, Moulton and Geller (33). This study, however, was primarily directed toward the design of a prototype system and did not present analytical or test data to support concept feasibility from a control point of view. The most extensive effort to date, however, is that completed by NASA (34). The successful use of the NASA developed hand held thruster unit on Gemini flights 4 and 10 demonstrated the feasibility of this method of thrust vector control for short range line-of-sight translations.

(2) Jet Shoes - A simulation study of an extravehicular maneuvering device concept incorporating thrusters positioned on the operators feet has indicated the feasibility of controlling orientation and translation under zero gravity conditions (35).

(3) Space Jeep The Marquardt Corporation has recently completed the design of a pulling type thrust vectoring system incorporating a universal joint between the propulsion system (i.e., point of thrust application) and the astronaut (24). This design was based on the fact that a two-body system, when acted upon by a thrust misaligned with the center of mass, will undergo a relative positive change of the two bodies so that the moment arm of the applied thrust tends to decrease with time. Since the operator, with his inherent variable damping features, can minimize oscillations the system can be considered to be dynamically stable.

(4) Zero-G Belt - A high pressure nitrogen gas research maneuvering device was fabricated by Bell Aerosystems Company in 1962 and flight tested in the C-131B aircraft (36). The system incorporated orthogonally positioned nozzles located around the man's c.g. The thrust levels and lever arms incorporated in the design, coupled with the oscillations of the aircraft, made it difficult to reach firm conclusions on system controllability without some form of stability augmentation.

Although each of the above described concepts has individual design characteristics, they all require manual aiming for control of the six degrees of freedom. At present, it appears that a wide range of missions can be performed by such unstabilized devices; especially missions performed in close proximity to the parent spacecraft which do not require precise maneuvering or stationkeeping. However, until operational testing under actual orbiting conditions is accomplished, the full potential of vehicles of this type will remain uncertain.

Because the main interest of this paper is in the area of manual stabilization and control, the balance of this section is devoted to a brief discussion of the effects of the orbital environment on the employment of systems incorporating thrust vector control.

APPLICATION OF THRUST VECTORING CONTROL SYSTEMS IN EARTH ORBIT

The operation of a small propulsion device of the thrust vectoring type, in orbit, differs from similar type systems used in flying over the earth or the lunar surface with respect to guidance cue effects, mass and inertia effects, and zero gravity effects. A brief discussion of each of these effects and their impact on vehicle stabilization and control is presented below.

Guidance Cue Effects

The techniques of guidance and control of vehicles maneuvering in orbit vary according to the range involved, the time available for the maneuver, the type of vehicle being employed and the type and amount of instrumentation and supporting equipment available to support the operation. For the longer ranges, in which the time of transit is also long, orbital guidance techniques are used which compensate for the long term effects of the small forces resulting from the orbital mechanics. This, in turn, requires precise aiming and thrusting at angles obtained from on-board guidance and control equipment. Because of this, orbital guidance techniques of this type are almost invariably limited to stability augmented vehicles.

The guidance cues required to perform the in-orbit maneuvers differ considerably from those of earth and lunar surface operations. In over-the-surface operations, the operator will have visual, dynamic and vestibular cues to determine his flight trajectory and to use for throttle and attitude control. In orbit, the vestibular and dynamic cues will be appreciably modified. Therefore, the guidance cues the operator will have for determining his thrusting actions will be primarily visual. These cues may be derived from a number of different sources, including referencing the target object with respect to the star background, the horizon, stabilized axes of the maneuvering vehicle or to the target vehicle and other surrounding objects.

(1) Star Background - The star background may be used as the visual reference in determining line of sight rotational rates between the target and the maneuvering vehicle in cases where the astronauts eyes are dark adapted. However, on the daylight side, the earth albedo tends to raise the level of dark adaptation so that the stars are not always visible enough to use as primary guidance cues.

(2) Horizon - The horizon may be used as a guidance cue when the translation mission places the target vehicle within the line of sight to the horizon. Since many missions do not place or maintain the target vehicle within the line of sight to the horizon the use of the horizon as a primary guidance reference is questionable.

(3) Stabilized Axes of the Maneuvering Vehicle - Maneuvering vehicles, which are automatically stabilized in attitude, provide an extremely convenient and effective guidance cue during a translational maneuver. If, for example, a closing speed has been established between two vehicles but the vehicles are not headed directly at each other, the operator in the maneuvering vehicle will be able to recognize the situation by noting the extent of target vehicle lateral or vertical movement within his field of view. This type of control can be used by stability augmented vehicles over fairly large distances. However, because the vehicles using thrust vectoring techniques do not have attitude stabilization, this technique does not apply.

(4) Referencing to the Target Vehicle and Other Nearby Objects - Orbital flight experience and simulation studies have indicated that the operator in the maneuvering vehicle can obtain sufficient guidance cues to maneuver himself by simply referencing his position with respect to the stabilized axes of the target vehicle. This maneuver technique is somewhat similar to that using stabilized axes of the maneuvering vehicle (see 3 above) except that in this case the operator must interpret his positional data by referencing to a set of axes and objects remotely located. Apparently, this is relatively easy to do as long as the operator can clearly distinguish details on the vehicles and objects which surround him. As separation distances increase, however, the usefulness of this type of cue will quickly deteriorate. Therefore, range of operation for orbital thrust vectoring maneuvering systems may be severely confined. This useful range of operation has yet to be determined.

At close ranges, where separation distances and times of transit are small and when a relative velocity between the maneuvering vehicle and the target object is established, the orbit accelerations are not sufficient to change either the magnitude or angle of the velocity. As a result, the mechanics of flight closely resemble that of free space. Thus, the pilot, by means of one or more of the guidance cues discussed above, is able to maneuver with respect to the target object, simply by aiming and thrusting in the directions in which he wishes to travel. This type of maneuvering has been studied extensively in many different simulations as well as in several Gemini rendezvous missions. It has been proven to be an effective means of control.

Zero Gravity Effects

The operation of a thrust vectoring propulsion system in the presence of gravity requires continuous thrusting during flight, during which time attitude and velocity are controlled by the thrust vectoring techniques. In orbit, however, if we neglect orbital mechanics effects, continuous thrusting is not required. Therefore attitude and velocity control must be accomplished during the short thrust applications required to initiate desired translational velocities or changes in system attitude. During these periods of thrust application, the operator's control action should be similar to that of the earth or lunar vehicles; that is, the operator must keep his thruster positioned in line with the direction in which he wishes to accelerate. In thrust vectoring systems, since the point of application of thrust is ahead of the man-machine system c.g., the system will oscillate in attitude with a dumped pendulum type motion. Since the moments being applied to the vehicle are independent of gravity, its absence will have no effect on this pendulum type motion.

Since the orbital thrust vectoring system does not have to work against gravity, the thrust levels can be considerably reduced. This, coupled with the high masses and inertias anticipated for the orbital systems, results in systems with irregular control powers significantly less than those present in systems designed to operate in gravitational fields. However, as was shown in transferring from the earth to the moon, the disadvantages of reduced control powers should be more than offset by the longer allowable flight times, and reduced requirements for operator response rates associated with the reduced gravitational fields. As a result, improved vehicle handling qualities should result.

CONCLUSIONS

Analytical studies, zero g flight, simulations and limited orbital flight experience have indicated that simple thrust vectoring systems are effective for limited range maneuvering in support of simple extravehicular activities in space. Because of uncertainties regarding the relationships between visual cues and operator control of the vehicle, the total safe range of operation has yet to be determined. In addition, because of a correspondingly large number of potential missions and therefore a range of system requirements, it is expected that no one particular design will be optimum for all areas of application. Until in-orbit testing data are available it will be difficult to establish the full potential of vehicles of the thrust vectoring type of earth orbital locomotion.

SUMMARY

This paper was directed at summarizing the major studies on personal propulsion devices which have been completed in the last decade. Primary emphasis was placed on the Small Rocket Lift Device (SRLD) concept developed by Bell Aerosystems Company and extrapolating it's performance potential and control concepts to simple mobility systems for use on the lunar surface and in earth orbit.

The data presented indicate that the primary means of flight control used in flying the earth SRLD incorporates thrust vector control; i.e., the operator maintains attitude and translational control of the vehicle by rotating his thrust vector relative to the system c.g. The operator's variable damping characteristics serve to dampen any resultant oscillations.

Extrapolation of the SRLD capabilities to operation over the lunar surface clearly indicated operational feasibility, after accounting for the major environmental differences which would be experienced, such as full pressure suit effects, absence of aerodynamic drag, changes in the system mass inertia and c.g., and reduced gravity effects. This conclusion was supported by the results of fixed base simulation studies.

The application of personal propulsion devices employing thrust vector control under orbital conditions was briefly discussed. Based primarily on the successful employment of the hand held thruster on Gemini flights 4 and 10, but also supported by numerous ground simulations and zero g aircraft testing programs, it was concluded that thrust vector control can be utilized under orbital flight conditions. However, it was emphasized that such systems will probably be limited to short range translation missions based upon guidance and ΔV optimization criteria. Thus, it was concluded that systems employing some form of augmentation are required if a wide range of orbital support functions is to be accomplished.

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Solved and Unsolved Space Medical Problems International Status 1966-1967

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SOLVED AND UNSOLVED SPACE MEDICAL PROBLEMS
INTERNATIONAL STATUS: 1966/1967

Hubertus Strughold, M.D., Ph.D.

After the subsonic and supersonic flight phase of aeronautics in man's fast advance on the "vertical frontier," the first milestone in aeronautics is already behind us with the achievement of numerous orbital flights, with a duration record of 14 days in near earth space. Rendezvous, docking operations and fantastic extravehicular excursions have been successfully performed. Now, preparations are underway for longer orbital flight durations and for manned lunar and planetary landing missions.

This is the time to look back at the problems that have been solved and at those that are still open in manned orbital flight, and to make extrapolations from the medical experiences in near earth space with respect to the long-range flights to the neighboring celestial bodies. In this respect, we are now in the fortunate position to make use of a rich source of physical environmental data gained by means of space-bound rocket astronomy such as automated space probes, Lunar orbiters and landers, and planetary fly-bys; and last but not least, of the remarkable progress made in modern earth-based optical, radio- and ultraviolet-astronomy.

It is, of course, impossible to present in one hour an overall review of the solved and still unsolved problems. Therefore, I would like to confine myself to certain freely selected timely topics, with emphasis upon the environmental medical aspects of the Earth, space, of the Moon and Mars, or the ecophysiological factors along the line from Aerospace Medicine to Lunar and Mars Medicine.

Beginning with the earth's environment, there are some distinct altitude levels of special medical and flight operational interest. They can be summarized as follows:

First, the Atmosphere:

Extension of the inner atmosphere: 0 to 700 km

Extension of the outer atmosphere, or exosphere: 700 to 5,000 km

At 4 km -- threshold of subcritical hypoxia

At 7 km -- critical hypoxia

At 20 km -- boiling of body fluids, or ebullism (Armstrong Line)

From 50 to 80 km -- limit for aerodynamic navigation (von Karman Line)

100 km -- official demarkation line between atmosphere and space (Federal International Aeronatique, Geneva, 1964)

150 to 200 km -- border of the aerodynamically effective or sensible atmosphere

At 20 km the atmosphere attains the characteristics of partial space equivalence which widens to total space equivalence at the border of the sensible atmosphere.

The circumterrestrial environment includes two fields of forces:

the Magnetosphere as the background force of the van Allen Radiation Belts. On its sun-directed side the magnetosphere, with its boundary the magnetopause, is compressed by solar plasma wind to about 10 earth radii, and on the opposite side it is elongated in the form of a tail reaching far beyond the Moon (magnetic tail).

the Gravisphere, i.e., the region within which the earth can hold a satellite in orbit, extends to 1.5 million km. Up to several times this distance its gravitation field is still influential, as manifested in its effect upon the velocity and direction of space vehicles (gravipause). The Moon's gravisphere extends to about 60,000 km. So much about our present knowledge of the gross morphology of the physical environmental (atmospheric, magnetic, and gravic) profile of the earth.

In contrast to the radically changing physical environment along the vertical frontier, the physiological "milieu interne" (Claude Bernard, 1860), of the human body has the tendency to constancy, or homeostasis, a concept advanced by W. B. Cannon, Boston, in 1929 (1). The human body tends to keep the physical properties and chemical composition (temperature, oxygen, salt, ion concentration, etc.) of its internal milieu, i.e., intercellular, or interstitial fluid, called "fluid matrix," in any external environment nearly constant.

> Whereas, with regard to his surrounding environment, man is an air inhabitant, his basic living units, the cells - trillions in number - are water inhabitants, just the same as the microorganisms in the physically rather constant deep sea. His internal intercellular ocean, amounting to about 12 liters, connected via the moving blood and lymph streams with the moist surfaces of the lungs and kidneys, has to be kept in a nearly steady state, a

precondition for man's health, well-being, and intact sensorimotoric and intellectual activities.

If one of the physical or chemical components of the external environment deviates from the normal, but is still above the physiologically required minimum or below the permissible maximum, the human body reacts effectively with coordinated compensatory or defensive responses (changes of metabolic rate by muscular action, respiratory, cardiovascular and renal reactions, perspiration, etc.). Deviations beyond those two ecological "cardinal points" lead to pathological effects upon the cells, particularly the brain cells, and as a result the psychophysiological functions deteriorate. Maintenance of a nearly steady state of the body's "fluid matrix" is the function of autonomic and endocrine systems, governed by a control center in the Thalamus and Subthalamus of the Diencephalon, or interbrain. This makes the human body a self-regulating system, but only within certain limits.

I have referred to this fundamental physiological phenomenon, homeostasis, because it is an ideal departure point for a medical study of the human body in relation to any environment, or for an ecophysiological analysis of the "fitness of an environment" for man. Application of this concept is now particularly useful with regard to the natural environments beyond the life-supporting regions of the earth's atmosphere, in space, and with regard to the artificial environs in space ships, space suits, and in lunar and planetary stations.

During the past 10 years considerable progress in research has been made concerning the kind of atmosphere for space cabins, such as two-gas atmospheres with nitrogen, helium, neon, or argon as a diluent of oxygen, one-gas atmosphere (pure oxygen), its toxicity and fire hazards, chemical and biological regeneration of the air, prevention of chemical and biological contamination, depression prior to egress for extravehicular activities, survival time of chimpanzees after sudden exposure to vacuum conditions, etc. (2). In addition to these experiments on man and animals in space cabin simulators, lasting many weeks, practical experiences have been gained in actual manned space flight up to a fourteen-days' record duration. Principally, the environment in a spacecraft should be as terrestrial as possible, and this applies particularly to the atmosphere which should be a two-gas atmosphere, particularly for long-range operations (3).

A leak of the space cabin can endanger the homeostatic system of the occupants. One possible cause, often considered in the literature, could be a hit by a meteoroid with puncture capability; but the situation in this respect, at least in circumterrestrial space flight, looks better today than had been expected 10 years ago in the presatellite time. Most of the meteoroid material in near earth space is of cometary origin and this kind, according to Fr. Whipple (4), is soft "fluffy stuff," neither as frequent nor as violent as had been feared earlier. But recently the temperature of the nucleus of a comet, Ikeya-Seki, has been measured by means of infrared sensors; it increased from 371°C at a distance of 74 million km from the sun to 649°C when the comet came within 32 million km of the sun. On its return, the temperature dropped back to 371°C. This high temperature at the perihel has been interpreted as an indication that comets consist not only of dirt and snow but also of some metallic material. We can expect more information on this question when automated space probes fly through the tail of a comet, collect and analyze its material, and send the data back to earth. An opportunity for such an exploration on the spot by a cometary tail probe will come when Halley's Comet returns in 1985. Be that as it may, during the total manned space flight time no macrometeoritic incident has occurred and, so far, four extravehicular excursions have been made without even micrometeoritic interference. Moreover, it might be interesting to note that up to now four manned spacecraft have been in orbit at the time when the earth crosses yearly the orbit of a permanent meteor stream. But stream meteoroids are also occasionally concentrated in the form of a meteor swarm. When the earth passes through such a swarm--which is a rare event--we see the spectacle of a meteor shower such as that in 1933, 1946, and 1966.

All in all, the situation concerning meteoroid hazards at the earth's solar distance is no longer considered of first-rate concern. But this rosy picture might be somewhat dimmed by the possibility of a collision of the spacecraft with the stone and iron meteoroids of asteroidal origin in extended space operations to Mars and beyond, near the belt of the asteroids where they should be more numerous.

Protection against puncture by means of "meteor bumpers," (Fr. Whipple) including self-sealing devices, therefore, will remain the concern of the engineers and the space doctors.

Concerning micrometeoroids, preventive measures against corrosion effects on windows and communication equipment have to be taken, particularly on long duration flights. Satellites such as Pegasus and Gemini XII-Agena by means of micrometeorite collection packages have already provided important information about the distribution of micrometeoroids in near earth space.

Turning to another space environmental factor, energetic particle rays, what is their hazard potential as we see it today? The radiation dose absorbed in manned orbital flights in circumterrestrial space between 50 degrees North and South Latitude has been maximally less than one millirad per hour, or about 15 millirad per day, as recorded in both the Gemini flights and the Russian flights. Thus, in low orbits we can look upon the radiation problem with no particular concern. This is different in high orbits, i.e., above 800 km, within the van Allen Radiation Belts, where we must reckon with up to 5 rad per hour in the inner belt around 3,000 km, and with 10 millirad per hour in the outer belt around 16,000 km. These belts, therefore, are "off limits" for space flights of the orbital type. In deep space beyond the magnetosphere, the dose rate might be several rad per month. Such is the particle radiation climate for the astronauts during the time of a quiet sun, if the absorbing power of the cabin's wall is equivalent to 1 cm of steel. There are other more optimistic and pessimistic estimations; be that as it may, the intracabin radiation dose can still be reduced by heavier shielding.

Concerning a proton outburst after a solar flare, astronauts orbiting in near earth space and constantly in communication with the earth-based Solar Flare Prediction Center, will have more than 10 hours time to take protective measures. Extravehicular excursions are, of course, not advisable for several days after a solar flare. With increasing distance from the sun, as en route to Mars, the proton streams become gradually less vicious. In near Mars space there is no effective magnetosphere to trap particle rays, according to Mariner IV (5). There are, therefore, no restrictions from a van Allen-type Radiation Belt for the selection of the altitude for a parking orbit. The same is true about circumlunar flights, according to recordings of Lunar orbiters.

With regard to electromagnetic radiation, I would like to confine myself to its visible section as an environmental factor. In circumterrestrial orbital flights the photic environment includes a variety of components: sunshine, intensity: 140,000 lux; earthshine: several lux; moonshine: about 1/2 lux, and the earth's shadow, all to some extent overlapping and encountered by the astronauts within the short orbital period of 90 to 130 minutes. This is certainly in sharp contrast to the 10 times longer regular light and darkness cycle of 24 hours on earth with which our physiological sleep and wakefulness cycle is synchronized. This Circadian Cycle (Halberg) is another basic property in the physiological nature of the human body; it shows a tendency to near constancy and is actually integrated in the homeostatic system insofar as the changes in metabolic rate, oxygen consumption, activity of the exocrine and endocrine glands, temperature, etc., fluctuate around their homeostatic baselines.

This physiological Circadian cycle is firmly established in man and can be shortened only to about 18 hours and extended to 28 hours (N. Kleitman). Man is, so to speak, cyclostatic. Preservation of this physiological cyclostasis, i.e., alternation of sleep and activity within nearly the inherited time frame is a precondition for man's health and performance capability (6). Astronauts, therefore, have to follow the dictate, or better tick-tock, of their physiological clock by a well-regulated sleep and activity regime.

Fortunately, sleeping under weightless conditions in space flight seems to pose no particular problems. All of our astronauts and the Russian cosmonauts had a sound sleep in the silence of space when noise was kept at a low level (7, 8). In case that two astronauts are in a space ship, it has been found desirable that they sleep at the same time, as it has been arranged for the last Gemini flights (7). In case of a crew of more than two, a shift in the sleep and activity cycle will be required, and one of the astronauts has to be kept synchronized with the time zone of the Manned Spacecraft Control Center for communication reasons.

The Moon's day-night cycle of 27 terrestrial days does not provide a time cue for the physiological clock of the occupants of a lunar station. Their sleep regime has to be arranged independently of the lunar photic environment. Nevertheless, since the lower gravity on the Moon might probably cause fewer sleep-interrupting body movements than experienced on earth, due to the so-called "pressure points," the sleep might be more refreshing in the gravitational arms of Luna, the Goddess of Night.

On Mars--the day-night cycle is only 37 minutes longer than on earth and offers, therefore, a time cue familiar to terrestrial visitors for their physiologic sleep-activity regime.

Basically, then, there are no particular problems concerning the physiological clock for space travelers; probably less than encountered by air travelers who, after crossing a half-dozen time zones, are for several days desynchronized (6).

In all medical aspects of space flight the duration plays an important role. What might be the time limits in this respect? A flight to the Moon is no problem since this takes only about three days. But a flight to Mars, based on an economic, i.e., minimum energy trajectory, lasts more than eight months. This is the simplest method for unmanned, automated planetary probes such as the Mariner IV.

But is such a long duration also acceptable for a manned planetary mission? To get a realistic judgment in this respect we must consider the whole complexity of life of the mission crew, a team of perhaps six or more, living in a cramped, closed ecological world with its own economy and autonomy. Their activities include power control, navigation, exploration, telecommunication, control of the life-support system, hygiene, housekeeping, etc. Weightlessness complicates some of these activities, others are facilitated.

The astronauts, after some 20 hours of flight, should be in a state of "relatively stable adaptation to weightlessness," as has been concluded from the medical observations in orbital flight. Anthropometric comfort, appropriate exercise and a well-regulated sleep regime might enable them to endure space flight in the order of months. Artificial gravity might not be required. Be that as it may, it is medically advisable, if not even a requirement, to base a flight plan to Mars on a high energy trajectory to shorten the duration of the minimum energy trajectory of about eight months to 30% or 20% of this time, which can be achieved by nuclear propulsion.

In addition to the man-machine-intracabin environment complex, the external space environment also must be taken into account. A shorter time reduces the possibility of meteoritic incidents and the radiation hazards after solar flares.

In brief, a minimum in time and an optimum in comfort is the medical prescription in order to achieve a maximum of success of any manned planetary landing mission (9). Of course, astronauts with week-long experiences in orbital flight and the space medical "practitioners" who have controlled these flights will have a decisive voice in this respect.

In case of long-range space operations, as for instance a flight to Mars, preflight prophylactic surgical measures in addition to preventive dentistry must be considered. Appendectomy and even chlolecystectomy would certainly be advisable if not more advanced diagnostic methods can prove that the astronaut is free of negative gall bladder stones (not visible in present-day x-ray examinations).

The human body is not only, with regard to its vegetative functions, a self-regulating system but also with regard to its sensory motoric functions or statokinetics. This is now particularly interesting concerning extravehicular activities, the most fascinating achievement in manned space flight. I would like to make a few comments about the sensorimotoric control of equilibrium and orientation during walking under reduced gravity down to zero g.

The sense organs involved in these functions are: the eye, the labyrinthine (otoliths, semicircular ducts), and extra-labyrinthine peripheral mechano-receptors. Usually the labyrinthine organ is in the center of the discussion about this threefold equilibrium control system or "orientation trias" (10, 11). I, therefore, would like to confine myself to the extra-labyrinthine mechanical senses. They are: the muscle sense, the pressure sense, and the posture sense, with their well-known receptors. Responding to mechanical stimuli such as pressure, tension, stretching, etc., they control sensorically to a great extent position and movement of the body and its parts by coordinating the required muscular reactions, as indicated by the electromyogram.

First, let us assume a man of 70 kg mass, or 70 kilopond, (= 70 kg weight) walks on the earth's surface with its 1 g condition, the pressure upon the mechano-receptors in the soles of his feet and particularly the muscle tension provide adequate stimulation for the coordination of the flexors and extensors; moreover, during walking upstairs and downstairs or on a rough surface the increased and abruptly changed muscular tension produces supporting or correcting proprioceptive muscle reflexes.

On the Moon a 70 kg man has a weight of 12 kilopond. This might still produce enough gravitational stimulation for the mechano-receptors in the legs. But keeping balance during walking might be facilitated by increasing the astronaut's weight by carrying, in addition to the life-support equipment, some 30 kilopond of material, maybe Moon pebbles, in pockets around his waist or shoulders. This would increase the tension in the extensor muscles of the legs and might even trigger proprioceptive reflex support, and thus should make walking on the moon's pebble-covered surface safer. It would make the stimulation of the peripheral mechano-receptors more earth-gravity equivalent. Of course, it would not affect the otoliths. (By the way, similar measures are used by aquanauts when walking on the bottom of the sea.) This is the method of walking on the Moon I suggested at the Symposium of the Lunar International Laboratory Committee of the International Academy of Astronautics in Madrid, 1966 (12).

In contrast to this method of walking, R. Margaria, Milano, suggested at the same meeting that advantage of the Moon's low gravity should be taken by jumping. This might be acceptable if the surface is smooth; but, on a rough surface if the "Moonhoppers" should lose their balance and hit the ground they might risk a leak in the pressure suit. Thus, the method of increasing the weight might be generally safer.

Furthermore, a one-man rocket propulsion device, too, seems to be very useful on the Moon; in the personal control of this system the peripheral mechano-receptors, in addition to the otoliths and eye, play an important role.

> Interestingly, there is an analagon to this device in the animal kingdom. The Medusa of the phylum Coelenterata swims by taking water slowly into a cavity through an opening and by expelling it again by a fast contraction. This is an individual water propulsion device which has been in existence for some 300 million years.

Back to the space age; during the zero g extravehicular activities in space, orientation and balance depend exclusively upon vision and the proprioceptive perceptions of the peripheral mechano-receptors. The important role of the latter is indicated by the fact that the astronauts feel better oriented when they touch a handrail on the spaceship, which gives them additionally some exteroceptive perceptions. By the way, when the Russian cosmonaut, G. Titov, in his Vostok ship had some dizziness, he felt immediately better when he pressed his buttocks against his seat. This is a kind of space analagon to "flying by the seat of the pants" in an aircraft.

On Mars, with a gravity of 0.38 g, there should be no balance difficulty in walking around outside the station to explore its surface mysteries.

In this respect, I would like to make a few concluding remarks about what we have learned from the recent discoveries of Mariner IV and from modern earth-based astronomy for Mars Biology and Mars Medicine, particularly how they might affect the Martian Life Theories (13-15). In terms of planetary analogy and terrestrial biology this can be summarized as follows:

First, concerning the relief of the Martian surface, the generally accepted opinion is that the reddish areas are highlands and the dark regions are lowlands. This seems to be confirmed by the radio occultation measurements of Mariner IV, according to which a certain reddish area named Electris is 5 km higher than a dark region called Mare Acidalium (16).

The dark areas, according to most observers show seasonal color changes from dark to bluish-green, yellow-gold, to brown, and back to dark, which is interpreted as an indication of green vegetation on Mars. But to some observers they appear always to be dark gray. This can be accepted only if they have medically examined normal color vision.

The bluish-green color is also considered to be a visual contrast phenomenon against the ocher-reddish surroundings. Visual contrast effects certainly occur, especially if the areas are small, but the bluish-green coloration of large areas such as the Syrtis Major is in all probability real. This is also supported by the observation of C. Tombaugh, according to which certain areas occasionally look dark when others look green, despite the fact that both are surrounded by reddish areas (17). The final answer in this color dispute might come from color photographs made by future fly-by probes. But green or not green, it is not decisive for life "to be or not to be" on Mars.

Fifty years ago, Sv. Arrhenius advanced the theory that the dark areas are salt beds of dried-out oceans which respond to changes in atmospheric humidity and concluded that "Mars is indubitably a dead world." But in the Dead Sea, which is an extraordinarily salty medium, numerous species of microorganisms (algae and bacteria, etc.) flourish there abundantly (18).

The Dead Sea, therefore, is not so dead at all, as it was believed. And the Red Planet might not be so dead, as well.

The dark areas have also been explained as being deposits of volcanic ash blown over them by the prevailing winds, and the color changes have been attributed to reactions to seasonal variations in humidity, or in radiation. This, of course, does not exclude the possibility of life, because terrestrial bacteria -- lichens and mosses -- can grow on lava. Actually, bacteria can grow on practically any material, even in oil wells and jet fuel containers, as indicated by the new bacteriological branch, petroleum bacteriology.

Concerning the atmosphere, the earlier estimations of its pressure at ground level, based on spectrographic studies, ranged from 85 to 10 millibar. The occultation experiment of Mariner IV suggests a pressure of 10 to 5 millibar (19). Could microorganisms survive such low pressure? Recent experiments in space environmental simulators and in containers carried outside a spacecraft (7) have shown that bacteria and particularly spores are resistant even to a vacuum.

Oxygen so far has not been detected in the Martian atmosphere. This does not exclude life, as proven by the occurrence of various types of anaerobic bacteria on Earth. Anoxybiosis might be the Martian way of life if no organisms exist there capable of producing their own oxygen by means of some kind of photosynthesis. This process requires carbon dioxide and water as raw material.

Recent spectroscopic studies indicate that the carbon dioxide pressure in the Martian air might amount to 3 millibar, i.e., 10 times as high as on earth. This would even be of advantage for the growth of green vegetation, since carbon dioxide in this pressure range increases photosynthesis. Beyond 22 mm Hg it has an inhibiting effect upon this process.

Water vapor has been detected in the Martian atmosphere, but it is extremely scarce, only about 1/1000 of the mean humidity of the terrestrial atmosphere. If the barometric pressure is below 7.5 millibar, this is below the "triple point" of water, i.e., H_2O can exist only in the state of vapor and ice. But in the lowlands of Mars the air pressure might be around 10 mb, in this case it could occur also in the liquid state in the soil. The "wave of darkening" moving from pole to pole in spring is an indication of soil moistening. Water is decisive for the existence of life. But some terrestrial microorganisms can survive long periods of complete desiccation. Seasonal periods of extreme dryness of the Martian surface would not destroy them. Hydroecologically, the situation on Mars is severe but not to the extent that it is prohibitive to life of the low-level terrestrial type. Moreover, there might be subsurface ice layers which could increase the soil's humidity locally. They are considered to be remnants of ancient oceans, now covered by some 100-meter thick layer of solidified dust. This theory, advanced in 1910 by Bauman in Zuerich (20), later somewhat forgotten but recently revived, is very attractive if combined with two other concepts (21).

In 1937, P. A. M. Dirac (22) advanced the hypothesis that the gravitational constant has decreased slightly during the life of the solar system and continues to decrease. This has led to an expansion of the earth, causing "tension cracks" or fissures on land and at the bottom of oceans, as recently described by R. H. Dicke (23) and P. Jordan (24) who both confirmed Dirac's first generally not accepted theory. The splitting of the two giant original supercontinents, Gondwanaland and Laurasia, about one billion years ago into several secondary continents, now widely separated by a continental drift (A. Wegener), is attributed to this gravitational phenomenon.

It is logical to assume that on Mars, too, this gravitational decrease has caused similar effects, namely, volume expansion and tension cracks after it had cooled off at the end of its protoplanetary phase and had reached a temperature equilibrium. And meteoritic impacts in addition to volcanic Marsquakes could have triggered fissures of tremendous lengths, particularly in a crust of different layers, including a subsurface ice layer. This threefold environmental combination: subsurface ice layer, tension expansion due to gravitational decrease, and meteoritic impacts, might well have been the mechanism behind the scene of the dark spots called oases and the dark linear marking radiating from the dark spots over enormous distances. A subsurface ice table, or hydrocryosphere, would increase the humidity locally, i.e., in and around the meteoritic impact craters and in and along the fissures, making them ecologically more suitable for the growth of vegetation. Actually, it might be the soil's humidity and vegetation that make these aerographic surface features visible to earth-based optical astronomy in the first place.

To conclude this water dispute - if there should be native life on Mars, this would not be conceivable if there had not been ancient open waters for its origin.

The Martian surface temperature in summer is for about five hours each day ecologically adequate, and it can reach a maximum of 30°C, but all the other times it remains below the freezing point of water; it drops to a minimum of -60°C, a condition which appears particularly prohibitive to life. But we know of bacteria and spores that survive temperatures close to absolute zero; furthermore, it has been found recently that the terrestrial bacterium (Aerobacter Aerogenes) survives when experimentally exposed to a diurnal freeze-thaw cycle. Generally, then, a biology of Mars during its cold nights turns always into cryobiology. However, locally there might be exceptions in the form of perma-warm spots on the surface similar to those on earth, as for instances in Alaska (25), Wyoming, Iceland and New Zealand. There is no reason in terms of planetary analogy why similar perma-warm spots should not exist on Mars, possibly above dormant volcanos, which would not have the low night temperatures and, therefore, would have a higher ecological potential. Scanning the surface with heat sensors by future automated Martian orbiters may answer this question.

The low density of a 10 millibar pressure atmosphere might not provide effective protection from harmful solar ultraviolet and x-rays, it is argued. But, first of all, the intensity of solar irradiance at Mars' distance from the sun is less than half of that at the earth's solar distance; furthermore, a certain amount of these rays is certainly absorbed within the atmosphere. It is, of course, well-known that ultraviolet rays, particularly in the range from 2500 to 2800 Angstroem, are indeed very destructive to most terrestrial microorganisms. For this reason they are used for sterilization of food and even of lunar and planetary probes to prevent contamination. But there are various degrees of resistance to ultraviolet and x-rays; certain microorganisms are even stimulated in growth when exposed to low intensity ultraviolet and x-rays. And, finally, some microorganisms, plants and animals are less susceptible to ionizing radiation under hypoxic and hypothermal conditions. This is particularly interesting with regard to Mars with its oxygen-free atmosphere and low temperature.

Finally, energetic particle rays of solar and galactic origin are considered as possible adverse factors to life on Mars because they can reach its atmosphere unhindered by a magnetospheric shield. But because of the greater distance from the sun the influx of particle rays of solar origin is certainly lower and the so-called microenvironment provided by caves, craters, and fissures might offer effective protection.

Considering all of the physical, chemical and biological factors and their interrelations, and particularly the adaptability of life to adverse conditions, we must come to the conclusion that the occurrence of life on Mars is more in the realm of probability than of possibility. Some of the findings of Mariner IV and of modern earth-based astronomy are more hostile to life, but others are more favorable. In the years ahead life-detecting instruments on board unmanned landers will be sent to Mars for acquisition and analysis of soil samples and for transmitting the data back to earth (26, 27); but the final and more detailed answer concerning a Martian biosphere might come from a manned Mars landing mission. If the answer is: no life on Mars, this would give the explorers a unique opportunity to study the chemistry of a virgin planet of the terrestrial group. If the answer is: yes, then we would be interested to know if the Martian life is similar to that on earth, based on carbon biology, or of a completely different kind unknown to us. Be this as it may, it would broaden our present earth-related Cenozoicum into a universal spectrum, the Cosmozoicum.

With regard to Mars Medicine (9) involved in a manned Martian landing mission, I would like to mention only that if the barometric pressure on the Martian surface is 10 millibar, boiling of the body fluids of terrestrial visitors, suddenly exposed to this environment, would occur at the surface and not at an altitude of 5 km, corresponding to the earlier assumed pressure of 85 millibar. Barometrically this means, in terms of human physiology, that the atmospheric environment is partially space-equivalent immediately on the surface. The atmosphere offers certainly some protection from ionizing electromagnetic and particle radiation and micrometeorids, and if there are ice layers below the surface, this would help to solve some of the logistic problems. All in all, a manned Mars landing mission is medically conceivable if, as emphasized earlier, time reduction of the interplanetary journey can be achieved.

In conculsion, the achievements in man's advance on the vertical frontier so far have been spectacular, and will be even more fantastic in the years ahead; nevertheless, in its medical aspects we must be realistic and keep common horse sense in our extrapolations for long-range manned missions. After all, a horse, Pegasus, the winged horse of Apollo, was the first to roam around high in the sky -- in ancient mythology.

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