NASA SP-205

BIOTECHNOLOGY

A conference held at
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Blacksburg, Virginia
August 14–18, 1967

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

This publication brings together the 21 papers presented at the Conference on Biotechnology during the week of August 14 through August 18, 1967, on the campus of the Virginia Polytechnic Institute at Blacksburg, Va. The conference, undertaken as part of the National Aeronautics and Space Administration's Human Factors Systems Program, was sponsored by NASA's Langley Research Center and VPI.

The purpose of the conference was to help the life scientist, the physical scientist, and the engineer to appreciate more fully the role that each plays in the evolution of the complex man-machine systems required for space flights of extended duration. The intent of this publication is to make the information exchanged readily available to both participants and nonparticipants.

Psychological, physiological, biological, medical, physical, and engineering factors associated with manned space missions lasting several months or more are examined in these papers. In many instances the authors forecast problems (and possible solutions) that have arisen as the technology advanced. Several of these prognostications are, and will continue to be, subjected to the test of actual experience.

WALTON L. JONES,
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JUNE 1969

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SESSION I

An Overview of Manned Space Flight

Chairmen: **G. H. BEYER and R. S. THRUSH**

Future Manned Space-Flight Implications Derived From Gemini

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Each of the selected topics to be addressed here during the next several days is intensely interesting to all of us in NASA and particularly to those of us in Manned Space Flight. While we have enjoyed considerable success to date, only the reckless feel that we have answered all the questions involved in man's ability to live and work in the space environment. Future manned space flights will pose problems that make past difficulties seem insignificant by comparison and will seriously challenge not only our ability but also our motivation. The conference topic, bioastronautics, is particularly appropriate at this time when the next generation of manned space missions is being planned.

My remarks are a frame of reference in which to arrange our past achievements in manned space flight to provide a glimpse of the future. The history of the Mercury and Gemini programs provides us with the confidence to proceed. I will concentrate on the Gemini program—not that its achievements are, relatively speaking, any more significant than Mercury's—but because in Gemini more things were attempted, and there was far greater opportunity to explore the role of man.

As recently as 5½ years ago, the Nation's manned space-flight program consisted of a great deal of enthusiasm, a well-defined objective, and very little experience. We were on the verge of orbiting the first American astronaut, and I think all will agree that it was a most exciting time. Since then we have, by any standard, I believe, come a long way. My discussion today is concerned with those things we have learned in the last several years and the resulting implications for future programs.

When this topic was suggested, I was asked to pay special heed to the bioastronautics legacy of earlier programs. This subject, properly addressed, cannot help but include bioastronautics. Indeed, perhaps the most significant implication for the future is biological in character—man's capability to perform the space missions that will come.

The Mercury flight program began with Alan Shepard's suborbital Mercury Redstone flight on May 5, 1961. This was followed by a second suborbital flight on July 21 in which Gus Grissom was the astronaut. The following February, John Glenn became the first American to experience orbital flight. Despite the Soviet activity to date, Glenn's flight provided the first real evidence that with proper preparations, the space environment was not as ominous as had been feared in some circles. As Dr. Berry said:

> 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 it. [I might interject here that the community's reservations were widely shared.] Some of these anxieties were reduced following the first flights, although most observers believed the evidence insufficient to reject any of the dire predictions.

Glenn's flight was followed on May 24 by MA–7 with Scott Carpenter and on October 3 by MA–8 with Wally Schirra for six orbits. The Mercury flight program ended on May

16, 1963, with the completion of Gordon Cooper's 22-orbit flight in Faith 7. It was to be almost 2 years before another American would go into orbit.

We had now achieved 52 hr of orbital flight. Each hour contributed to the growing confidence that man could, if properly protected, endure the experience with negligible detrimental effects.

GEMINI PROGRAM OBJECTIVES

The Gemini program followed, and the store of knowledge regarding man's ability to fly in space and perform useful functions in space grew by several orders of magnitude. This program came into being after the start of the Apollo program for the specific purpose of bridging certain gaps remaining between Mercury and Apollo. The Gemini objectives, being straightforward and well defined from the beginning, aided program execution immeasurably. Broadly speaking, Gemini was to increase operational proficiency and knowledge of technology in manned space flight by the following specific accomplishments:

(1) Investigation of long-duration flight
(2) Development of rendezvous techniques and postdocking manuevers
(3) Development of reentry flightpath control
(4) Attainment of flight- and ground-crew proficiency
(5) Development of extravehicular capability
(6) Scientific experimentation

Investigation of Long-Duration Flight

This was in direct support of the lunar landing objectives and was, primarily, physiologically oriented. Could an astronaut endure the environment for the time needed to journey to the Moon, land, and return to Earth?

The long-duration objective was approached in a deliberate fashion. Gemini 4 was 4 days' duration followed by Gemini 5 of 8 days, and Gemini 7 of 14 days. This plan of doubling man's flight duration and observing the results in relation to the next step has been successful and effective. There is no apparent reason to alter this plan in determining the next increments in manned space flight.

Development and Advancement of Rendezvous Techniques

A crucial element of the Apollo mission involves rendezvous (fig. 1). In Gemini a program to explore a variety of types of rendezvous using varied initial conditions was executed.

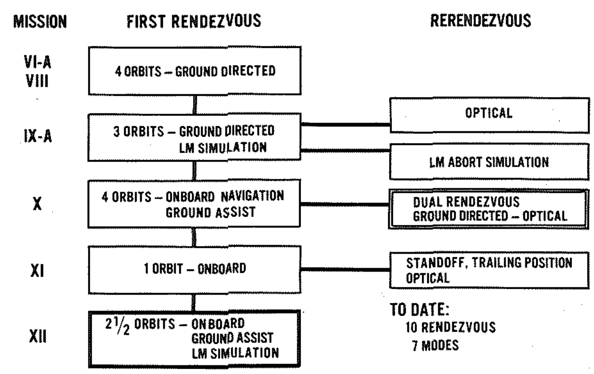

FIGURE 1.—Rendezvous experience.

Ten separate rendezvous were accomplished on six different missions. Seven different techniques ranging from visual/manual control to ground/computer control were employed. The variety of techniques was to develop a cross section of knowledge of the rendezvous problem in addition to simulating certain Apollo mission conditions requiring immediate rendezvous. The objective was successfully achieved.

Development of Reentry Flightpath Control

Reentry from lunar distances requires most precise flightpath control. Gemini programed both manual and automatic reentries to determine both manned and mechanical capabilities.

The following are elements of reentry flightpath experience:

(1) Gemini 3: Lift coefficient
(2) Gemini 4:
  (a) Onboard computer
  (b) Zero-lift reentry

(3) Gemini 5: Programing error
(4) Gemini 6–A through –10: Crew control
(5) Gemini 11 and 12: Closed-loop control

Landing accuracies of 7 miles or less from the aim point were achieved on every Gemini manned mission except 2, 4, and 5. The average miss distance for the last five missions was approximately 2 n. mi. The Apollo capsule reentering the Earth's atmosphere from lunar distance will have a velocity of approximately 25 000 mph. A reentry corrider of about 2° is required. Gemini repeatedly bettered this requirement.

Attainment of Flight- and Ground-Crew Proficiency

This Gemini objective was a clear reminder that all activity in the program must be directed toward developing the skills and techniques required to conduct manned space flights. This was a so-called human factor that dealt with all human aspects of the program—the flight crews, the checkout crews, the mission planners, the flight controllers, and all those associated with a manned flight.

The Gemini missions portrayed clearly the development of high proficiency among flight and ground crews. Each mission included numerous examples of a highly developed professionalism. During later missions, as flight plans became more complex, this capability was increasingly evident.

While certain of these objectives were designed for specific application to Apollo, they were also necessary to fulfill the broad Gemini objective of increasing operational proficiency and knowledge of technology in manned space flight. The remaining Gemini objectives were specifically directed toward the broad view and were only incidental to accomplishing the Apollo mission. These were:

Development of Extravehicular Capability

From the physiological point of view, this appeared to be our most ambitious objective. As it turned out, it was also one of our more trying or evasive objectives. Dr. Mueller stated the case rather well when he commented after Gemini 11, "It is noteworthy that past EVA has revealed problems that appear less yielding to straightforward engineering solutions than other problems encountered in the Gemini program."

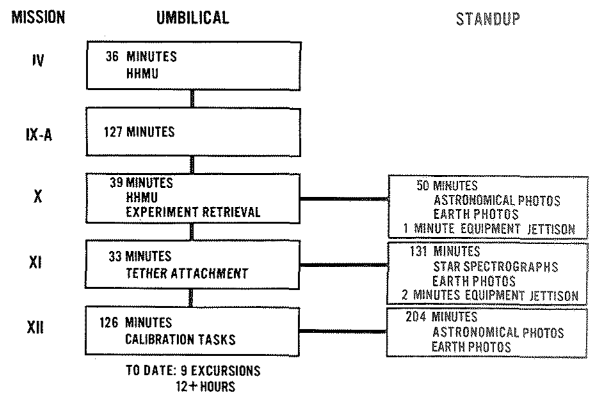

FIGURE 2.—Extravehicular activity experience.

The EVA (fig. 2) during Gemini was one element of the program that provided us with considerable insight into the rules for working in the space environment. Here we discovered that little forces sometimes create big disturbances and that the familiar rules of activity no longer apply as they do on Earth. The frustration level became rather high. Late in the program, we started using underwater training for both preflight training and postflight critiquing by an EVA astronaut. This proved to be an excellent complement to our other EVA training procedures, providing for the first time the capability to go through an EVA timeline sequentially without interruption. On Gemini 12 we went back to basics with EVA and concentrated on fundamental movements, actions, and simple yet progressively more demanding tasks. The Gemini 12 EVA was highly successful.

Scientific Experimentation

In the Mercury program, many scientists both in and out of NASA sought to make use of this vehicle for experiments. Mercury, however, for rather obvious reasons did not accomplish much outside what might be considered program-oriented experimentation. The flights were short, the spacecraft were small, and the need for biological instrumentation was overriding. Consequently, very few experiments were attempted.

During the Gemini program, however, it was a different story. The experiment program (tables I and II) became a very key element in mission planning and resulted in 52 different experiments (8 medical, 17 scientific, and 27 technological), many of which were performed on more than one mission. Of the technological experiments, 15 were sponsored by the Department of Defense.

GEMINI FUTURE IMPLICATIONS

From the Gemini program have come many factors that bear directly on the future course of manned space flight—not only Apollo but on Apollo Applications and on programs not yet identified. Mercury and Gemini have given us confidence that our flightcrews can sustain extended-duration missions; this is fundamental to an effective space exploration program. The programs have also suggested disciplines of space research that will become possible through the longer flights. Of course, with these will come the larger and more versatile space vehicles that will evolve.

Another aspect that is vital to the success of any future manned space flight is found in the abilities developed in our ground support crews and systems. The skill with which the Gemini missions were conducted provides substantial evidence of the proficiency of our ground crews and their various

TABLE I.—*Technological Experiments*

	III	IV	V	VI–A	VII	VIII	IX–A	X	XI	XII
Electrostatic charge		√	√							
Proton-electron spectrometer		√			√					
Triaxis magnetometer		√			√			√		√
Optical communication					U					
Beta spectrometer								√		√
Bremsstrahlung spectrometer								√		√
Color-patch photography								√		
2-color Earth's limb photographs		√								
Landmark contrast measurements					E			M		
Reentry communication	√									
Manual navigation sightings										√
Basic object photography			√							
Nearby object photography			M							
Mass determination						M			√	
Star occultation navigation					E			√		
Surface photography			√							
Space-object radiometry			√		√					
Radiation in spacecraft		√		√						
Simple navigation		√			√					√
Ion-sensing attitude control								√		
Astronaut maneuvering unit							M			
UHF–VHF polarization						M	√			
Night image intensification						M			√	
Power tool evaluation						M			M	
Ion wake measurement								√	√	

√ = Experiment successful.
E = Experiment unsuccessful because of equipment failure.
M = Experiment incomplete because of interference by a mission requirement.
U = Experiment unsuccessful because of another reason.

TABLE II.—*Medical and Scientific Experiments*

	III	IV	V	VI–A	VII	VIII	IX–A	X	XI	XII
Cardiovascular conditioning			√		√					
In-flight exerciser		√	√		√					
In-flight phonocardiogram		√	√		√					
Bioassay body fluids					√	M	√			
Bone demineralization		√	√		√					
Calcium balance study					√					
In-flight sleep analysis					√					
Human otolith function			√		√					
Lunar UV spectral reflectance										
Celestial radiometry			√		√					M
Astronaut visibility			√		√					
Zodiacal light photography			√			M	√	√		
Sea urchin egg growth	E									
Frog egg growth						√				√
Radiation and zero *g* on blood	√								√	
Synoptic terrain photography		√	√	√	√		★	√	√	√
Synoptic weather photography		√	√	√	√			√	√	√
Cloudtop spectrometer			√			M				
Visual acuity			√		√					
Nuclear emulsion						M			√	
Agena micrometeorite collection						M	M	√		√
Airglow horizon photography							√		√	√
Micrometeorite collection							√	M		√
UV astronomical camera								√	√	√
Libration region photographs										
Dim sky photographs orthicon									√	E
Daytime sodium cloud										E

√ = Experiment unsuccessful.
E = Experiment unsuccessful because of equipment failure.
M = Experiment incomplete because of interference by a mission requirement.
★ = Experiment conducted but not assigned.

launch, mission control, and recovery operations. Gemini also pioneered in such intricate and previously unattainable necessities of future programs as rendezvous and docking, docked maneuvers, and prolonged stationkeeping. Of these three, rendezvous and the docked maneuvering were, perhaps, the most dramatic. The high-altitude excursions of the Gemini 10 and Gemini 11 spacecraft are truly the forerunners of a vastly increased capability to maneuver in space. As a result of these missions, it is now completely feasible to consider space engines that may be periodically replenished and used for auxiliary propulsion of manned vehicles. The rendezvous experience of Gemini was highly successful and has provided assurance that we will not only be able to accomplish the nominal rendezvous required by the Apollo mission but also nonnominal situations that may arise.

The idea of tethering two orbiting vehicles came into being about halfway through the Gemini flight program and the Gemini 10 mission provided a very clear example of possible benefit. On that mission, an EVA while stationkeeping with the target vehicle had to be terminated because of a shortage of maneuvering fuel. The tether exercises that followed on Gemini 11 and 12 were highly successful and point the way toward long-term, low-cost stationkeeping, preferred attitude control, or even generation of a gravity field of selected intensity.

Consider at this point the assurance with which we could develop and operate an orbital laboratory for research, training, or experimentation. In years to come, I think we will see just this sort of thing.

The Gemini experiment program has given impetus to much of our future planning. Although modest in scope, these experiments not only demonstrate the indisputable worth of the man in the loop, but they also hold promise of real and direct benefit to mankind. While the experiments in Gemini were constrained not to interfere with higher priority mission elements, this is not the case in the Apollo Applications Program (AAP). Here, the experiments are the heart of the program.

The U.S. manned space flight program has indeed come a long way in these 5 yr. Now, instead of debating whether man can survive the environment, we hear questions raised as to his value or the worth of such a program in the face of other national needs. I suppose every endeavor of this magnitude, exposed as this is, raises numerous doubts—some real, others not so real. We have matured in our ability to pursue the goal of manned exploration of space, as there are many somewhat subtle indications. The latest selection of astronauts, for example, was made, not for test-piloting skill, but rather for their scientific background. There was not a jet pilot in the group. Gemini even contributed here with the selection of Dr. Karl G. Henize, a prominent Gemini experimenter in astronomy.

Apollo, with its much increased size and far more flexible systems than Gemini, will provide the initial hardware base for the future. The Apollo Applications program will be the initial venture beyond Apollo and will expand the base of technology and knowledge while bringing direct benefit to earthly pursuits. There is not the time to describe, in detail, plans for AAP, but it is certain you will hear more of them as the conference progresses. Rest assured, however, that the future will involve man. It will require rendezvous for purposes of resupply, orbital assembly, crew changes, and equipment repair. Extravehicular activity will be necessary for support of many of these same functions as will stationkeeping and maneuvering in space. Overlying all of this and perhaps of more direct or immediate concern to this group is the aspect of long duration.

Long duration—30 days, 90 days, or longer—will pose the challenge—not only for the equipment but, more importantly, for the man. Ability to survive is a necessary although insufficient condition. Man must be able to work and work efficiently for long periods in this medium.

Jim Lovell, the astronaut with the longest duration, is most emphatic about the things yet to be learned from long-duration missions. Among these he includes determination of a good floorplan or interior arrangement of the spacecraft to optimize the various parameters: waste management and appropriate work/rest cycles.

It is interesting and most appropriate, I think, that our country is also on the verge of learning to live and work in the ocean environment. Certainly, many of the same techniques are applicable, and we anticipate a continuing close relationship between the space and deep-submergence programs. It is difficult to estimate the assistance that the manned space-flight program has derived from the Navy's submarine habitability research programs and, perhaps, in the future, we will be able to return the assistance in kind. Scott Carpenter, an astronaut for 8 yr, has recently become the Nation's No. 1 aquanaut.

With the advent of long-duration flights in vehicles large enough, properly equipped, and with crewmembers having appropriate research skills, I am confident we will learn to work and work efficiently in space. We will also learn to design, develop, and use the necessary tools, facilities, and techniques. Imagine a laboratory in which a wide variation in gravity force can be effected or a vacuum better than any achievable on Earth. A few years ago these things were beyond our reach. Now we can start planning how to make the most of them.

The successful achievement of this goal, however, will require the most careful and deliberate cooperation between the engineers and physicians. Dr. Berry reported that he believed this had been achieved in Gemini. In my view, the future will demand not only a continuation but a strengthening of this bond, because learning to live and work in this environment is not just a medical or an engineering problem. Few engineering problems are completely free of physiological considerations, and manned space flight is no exception. Indeed, every facet of engineering for the manned exploration of space will require consideration of man, his strengths and his weaknesses, to an extent never before contemplated. We are not growing up in this environment, nor do we at this point anticipate residing in it on a permanent basis. Consequently, there is no requirement for and there most certainly is not time for biological evolution to fit these surroundings, as some of the science-fiction writers have proposed.

Typical of the strangeness of the space environment and indicative of the need for further research was the extravehicular activity experienced on Gemini. As late as the Gemini 11 mission, it appeared that very little progress had been made in perfecting techniques required for EVA. At that time there was much discussion of EVA and the difficulties that had been encountered.

In an attempt to explain what had transpired, I, half in jest ventured the opinion that our EVA difficulties had resulted from the application of $1g$ engineering in a $0g$ environment. However, the more I consider this prospect, the more intrigued I become with the idea of variable-gravity engineering and the need the space explorer will have for it.

Prof. Isaac Asimov, in an article published earlier this year entitled, "Moon Exploration: Advent of the New Engineering," used the phrase "low-gravity engineering." As he put it, "Our every action here on Earth, our every assumption, our very inner calculation depends on an unconscious feeling that weight and inertia are equal. If we are to be successful in manned exploration of space and planets, we must learn to associate small weights with large inertias as a matter of life and death, sometimes, and that will not be easy." Asimov calls for new engineering to meet this challenge. This is engineering in its purest sense. It will include psychobiology and physiology as fundamental considerations. It is going to require the combined talents of all these disciplines to meet this challenge of the future.

Perhaps in certain programs the less elegant solution of generated gravity fields will serve, but I cannot imagine this approach satisfying all needs, particularly as we begin to explore and learn to live on the Moon.

Thus, we have reached the point where we now have a better view of the future. It is true that achievements to date have been substantial, although only in a relative sense. The future holds great promise and serious challenge for all of us. The implications for the future provided by the Gemini program are unmistakable—man can survive; he can function; he adapts. As he was the key to the major success of Gemini, so will he be the key to the space exploration programs of tomorrow.

To paraphrase one of Churchill's remarks: Gemini is not the end; it is not even the beginning of the end; rather, it is the end of the beginning.

Physiological and Psychological Problems in Space Flight

WILLIAM M. HELVEY
Lockheed Missiles & Space Co.

April of this year marked the fifth anniversary of the first successful space flight and return of a manned vehicle in Earth orbit. In October of this year will be the 10th anniversary of the space age: the anniversary of the successful launch of the Sputnik vehicle into orbit in October 1957.

Already we can look back on mission durations of up to 2 weeks. A total of 29 individuals have flown in 23 different flights and have spent a total of over 100 man-days in space. As we look back on the successful completion of the Mercury and Gemini programs in this country, and the Vostok and Voskhod flights in the Soviet Union, it may be appropriate to borrow a term from Winston Churchill and say that "This is the end of the beginning" of man's conquest of space. We look forward to safely landing and returning a man from the Moon, exploration of the Moon, prolonged Earth-orbit missions, and the exploration of our planetary neighbors. We will be looking in depth at some problems of spacecraft engineering, as well as medical problems.

The management of and technical challenges to our generation of pioneers, who will commit vast resources of personnel and facilities and billions of dollars, demand effective interdisciplinary teamwork. The days of "cookbook" human factors or physiology by engineers as an acceptable method of design are a thing of the past. Certainly, the complexity of current technology, the quality and reliability required, the magnitude of the risk, and the investment require nothing less than a well-coordinated team effort. The Soyuz 1 and the Apollo tragedies should be adequate stimulation toward effective interdisciplinary teamwork. To insure success in this endeavor, we must learn the lessons of history: both those within the last 5 yr, and in the broader perspective, the important ones of the last 50 yr.

In addition to this recent space-flight experience, a broad base of directly related activity is to be found in aerospace medicine. Space medicine is largely an extension of aviation medicine, just as aerospace technology is an extension of aviation technology. We look back over a significant experience in aviation medicine to the 1917 and 1918 World War I period that required extending men and machines to their operational limits. They soon encountered environmental problems, such as hypoxia and temperature extremes, that impaired their performance. In more recent years, with the advent of faster and higher flying vehicles, high-altitude problems presented themselves, including explosive decompression and bends, requiring positive-pressure breathing and the forerunner of our spacesuits. Concurrent with the improving technology were changing medical problems. When the cockpits were closed, carbon monoxide and other toxicant problems arose; when an oxygen system was provided, oxygen contamination appeared; with high-speed aircraft, g-loads; and with increased maneuverability, vertigo. And so it was the rule, rather than the exception, that new and potentially serious medical problems accompanied changing technology. The successful solution to these problems included changes in selection and training of the crew, modification of personnel equipment, and vehicle design. The lives of several hundred pilots were lost during this evolution. Although space flight is new, environmental medicine is not. As we look to the coming decade of space-flight missions, Earth-orbital missions of a month or longer and planetary missions that require 6 months, even the optimists must conclude that we will have significant medical problems. We have only limited ability to predict the nature, frequency, or magnitude of these problems. Thus, we must examine carefully the experience of the past 5 yr.

A HISTORY OF MANNED SPACE-FLIGHT EXPERIENCE

A summary of the manned space-flight experience to date is shown in table I. Gagarin's successful orbit in Vostok 1 on April 12, 1961, was of less than 2-hr duration. It was followed in August of that year by Vostok 2 in which Titov orbited the Earth for 17 revolutions in a little over 24 hr and experienced unusual and provocative sensations that were the first indication of motion sickness as a significant factor in space flight. In the interim between these two Vostok flights, two suborbital flights of 15-min duration by Alan Shepard and Virgil Grissom were completed. In 1962 there were three Mercury flights. John Glenn's first orbital flight lasted almost 5 hr, as did Scott Carpenter's flight; Walter Schirra's flight in MA-8 was for six orbits and lasted over 9 hr. Gordon Cooper in May of 1963 performed the final Mercury flight in which MA-9 completed 22 orbits in over 34 hr and brought Project Mercury to a close. In 1962, the first team flight was performed by the Soviets. Two vehicles, Vostok 3 and 4, were aloft at the same time for durations of 2 and 3 days. Nikolayev and Popovich performed their duties as assigned, although they had symptoms similar to Titov's, but of lesser magnitude. Both experienced postural illusions but did not have disagreeable symptoms that could be described as motion sickness. The second team flight, performed by Vostok 5 and 6 in June 1963, included the first woman cosmonaut, Tereshkova in Vostok 6, who was aloft for almost 3 days. Bykovsky, preceding her in Vostok 5, was aloft for almost 5 days. The first Voskhod vehicle was the only space flight of 1964, and included the first three-man crew, which consisted of a pilot, a physician, and a physicist engineer, which Soviet scientists have indicated is an appropriate crew for lunar and planetary flights. It was also the first time in which none of the crew wore pressure suits, but worked in the comfort of the earthlike environment and sea-level pressure in the Voskhod spacecraft.

The Mercury vehicle, by the end of 1963, had flown two suborbital and four orbital missions with a total flight time of almost 54 hr between May of 1961 and its final flight in May of 1963. The Vostok vehicle of the U.S.S.R. had flown six flights through a similar time period with approximately 17 days of flight time. All flights in both vehicles were solo flights.

In 1965, Voskhod 2, carrying Belayev and Leonov, flew slightly longer than a day and was notable for the use of an airlock that permitted Leonov to be the first man to exit into space protected only by a spacesuit attached to the spacecraft by an umbilical line. He returned after 20 min, having performed his extravehicular maneuvers with success and no ill effects.

After a period of over 2 yr with no U.S. flights, the Gemini program was initiated by veteran command pilot Grissom and pilot Young in March, followed by four additional flights by December. These flights were of increasing duration. The second flight by McDivitt and White was over 4 days and included the first exit into space by an American, Ed White, in an extravehicular maneuver activity. The subsequent Gemini flight increased the duration to 7 days, and,

TABLE I.—*Manned Space Flight*

[The First 10 Years of the Space Age, 1957–1967]

Date	Vehicle	Crew	Orbits	Duration			Remarks
				Days	Hr	Min	
4/12/61	Vostok 1	Gagarin	1	.....	1	48	1st successful manned flight
5/5/61	Mercury (MR–3)	Shepard	Suborbital	.....	.....	15	1st U.S. manned space flight
7/21/61	Mercury (MR–4)	Grissom	Suborbital	.....	.....	15	
8/6/61	Vostok 2	Titov	17	1	1	18	24-hr flight; motion sickness
2/20/62	Mercury (MA–6)	Glenn	3	.....	4	56	1st U.S. orbital flight
5/24/62	Mercury (MA–7)	Carpenter	3	.....	4	56	
8/11/62	Vostok 3	Nikolayev	64	3	22	9	1st team flight (without rendezvous)
8/12/62	Vostok 4	Popovich	48	2	22	57	
10/3/62	Mercury (MA–8)	Schirra	6	.....	9	14	
5/15/63	Mercury (MA–9)	Cooper	22	1	10	20	Final Mercury flight
6/14/63	Vostok 5	Bykovsky	81	4	23	6	2d team flight, 5-day mission, first woman in space
6/16/63	Vostok 6	Tereshkova	48	2	22	50	
10/16/64	Voskhod 1	Komarov Yegorov Feoktistov	16	1	1	17	1st 3-man vehicle 1st physician and scientist crew-members. No spacesuits worn
3/18/65	Voskhod 2	Belayev Leonov	17	1	3	2	1st walk in space (EVA)
3/23/65	Gemini (GT–3)	Grissom Young	3	.....	4	52	1st Gemini mission
6/3/65	Gemini (GT–4)	McDivitt White	62	4	.....	56	1st use of EVA-maneuvering unit
8/21/65	Gemini (GT–5)	Cooper Conrad	120	7	22	56	1-week mission
12/4/65	Gemini (GT–7)	Borman Lovell	219	13	18	35	2-week mission
12/15/65	Gemini (GT–6)	Schirra Stafford	18	1	1	53	1st space rendezvous
3/16/66	Gemini (GT–8)	Armstrong Scott	9	.....	10	41	1st space docking
6/1/66	Gemini (GT–9)	Stafford Cernan	49	3	1	04	Docking: helment visor fogged in EVA
7/18/66	Gemini (GT–10)	Young Collins	48	2	22	46	Docked with two vehicles; two EVA
9/12/66	Gemini (GT–11)	Conrad Gordon	44	2	23	17	Docking and maneuver with Agena: 1st tether and artificial *g*
11/11/66	Gemini (GT–12)	Lovell Aldrin	59	3	22	37	Successful EVA
4/23/67	Soyuz 1	Komarov	19	1	4	6	New vehicle: cosmonaut killed in reentry

finally, a 14-day flight was performed by Frank Borman and Jim Lovell in Gemini 7 in December 1965. This flight included the first space rendezvous. Gemini 6, piloted by Schirra and Stafford, rendezvoused and came within 3 ft of the Gemini 7 vehicle. The first flight in 1966 accomplished a rendezvous and the first actual docking of two spacecraft when Armstrong and Scott docked their Gemini 8 with an Agena rocket on March 16. Three of the final four missions included extravehicular activities. Each Gemini flight was a dual-piloted vehicle, and the duration of these six flights increased from 1 day to 2 weeks.

EFFECTS OF SPACE FLIGHT ON MAN

To anticipate and assess the possible effects on the crew in space flight, it is useful to categorize the environmental factors to which the astronaut is subjected and the possible response of the major body systems to each of these factors. These factors are diverse but can be summarized as follows:

(1) Weightlessness
(2) Dynamic factors
(3) Radiation
(4) Spacecraft atmosphere
(5) Biological rhythms
(6) Psychophysiological factors
(7) Combined stress

Included are both factors characteristic of the environment itself, such as radiation and weightlessness, as well as those created within the spacecraft, such as the cabin atmosphere, trace contaminants, and interpersonal relationships.

Weightlessness, Dynamic Factors, and Radiation

Weightlessness is a state in which the net accelerative forces acting on the body are 0. The vehicle and personnel in Earth orbit are considered to be in the weightless state because the centrifugal force of the orbit is approximately equal to and opposite the gravitation pull of the Earth. The result is mass without weight. In fact, in an elliptical orbit, the centrifugal force at apogee is less than $1g$ and at perigee is greater than $1g$; so a true $0g$ does not exist. Nonetheless, in general, body fluids act free of hydrostatic pressures and other manifestations of gravity's effects. Dynamic factors include the acceleration forces of launch and reentry, angular rotation, noise, etc. The radiation environment of Earth-orbiting vehicles is a composite of three sources: radiation (magnetic field) belts, primary cosmic radiation, and solar flares. The orbits for all these vehicles were similar in nature in that they were low Earth orbits generally free of the Earth's magnetically trapped radiation fields. The Voskhod 2 had the highest orbit with an apogee of 304 miles. It experienced a radiation dose (70 mrad) over twice that of Voskhod 1 (30 mrad). Both were 24-hr flights. The Vostok flights were under 200-mile orbits for up to 5 days, and the maximum dose received was 81 mrad (Bykovsky). Heavy components of primary cosmic radiation were the cause of 85 to 90 percent of the dose. The experience in Mercury and Gemini was similar. Cooper, in the 34-hr Mercury flight, experienced less than 14 mrads, and Lovell, on the 14-day Gemini flight, registered a maximum exposure of 215 mrads. The low altitude and orbit inclination of all manned vehicles to date offer the protection of the Earth's magnetic field and have averted significant threat of solar-flare radiation.

Spacecraft Atmosphere

The current spacecraft cabin and life support design differ between the U.S. and the U.S.S.R. The Soviets use essentially an air mixture at sea-level pressure (20 percent oxygen and 80 percent nitrogen at 760 mm Hg). The relative humidity (RH) and temperature are well within the comfort range (RH: 36 to 69 percent; temperature: 50° to 86° F). Carbon dioxide is kept to 0.2 to 0.3 percent (compared to 0.03 percent in Earth atmosphere). In contrast, the American Mercury and Gemini vehicles have a 100-percent oxygen environment at 5 psi ($\frac{1}{3}$ atm) that provides slightly more oxygen than is available at sea level but at a reduced total pressure and with an absence of nitrogen, as compared to sea-level air of the Soviet vehicle. The increased oxygen and lack of nitrogen have been considered as possibly having deleterious effects on humans for prolonged periods; however, there is no conclusive proof of such effects to date.

The crew requirements for long-term habitability in the space vehicle are one of the more exacting challenges to the design engineers and environmental medical specialists. Although the physiological and comfort limits of temperature, humidity, oxygen, and carbon dioxide are well defined, the threat of toxicity from trace contaminants will increase with improved capsule sealing methods and longer duration flights. In addition to critical selection of materials and methods of monitoring and controlling the environment, adequate determination must be made of human tolerances under these conditions to recognized trace substances as well as those for which human sensitivity is unknown. Several dozen compounds have already been identified as being potentially toxic to the crew.

The thermal environment of the space vehicle is theoretically one of the serious hazards for the astronaut. In particular, the temperature environment outside the vehicle during extravehicular activity differs from 300° to 400° F between the sunny and shady sides of the vehicle. However, this problem and the heat pulse of reentry have been well controlled by the life-support and vehicle engineering systems, so that, currently, the thermal environment represents a minor concern. Experiences with the astronauts as recently as the Gemini 14-day flight do indicate that overheating, or, in the event of malfunction, excessive cooling of the suit and astronaut, can occur and create discomfort and potentially reduce the efficiency and performance of the astronaut, but have not been a major challenge to health and safety.

Biological Rhythms

It has been well established that a great number of biological species, including man, have inherent as well as secondarily conditioned biological rhythms. These recurrent cycles are evidenced in various behavior and performance parameters, as well as in basic biochemical indices in the blood and organs of the body. Of particular interest are those diurnal rhythms (also called circadian rhythms) that relate to the 24-hr day/night cycle of Earth. As many as 50 different functions have been studied and determined to have patterned diurnal variation. It has been established that human error varies relative to such schedules, and that activity and resistance of animals to noxious substances vary significantly in such a cycle. Thus, a necessary departure from the normal 24-hr day, as in the 90-min orbit of a low Earth-orbiting vehicle, requires consideration of the performance and adjustment of astronauts to these conditions.

Psychophysiological Factors

The psychophysiological factors encompass a number of variables that exist in a vehicle, including the restricted living accommodations, confinement, isolation, interpersonal relationships, work/rest cycles, etc. These factors are known to be significant in the working environment on Earth and require consideration in scheduling of spaceflight activities.

MEDICAL MONITORING OF CREW DURING FLIGHT

In assessing the physiological and psychological consequences of flight, it is important to consider both the mechanism of action, and the site of response, damage, or defense. A categorization of major body functions that is useful in an organized appraisal of the effects of environmental stresses is as follows:

Psychological performance	Metabolism
Circulation	Endocrine balance
Respiration	Fluid and electrolyte balance
Thermoregulation	Hematological response
Neuromuscular activity	Immunological response
Skeletal support	
Digestion	

The flights thus far have had a limited in-flight measurement capability. The medical monitoring capabilities are summarized in table II. All astronauts (U.S. and U.S.S.R.) have had the electrocardiogram, pulse (the U.S. program uses the ECG as a source of pulse), and respiration rate monitored during flight. Blood-pressure measure-

TABLE II.—*In-Flight Medical Monitoring*

	Vostok						Voskhod		Mercury						Gemini									
	1	2	3	4	5	6	1	2	3	4	6	7	8	9	3	4	5	7	6	8	9	10	11	12
Electrocardiogram (ECG)	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Pulse cardiogram (PC)	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Respiration rate (RR)	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Blood pressure (BP)							o				o	o	o	o	o	o	o	o	o	o	o	o	o	o
Body temperature (T)									o	o	o	o	o	o	o	o	o	o	o	o	o	o	o	o
Seismocardiogram (SMG)					o	o	o																	
Phonocardiogram (PCG)																	o							
Electroencephalogram (EEG)			o	o	o	o	o																	
Electrooculogram (EOG)			o	o	o	o	o																	
Galvanic stimulation rate (GSR)			o	o	o	o																		

ment has been common to the U.S. flights since the first Mercury orbital flight, and body-temperature measurement has also been unique to American vehicles. The seismocardiogram is a device developed by the Soviets for use in the 0*g* environment to evaluate cardiac activity and is a variation of the ballistocardiogram used in clinical medicine. It is designed to study the mechanical manifestations of cardiac activity in space flight. Each cardiac contraction creates vibrations of the whole body and these are measured by motion of a small magnet fixed between two induction coils placed on the chest. This device, in use with the ECG, permits a measurement of the time relationship between the electrical signal passing through the heart (electrical systole) and the muscular contraction that follows an electrical impulse (mechanical systole). The kinetocardiogram was used on an early Vostok flight and was a less effective measure of mechanical cardiac activity. In the U.S. program, the phonocardiogram, which is a simple microphonic pickup of the heart sounds taken from the chest wall, permits a similar correlation between the electrical activity (ECG) and the muscular or mechanical contraction of the heart, and was used on Gemini 5 for such an investigation. After Titov's flight, a number of additional measurements were initiated in the Soviet program for the remaining Vostok series, including the electroencephalogram (a measure of brainwave activity), electrooculogram (a measure of eye movement), and galvanic stimulation rate, which is a measure of the emotional status and function of the astronaut's nervous system. The only American use of any of these latter sensors has been the use of the electroencephalogram in Gemini 7 to evaluate the depth of sleep and the practicality of taking effective measures of brainwave activity on an active astronaut. An indication of the magnitude of additional testing performed in flight is illustrated by the following list of Gemini experiments:

(1) Cardiovascular conditioning, M–1
(2) Cardiovascular conditioning, M–2
(3) In-flight exercise, M–3

(4) In-flight phonocardiogram, M-4
(5) Bioassay of body fluids, M-5
(6) Bone demineralization, M-6
(7) Calcium and nitrogen balance, M-7
(8) In-flight sleep analysis, M-8
(9) Human otolith function, M-9

Biomedical experiments onboard the Voskhod vehicles include:

(1) Vision testing, including tests of visual acuity of the extraocular muscles, color perception, and operational visual effectiveness

(2) Movement coordination and retention of trained motor skills

(3) Work capacity and fatigability

(4) Reaction time and time to perform tasks

(5) Postural reflexes and vestibular tests

(6) Pulmonary function

(7) Neurological function

(8) Hand strength and coordination (dynamometer)

The presence of a physician, Yegorov, in Vostok 1 enhanced the experimental design. He evaluated group speech, execution of tasks, speed and accuracy of information processing, blood pressure, permeability of blood vessels, and took blood samples for subsequent analysis. He utilized a device called a polyinom in which a single channel recorded performance of the cosmonaut's writing coordination, figure drawings, electroencephalogram, electrooculogram, and dynamogram.

Although it is difficult or impossible to isolate each of the space environmental factors, because they act in combination and on various body functions, many of the noticeable effects of space flight have been largely attributed to the absence of gravity. The earliest and best known deleterious effect of weightlessness was the motion sickness experienced by Titov. In addition to a persistent discomfort, Titov's initial sensations of disorientation occurred just after injection into orbit and transition from the high-*g* forces of launch to the weightlessness of orbital flight. He experienced visual illusions and an unpleasant sensation of postural rotation. Although none of the other cosmonauts are reported to have had disturbances of disorientation, Nikolayev and Popovich had a similar sensation of floating and an illusion that the body position was forward and downward for about 2 min upon reaching orbit. Despite the illusions of spatial disorientation, they had no unpleasant sensations associated with motion sickness even when rapid head movements were attempted to stimulate such sensations. Popovich had a transient sensitivity to rotation for 2 or 3 days postflight. Yegorov and Feoktistov experienced disagreeable vestibular autonomic reactions, including mild nausea, and Yegorov had spatial illusions when eyes were open or closed. These symptoms appeared 1½ to 2 hr after launching and did not interfere with planned work, but persisted virtually throughout the flight. These sensations evidently had nothing to do with stabilization and rotation of the craft around its axis because they occurred both during stabilization and rotation at the rate of one turn in 20 to 40 sec. These illusions appeared to be reduced when the astronaut braced himself against his chair or was occupied with his tasks, and disappeared immediately upon the onset of retrofire. Leonov's rotation of the body in several planes gave no suggestion of an automatic disturbance as a result of vestibular stimulation. Visual information from space seems to be an adequate basis for orientation while outside the vehicle.

Yegorov performed a vestibulometric investigation to determine if the threshold of the otolith (one of the organs of equilibrium) to a galvanic current changed at 0*g*. There was no change in the threshold, although there was decreased precision in pointing and in a graphic test, which was felt to be caused by vestibular function change.

The Gemini M-9 experiment included the ability of the astronauts to estimate horizontal while in flight by positioning a thin line of light in a dark field with a special visual apparatus used on board. Normally, horizontal position is determined with gravity cues on the otolith in a normal $1g$ environment. It was determined that the astronauts could, in a $0g$ state, still determine with consistency a "horizontal" if contact cues were adequate. This horizontal may, in fact, deviate from the actual cabin horizontal by as much as 30°, but appears to be persistent and repeatable for the astronaut. There was no impairment of otolith function as determined by preflight and postflight evaluation of its sensitivity and the counterrolling of the eye that normally occurs with rotation of the body's vertical axis. Visual acuity, or resolving power, has been reported as normal by both Soviet and U.S. astronauts, although the functional visual efficiency (a measure of efficiency on a correction table) was diminished slightly. This operational visual efficiency deteriorated 20 to 30 percent in the Voskhod 1 and 2 flights. Visual perception of brightness of colored objects was slightly dull (in particular, for green and purple). The decrease was as great as 50 percent, as reported by Belayev. The negative fusion of the extraocular muscles (a measure of the muscle balance of the eye) was reported by Yegorov as being increased 40 percent. On a number of occasions, the fine motor coordination utilized in handwriting was impaired within the first hour of flight and never fully returned to normal during the flight. Performance was better after rest or sleep. This capability was measured by drawing double spirals, stars, and writing a signature. The impairment was minimal, however, and Morse code could be sent with ease. Gazenko and Gurjian report that the coordination of movements was fairly satisfactory; however, the time required in carrying out tasks in the beginning of the flight (first orbit by Komarov) was twice as long as required during subsequent orbits or on Earth. The same was true of Yegorov. On the Voskhod flights, a model control system was used with graduated random and sinusoidal signals in which the operator attempted tracking tasks with direct or delayed feedback. The operator error increased 25 percent during the space flight and was more noticeable at signal frequencies above 0.5 Hz. A number of cosmonauts reported increased fatigability and perspiration with less effort than on the ground. Studies with a dynamometer (to measure hand strength) demonstrated that Yegorov was less efficent during flight, and Feoktistov required more mental and physical exertion to carry out experimental work than on the ground.

A major effort in both space programs has been directed to the evaluation of the cardiovascular system during and following a weightless state. Experiments M–1, M–2, and M–3 of the Gemini program include the evaluation of the use of pneumatic cuffs on the legs to countereffect the deconditioning effect of $0g$. Although these cuffs are found to be effective in water immersion and bedrest studies in preventing symptoms of fainting during tilt-table studies in which the subject is raised from horizontal to a 70° angle, it was found ineffective on the Gemini 5 and 7 flights. A tilt-table response of the astronauts demonstrated that there was an increased pulse rate to a given stimulus following flight. Lovell experienced syncope on the first tilt-table trial after his 14-day flight. The response to in-flight exercise using the bungee (experiment M–3) showed a normal or persistent pulse response to a given workload during flight, although after return to Earth there was a general increase in pulse response for a given workload. Popovich experienced a pulse response 18 percent over preflight control and required 12 days to return to a normal response to exercise. Both Soviet and American astronauts reported a decreased tolerance to the reentry g-loads, and Popovich is reported to have grayed out during reentry. Feoktistov had an increased pulse response to exercise for a 3-day period postflight. Gazenko has described as the delay phenomenon the lag in return of pulse rate to normal after the acceleration of launch as compared to a similar g-load on a centrifuge. The phenomenon has been noted in U.S. and Soviet astronauts as well as in animal studies. In addition to this delayed and increased sensitivity to acceleration at time of launch and subsequent to reentry, pulse rates frequently showed a diurnal rhythm during flight related to a 24-hr cycle. A vagotonic reaction, or marked slowing of the pulse, occurred in Yegorov. During sleep his pulse slowed to 45 as compared to a minimum on the ground of 52.

With the use of the electrocardiogram and the seismocardiogram, the Soviets reported a delay between the electrical and mechanical systole as early as Titov's flight. Utilizing the phonocardiogram on the Gemini 5 flight, the M–4 experiment did not illustrate a similar delay between electrical and mechanical systole in the American astronauts. Differences in the waveforms of the seismogram also suggested an unusual filling of the heart and a lack of normal coordination in heart pumping during the weightless state. Astronauts Borman and Lovell reported a sensation in which they felt as if they were flying upside down or standing on their heads after the first 24 hr of flight. On questioning, other astronauts admitted to such a feeling, and Dr. Berry of NASA indicated this is probably caused by an increase of blood flow to the head and chest. Gorbov also quotes the cosmonaut physician, Yegorov, as testifying to a "unique sense of flowing of blood to the head with the appearance of a hazily expressed sensation of flight in an inverted position." Gorbov also attributes this to a vascular reaction and redistribution of the blood with a subsequent strain of musculature creating the false spatial perception. Respiration has been found to be routinely rapid during periods of emotional stress, such as launch and just prior to reentry. However, there has been no evidence of pulmonary difficulty during flight. In addition to increased fatigue and perspiration with reduced physical exertion, uric acid levels of the Soviet flights have been reported as increased, suggesting muscular catabolism or increased protein breakdown, although American studies have not confirmed this. There have been no difficulties in digestion or food absorption, and food has varied from pastelike substances and liquids to normal diet, including such delicacies as sausage. The appetite has been good and food intake has usually been high. Blood samples taken on the 2d and 12th orbits of Voskhod 1 showed no change in carbohydrate or salt metabolism, although blood urea had increased, suggesting protein decomposition. Cholesterol was significantly increased following flight and returned to normal within 2 weeks. Weight loss during flight is a common occurrence with a range of 6 to 10 lb, and the relative absence of thirst during flight usually accompanies this dehydration. Postflight, there is usually a significant increase in thirst; with water intake the body weight returns to normal usually within 1 to 3 days. Postflight kidney-function tests conducted on Leonov and Belayev by water loading showed water was being eliminated more slowly in the kidney than in preflight and in 2-week postflight tests. Bioassay of body fluids of Gêmini flights have demonstrated an anticipated increase in hormones associated with stress. American and Soviet space scientists have reported an increase in calcium loss in the urine during flight. This is a well-established phenomenon during bed rest or in water immersion studies. There is some concern that prolonged weightlessness might cause significant decrease in bone strength, the potential of kidney stones, and other serious consequences. Studies by calibrated X-rays performed as experiment M–7 on the Gemini flight measured calcium intake and loss as well as density of bone before and after flight and demonstrated significant bone density decrease in the foot and hand. However, the crew of the 14-day flight exhibited less change than the crew of the 8-day flight, and at this time bone demineralization is not considered a serious threat to the astronauts, with adequate exercise and calcium intake. The hematological response to space flight has almost universally shown an increase in white blood cells. One unexpected and as yet unexplained phenomenon has been the loss of red-blood-cell mass (7 to 20 percent) in the crews of Gemini 5 and 7. It is felt to be due to premature destruction of the red blood cells or destruction at a rate faster than that normally experienced. The plasma volume of these astronauts has increased, however, so that the resulting blood volume has remained approximately the same. Although there have been no reports of immunological changes in the astronauts, animal studies performed by the Soviets have indicated that immunological characteristics of animals as measured by change in response to micro-organisms had been significantly changed.

SUMMARY

Concerning the ability of astronauts to withstand the rigors of space flight, experience to date has been encouraging, and it is anticipated that astronauts will continue to perform successfully whatever in-flight tasks are required of them. It is equally apparent, on the basis of the broad experience of environmental medicine, that significant and potentially disabling aerospace medical problems may occur. Over a half a century of aviation medical experience provides substantial evidence for such an assumption. Early detection of these problems becomes increasingly important as astronaut duties and time in flight are extended. Having met the challenge of placing man in space, we have a challenge and a responsibility to insure that he can perform his duties in health and in safety.

Biotechnology in Spacecraft Design*

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Douglas Aircraft Co.

A broad spectrum of Earth-orbital missions has been investigated by the Douglas Aircraft Co. during the past 4 yr. These missions include those related to Earth-centered applications and those related to observations and measurements in the basic sciences, as well as missions related to general technological developments and to the support of extended space flight. These studies have indicated the practicality and research value of extended-life space laboratories in the 30 000- to 40 000-lb class with crew complements of six to nine men.

Based upon these studies, this paper offers a prognostication of some of the potential biotechnology problems that will influence spacecraft design and suggests options for possible solutions to some of the problems that may arise during extended manned space flight.

INTRODUCTION

Early in 1963, with the guidance of internal advisory committees and with external contractor support, NASA undertook serious investigation of the research potential offered by manned, Earth-orbiting laboratories for the support of scientific objectives and for the support of advanced engineering research and development (R&D) projects. In June of that year, the Douglas Missile & Space Systems Division was selected by NASA as one of two prime contractors directed to examine a number of design concepts for a manned orbital research laboratory (MORL), contract no. NAS1-2974. The design concept selected in that study, in turn, led to further preliminary design activities directed toward optimization of the MORL-system concept and the validation of the established, baseline-design concepts against the utilization potential of such a facility, contract no. NAS1-3612.

*Data presented herein were developed by the Douglas Missile & Space Systems Division for programs sponsored by NASA Langley Research Center, Virginia, under contract nos. NAS1-3612 and NAS1-2974.

In studies funded by NASA and those funded by Douglas independent research and development (IRAD) funds, this work has continued to date. During its course, researchers have learned a great deal about what could and should be done in space laboratories and a great deal about the engineering and economic feasibility of accomplishing the desired research objectives. This paper presents some observations regarding those biotechnological factors that, in the author's opinion, will have the greatest impact on future spacecraft design.

Physiological and psychological problems in space flight, environmental control and life support (EC/LS) requirements, and the problems of specific operational requirements, such as those entailed in extravehicular activity (EVA), have been discussed elsewhere. This paper, rather than repeating that information, will instead present a total systems-engineering viewpoint; it is only through the total systems approach to design that the subtle interplay and interaction of the biomedical, behavioral, engineering, and scientific requirements upon the spacecraft design can be identified.

DISCUSSION

By way of perspective, the MORL studies demonstrated the engineering feasibility of launching a 30 000-lb-class vehicle into a 28° to 50° inclination orbit using a Saturn IB launch vehicle. The facility (fig. 1) was designed to accommodate a six- to nine-man crew. With the use of a combined ferry-resupply logistics system consisting of

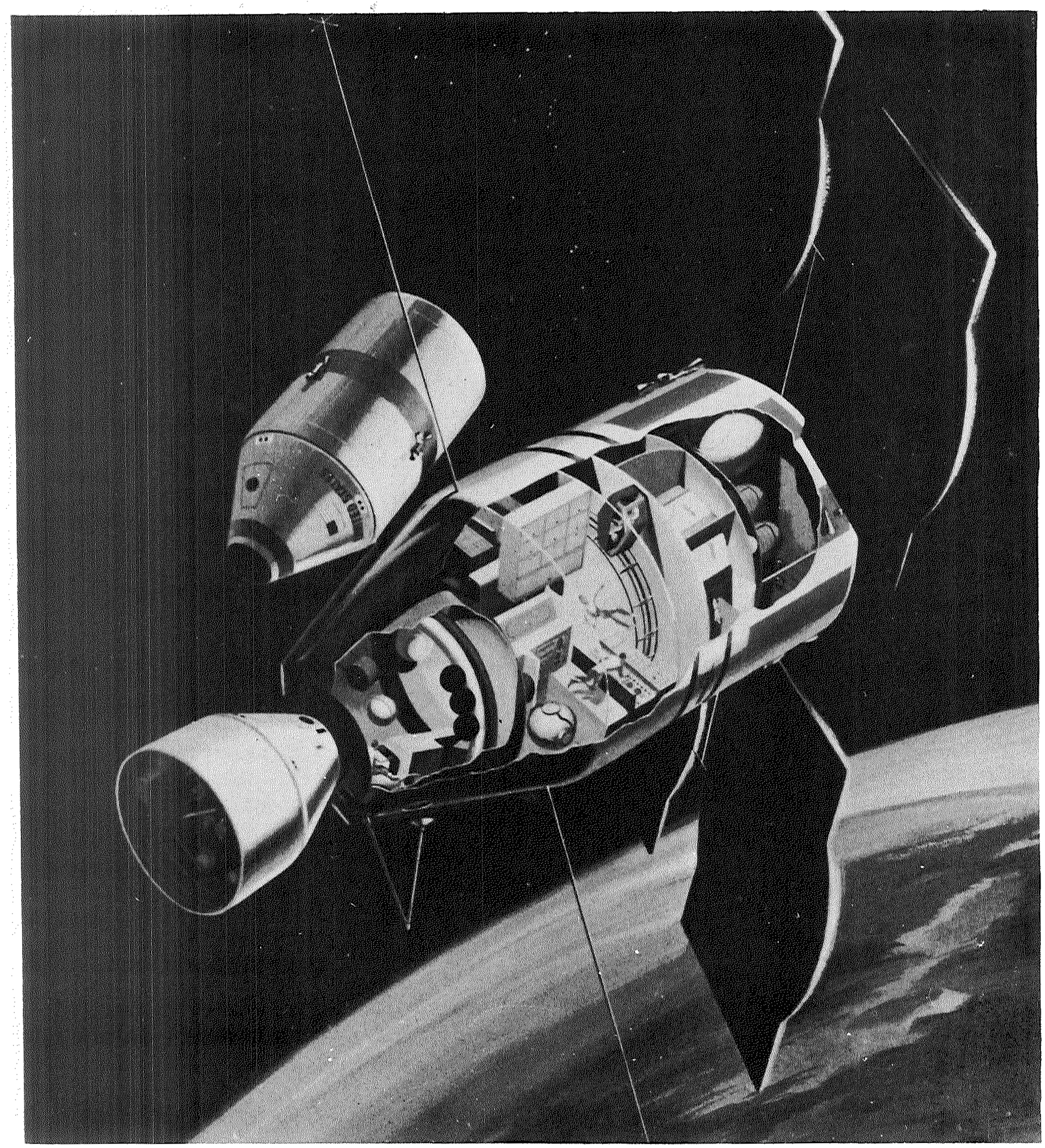

FIGURE 1.—Manned orbital research laboratory.

an Apollo command module, a cargo module, and an SIVB launch vehicle, the facility could have an effective lifetime of 5 to 10 yr. Tours of duty for the crewmembers were expected to range from 1.5 to 12 months. Progressive rotation of crewmen at 1.5-, 3-, 6-, 9-, and 12-month intervals was used for operational analysis as the nominal rate by which assessment of man's ability to adapt to the space environment would be made. Although designed for a 10-psi environment, the operational atmosphere was established as a 7-psi, 50 percent oxygen and 50 percent nitrogen environment (table I).

TABLE I.—*Habitability Design Parameters*

Metabolic requirements:	
Oxygen consumption	1.92 lb/man-day
CO_2 production	2.32 lb/man-day
Water consumption	6.17 lb/man-day
Urine production:	
Including solids	4.07 lb/man-day
Without solids	3.92 lb/man-day
Respiration and perspiration.	2.78 lb/man-day
Feces output:	
Including solids	0.34 lb/man-day
Without solids	0.26 lb/man-day
Metabolic water production.	0.79 lb/man-day
Wash water	3.00 lb/man-day
Heat output:	
Nominal	10 850 Btu/man-day
Design (shirt sleeve).	500 Btu/man-hour
Design (spacesuit)	1000 Btu/man-hour
Atmospheric requirements:	
Laboratory temperature.	75+5° F (adjustable range)
Laboratory humidity	50 percent (35° to 65° F dewpoint)
Laboratory pressure	7.0±0.2 psia
Atmospheric mixture	50 percent O_2, 50 percent N_2
CO_2 partial pressure	4 mm Hg nominal 8 mm Hg maximum
Ambient noise level	50 dB
Illumination:	
Command and control Personal hygiene Galley, eating, and reading	20 ft-c
Equipment inspection Bunks and storage Observation control Airlock and docking Enclosed centrifuge	15 lamp cp
Crew compartment	10 ft-c
Exterior (docking control)	32 000 lamp cp

Laboratory Facilities

The laboratory was divided into four main sections (fig. 2): (1) a hangar-test area, (2) a control deck, (3) flightcrew quarters, and (4) an internal centrifuge. The hangar-test area, separated from the forward pressure compartment by an inverse-pressure bulkhead, acted as a tranfer airlock for personnel moving from the logistics spacecraft into the main portion of the laboratory. The hangar-test area not only afforded interim storage for the cargo, but could provide emergency quarters for the crew for extended periods of time should problems arise with the main pressure shell. The control deck was also divided into four areas and included a filtered compartment for liquid processing, a biomedical- and behavioral-assessment station, maintenance areas, and the central laboratory control station. The flightcrew quarters included a wardroom, galley, bunks, and hygiene facilities. An internal centrifuge was located between the control deck and the flightcrew quarters. This device provided a mechanism by which the flightcrew could perform reentry simulation and undergo physical-condition testing, and it could possibly be used as a therapeutic device if required. The laboratory proper had a volume of 6700 ft^3 and the hangar test area included about 3300 ft^3.

Besides the specific areas within the laboratory assigned for the experimental operations that had been identified, experiment modules containing large and bulky or specialized equipment could be delivered to orbit by the logistics system and attached to the laboratory. On the basis of this overview of the system as it finally evolved, the influence of biotechnology on spacecraft design and, therefore, on the above configuration recommendations can be examined.

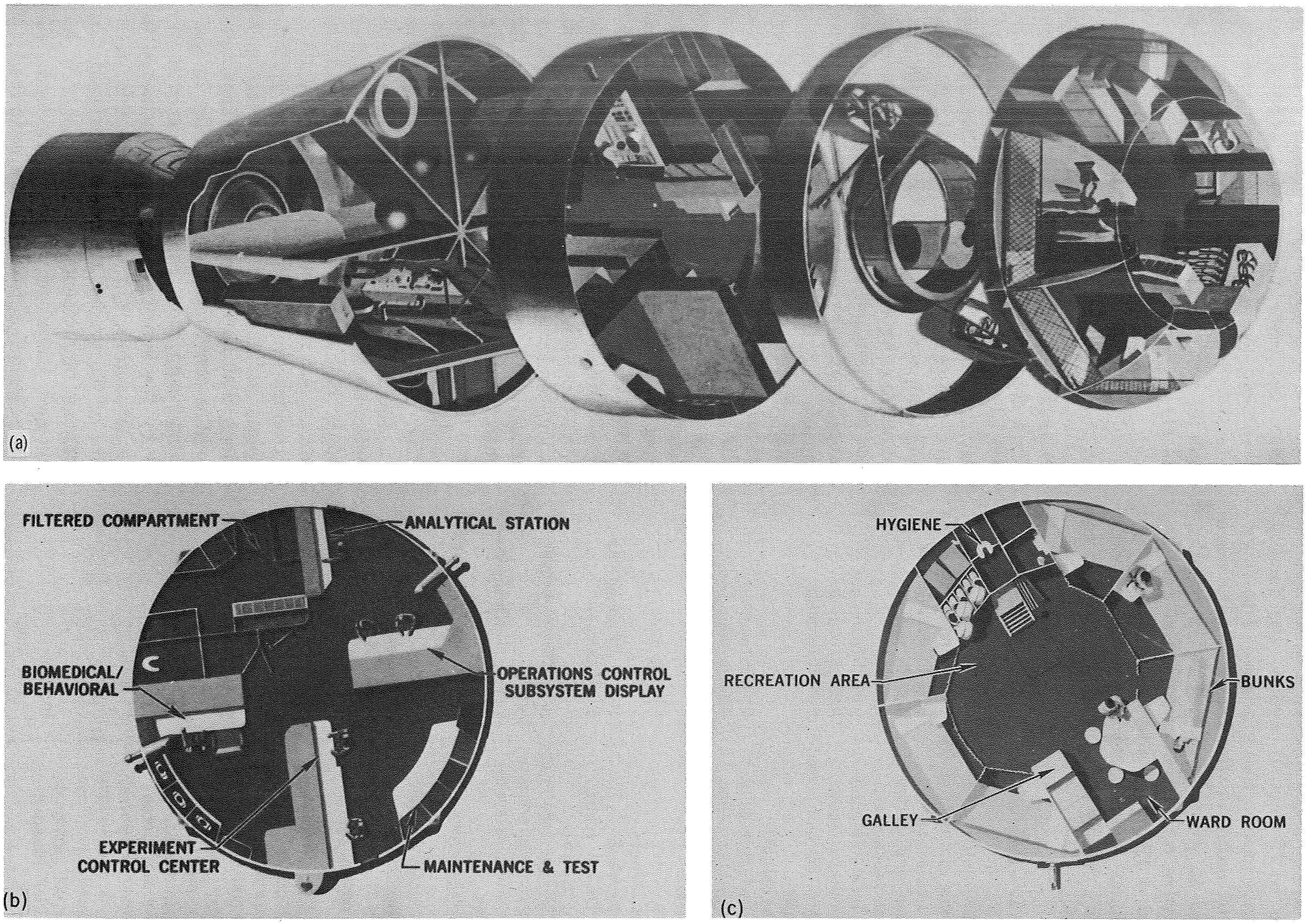

FIGURE 2.—MORL. (*a*) Cross section. (*b*) Control deck. (*c*) Flightcrew quarters.

MORL Research Objectives

The research objectives to be pursued in extended-duration space flight will be as follows:

(1) To make observations and gather information to extend the general scientific knowledge.

(2) To gather knowledge on physical phenomena, including performance of the equipment under prolonged exposure to the space environment.

One of the most important points to recognize is that man is an integral part of the total vehicle system necessary to pursue those objectives. He is there because he has a meaningful and significant role to play; a role that would be too expensive, if not totally impossible, to accomplish by any other means. Furthermore, because voyages of exploration to the planets are foreseen to require extended mission time (and because even the economic accomplishment of Earth-centered observations may require less frequent crew rotation), a further objective for extended-duration space flight may be added: assess the physiological and psychological tolerance of man to long-term operations in the space environment and quantify the effects of this environment on man.

System Design

The initial step in system design is to define the mission requirements. In the case of a laboratory, however, the dynamic nature of research and the quest for knowledge itself mean that the objectives will continually evolve and change. The design philosophy must, therefore, provide high flexibility and must be based upon the requirements of the most universal, yet realistic, experimental research plan possible. In the MORL study, some 734 experiments suggested by various Government, industrial, and university sources were reviewed. As might be expected, considerable redundancy, overlap, and duplication existed in the compilation. Also, different criteria governing the composition of experiments, as distinguished from parametric measurements, were found in the various source inputs. The first step in the analysis was to redefine or regroup the data within each source list to establish consistency in the definition of what was termed a measurement area. The next step was to collate the inputs from the various sources. The result was an integrated list of 157 measurement areas.

Figure 3 illustrates the distribution of these areas by potential area of research and by the laboratory man-hours required to accomplish the assigned tasks. As would be expected, the bulk of the suggested experiments, both in number and in their impact on the crew's workload, was oriented toward the basic sciences and the system-development area. If it can be assumed that this listing represented a reasonable and typical mix of the entire spectrum of potential experiments that might be performed on board an early orbital research laboratory, it could be concluded that an orbital laboratory designed to accomplish this representative sample of measurements and experiments could be expected to have the flexibility and capability of accomplishing the formal experiment program finally established. Accordingly, for each of the 157 measurement areas, a representative experiment was formulated and equipment requirements were developed that included weight, volume and power, crew requirements, and a representative experiment duty cycle.

Once a representative set of research requirements was developed, the design of the laboratory could proceed. The first step

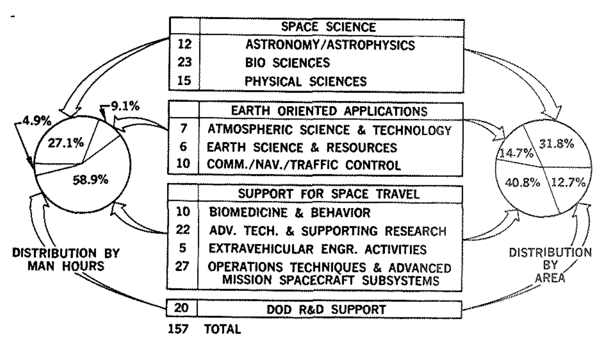

FIGURE 3.—Data bank experiment distribution.

in designing the laboratory was to determine the minimum crew size because, as will be shown later, this factor is fundamental to establishing the size and cost of the laboratory.

Time estimates for crew activities in the maintenance and operation of the vehicle were derived from a review and analysis of the mission profile, system and subsystem design specifications, functional schematics, an operations plan, and preliminary design drawings. From these data, a gross functions analysis was performed to determine the extent to which man would participate in each operation. Estimates were then made of the time required for a crewman to accomplish each of his assigned duties. The time estimates obtained for the biomedical, behavioral, engineering, and scientific experiments were derived from an analysis of the individual experiment designs. To these were added the time required for setup and for the maintenance of the experimental apparatus. Psychological and physiological activities (sleep, recreation, relaxation, and physical conditioning) were reviewed to estimate adequate time allocations for each. A contingency factor of 10 percent was allowed for those unforeseen emergencies or events whose probability of occurrence was so low that they would not normally be scheduled.

Table II summarizes the average duty hours per day for each crew activity for crew sizes of one, four, and six men. Figure 4 pictorially summarizes the crew workload distribution for crews up to nine men. It was found that some experiments (in the Earth-centered observations) required continuous operation for 24 hr or more. As can be seen from table II or figure 4, a minimum crew size of six men would be necessary

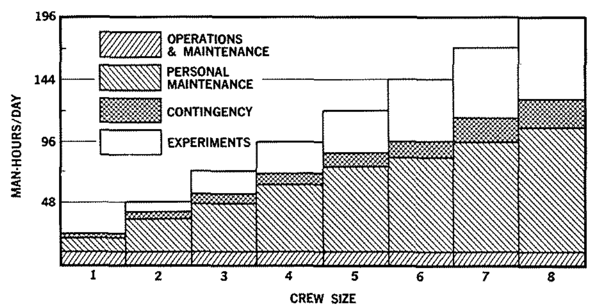

FIGURE 4.—Crew time utilization.

TABLE II.—*Crew Workload Average Duty Hours per Day*

Activity	Man-hours per day		
	Each man	4-man crew	6-man crew
Personal maintenance:			
Sleep	8.0	32.0	48.0
Food preparation, eating, cleanup	2.0	8.0	12.0
Personal hygiene	.8	3.2	4.8
Rest and recreation	1.5	6.0	9.0
Total	12.3	49.2 (51%)	73.8 (51%)
Station operation and maintenance	([a])	10.0 (11%)	10.0 (7%)
Behavioral experiments (including reentry training)	1.0	4.0 (4%)	6.0 (4%)
Biomedical experiments (including physical fitness)	([a])	8.0 (8%)	12.0 (8%)
Contingency factor (10 percent)	2.4	9.6 (10%)	14.4 (10%)
Total		80.8 (84%)	116.2 (80%)
Total man-hours available per day		96.0	144.0
Man-hours per day remaining for engineering and scientific experiments		15.2 (16%)	27.8 (20%)

[a] Variable.

for assurance that a 24-hr operation could be manned and still allow a 10-percent contingency factor for unforeseen events.

A minimum crew of six was also suggested by the range of skill requirements demanded of the crew (table III). Twenty skill categories were grouped into 11 identifiable specialty areas. Assuming that each crewman could be assigned a major area with a secondary skill for backup, a six-man crew would offer a greater reservoir of skills than a four-man crew and, in fact, could insure that all key skill categories were represented on board the laboratory at all times. Because the six-man crew also matches the carrying capacity of two Apollo spacecraft, a favorable economic tradeoff occurs in ferry and logistics costs. This type of reasoning led to the suggestion of a six-man nominal crew size, with occasional staffing by a total of nine men.

Once the crew size has been approximated, the requirements for the experimental equipment and their impact on space-station design can be identified. Figures 5 to 8 indicate the statistical distributions of experiment weight, volume, power, and crew time as identified from the data bank of 157 research areas. Also shown for comparison are the data obtained from a limited sample of experiments examined a year earlier. The comparison of the plots indicates the stability or reliability of the parametric estimates. Of more specific interest, however, is the typical J-shaped nature of the distributions and the predictions of resource demands that can be made from them. This is the type of resource loading that is typical of electric power-distribution systems, central telephone exchanges, water-distribution systems, and other similar systems, where a large proportion of the using population demands a small amount of the resource and decreasing numbers of users require larger amounts. By way of example, if a six-man crew represented 16 717 man-hours of available time per year for experiments, and if the average experiment required 206 man-hours for its accomplishment, about 81 such experiments could be accomplished

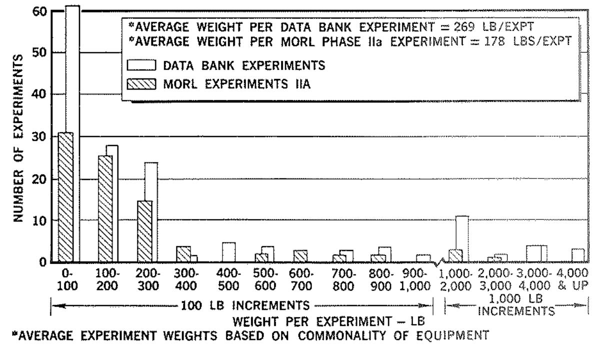

FIGURE 5.—Experiment weight.

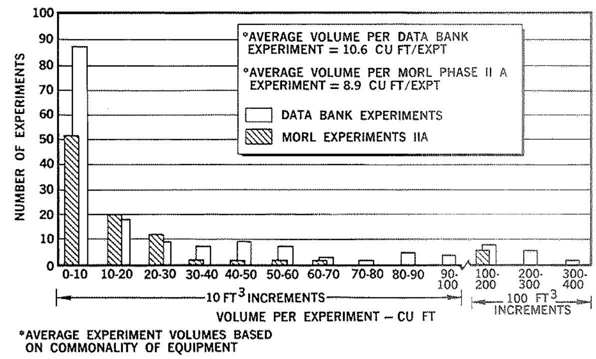

FIGURE 6.—Experiment volume.

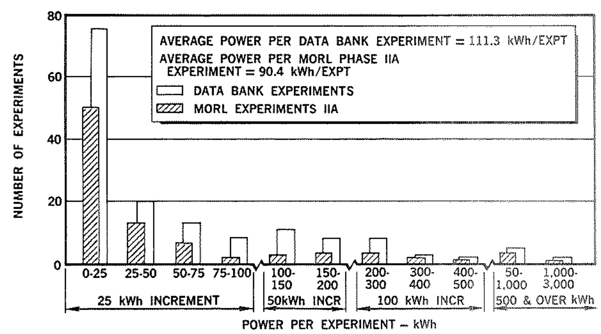

FIGURE 7.—Experiment power.

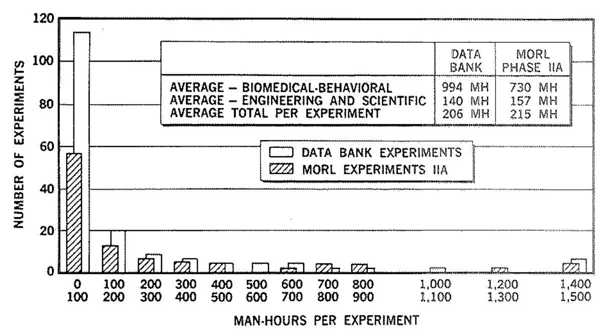

FIGURE 8.—Experiment man-hours.

TABLE III.—*Crew Skill Allocations*

Crew type	Crewman number	Title	Major skills	Combined skills
Primary crew	1	Flight commander	Astronomy/astrophysicist, electromechanical technician	
	2	Deputy flight commander	Optical technician oceanographer, electromechanical technician	Optical scientist
	3	Operations engineer	Electronic engineer, electromechanical technician	Navigation, radar microwave specialist, and communications
	4	Life scientist	Biology technician, physiologist	Microbiologist, biochemist, and medicine
	5	Physical scientist	Physicist, meteorologist, photo technician cartographer, electromechanical technician, and optical technician	Nuclear physicist, thermodynamicist, and physical geologist
	6	Medical doctor	Medicine	Biology technician, microbiologist, biochemist, and physiologist
Replacements	7	Engineer/scientist	Astronomy/astrophysicist, electromechanical technician	
	8	Engineer/scientist	Optical technician, oceanographer, electromechanical technician	Optical scientist
	9	Physical scientist	Physicist, meteorologist, photo technician/cartographer, electromechanical technician, and optical technician	Nuclear physicist, thermodynamicist, and physical geologist

in the laboratory per year. With knowledge of the average power requirement per experiment or the average weight or volume, estimates of the typical laboratory requirements for each resource could be made. With knowledge of the standard deviations of the distributions, estimates could also be made of expected variability of demands to any level of confidence. In this manner, once the crew size (or available number of man-hours) has been established, the vehicular design parameters can be developed.

In the analysis of the measurement areas, it was found that many of the equipment items required for performing various experiments were common among many areas. If equipment could be shared among experiments, substantial weight savings (more than 50 percent) could be realized. A similar trend was reflected in the equipment volume requirements. An even more interesting illustration of the significance of equipment sharing may be seen in figure 9, in which the number of equipment items required per experiment is plotted against the number of experiments as they were added to the data bank.

These comparative plots graphically illustrate the value and flexibility of a general-purpose R&D laboratory in making use of common equipment to support a broad-based experimental program. Flexibility, however, presupposes the availability of the crew capability for onboard assembly of units and their functional checkout. Because of the heavy time demands on the crew, however, the final recommendation will undoubtedly be a mixture of prepackaging and onboard assembly. Heavier and bigger prepackaged experiment apparatus will be traded against man-hours required for onboard assembly.

As noted above, a crew requirements analysis was conducted for each measurement area. Both the skill type and skill level for each area were determined in a joint analysis by human-factors specialists and research specialists representative of each scientific discipline. Figure 10 indicates the crew skills established from the various experimental areas and the percentage of time

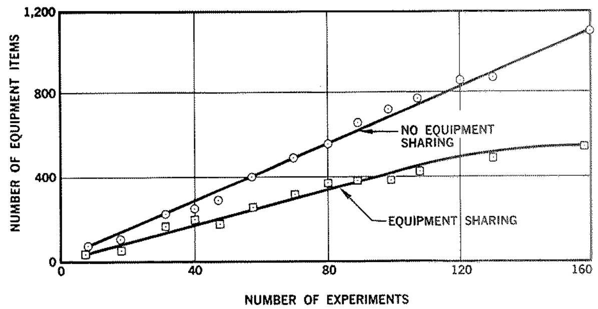

FIGURE 9.—Equipment growth requirements as a function of an expanding experiment program.

each skill would be required during the performance of the experimental program. Note that technical or engineering skills represent the greatest proportion of demand on onboard man-hours. This is not surprising, because previous experience has indicated that general system setup and checkout in terms of the calibration, maintenance, and repair of equipment require more time than actual operation of the equipment (or performing of experimental procedures). In interpreting these data, it is emphasized that the skill analysis is task oriented rather than man oriented. The data indicate only that the specific tasks to be accomplished, as identified, require the proportion of specialized skills indicated. Although the rather rare skill categories could be provided by specialists or research scientists on board the laboratory, note that the bulk of their time would have to be directed toward basic survival, routine maintenance, and equipment checkout. They would have relatively

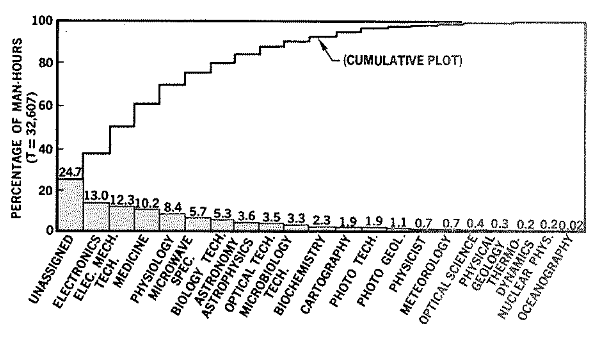

FIGURE 10.—Distribution of skill utilization.

few opportunities to use their specialized knowledge.

An alternative would be to keep the basic crew skills to a small, more general grouping and to redesign those experiments calling for rare-skill categories to eliminate the operational requirements for those skills to be on board the laboratory. It is suggested that the ultimate crew-selection procedure should be such that crewmen would be selected from the general specialty areas and given training in the specific experimental goals and procedures. On the basis of the 20 skill categories identified to date, it would appear that 11 different specialty areas should be established in the crew-training program, and each crewman should be assigned to one major area with a secondary or minor specialty.

As a part of the laboratory design validation study, a representative experiment plan was developed. With use of a computer simulation program, all experiments were scheduled within the constraints imposed by crew time and the available laboratory resources, such as power, volume, weight, and experiment priority. This simulation illustrated quite graphically the dependency of efficient laboratory operations upon crew training and selection. The most significant factor in limiting the breadth of the engineering and scientific studies appeared to be the potential saturation of crew time and skills or their potential unavailability at critical times. This situation is illustrated in figure 11, which shows the daily variation as well as the average utilization of crew time and power for the first year of the experimental program compared to the maximum time and power available. Because of the conflict between available skills and required skills, the average time utilization was 31.8 man-hours per day out of a possible 45.8. This problem can be resolved by rescheduling either the order for accomplishing experiments or the mix of onboard crew skills. As missions are defined, it can be anticipated that crew-composition requirements will continue to constrain the ability to schedule experiments. Obviously, having

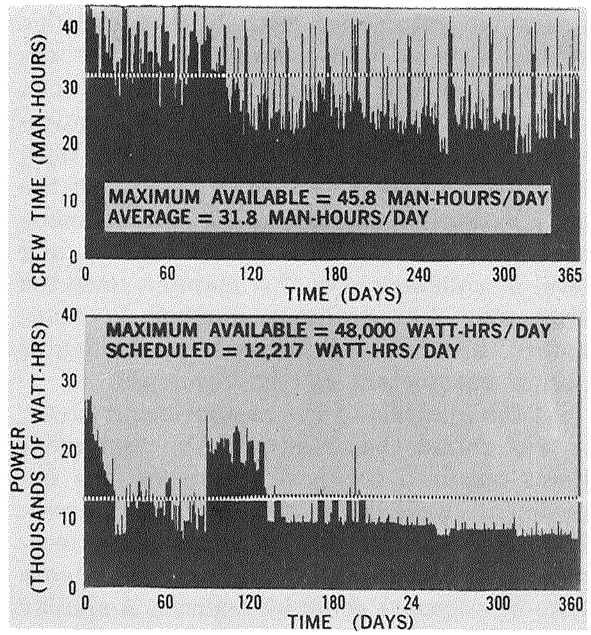

FIGURE 11.—Experimental load profiles.

the right man available at the right time is mandatory for the successful and timely completion of a given experimental program.

The approach taken toward defining biotechnological requirements, and, in turn, the space-station design parameters, as described previously, could be likened to the statistical approach taken in market surveys or opinion polling, in which a reasonably representative sample of the population is examined at length and the population characteristics of interest are predicted from that sample. Based on the assumption that the data bank is a representative sample of space research, the laboratory developed from the data-bank requirements should be flexible enough to accommodate a much larger spectrum of research in the life and physical sciences and in engineering research and development. However, by the very nature of examining only a relatively few areas, the data-bank approach does not provide insight into the absolute magnitude of the research to be performed in orbit.

To attempt to provide greater perspective regarding the true magnitude of orbital research tasks, selected areas in the category of Earth-centered observations were examined in considerable detail. Specifically, key problems in the fields of oceanography and atmospheric sciences that, because of their synoptic coverage requirements, could not be meaningfully approached by any other means than from a space platform, were examined in depth. One example in the field of oceanography (fig. 12) is the fact that the study of life forms in the sea and their distribution over the oceans of the world is of tremendous importance to the fishing industry. Every form of life feeds on a lower form, down to the lowest levels of phytoplankton. The distribution of plankton and their growth characteristics are dependent upon a critical mix of key environmental factors of temperature, sunlight, and nitrates and phosphates in the water. Location of plankton can be established at least in part by sea color. Color photography from space provides this possibility. Surface temperature can be assessed remotely by infrared (IR) detectors or microwave radiometers. An interesting possibility for remote assessment of surface salinity, however, is much less understood and demands further research. Because rotation of the electric-field vector occurs when an electromagnetic wave strikes a conducting surface, the possibility exists of measuring sea-surface conductivity by observing a reflected wave with a polarimetric device. For theoretical reasons, not of concern here, a beamed signal in the S-band (2200 mc) would appear to be desirable for this purpose. This would then require the development of an S-band polarimeter as a sensing device. If this system worked, with surface conductivity and temperature known, salinity could be established. One basic task requiring orbital activity would be to develop and validate an S-band polarimeter. In similar fashion, the orbital research tasks required in sensor validation, correlation, and data collection

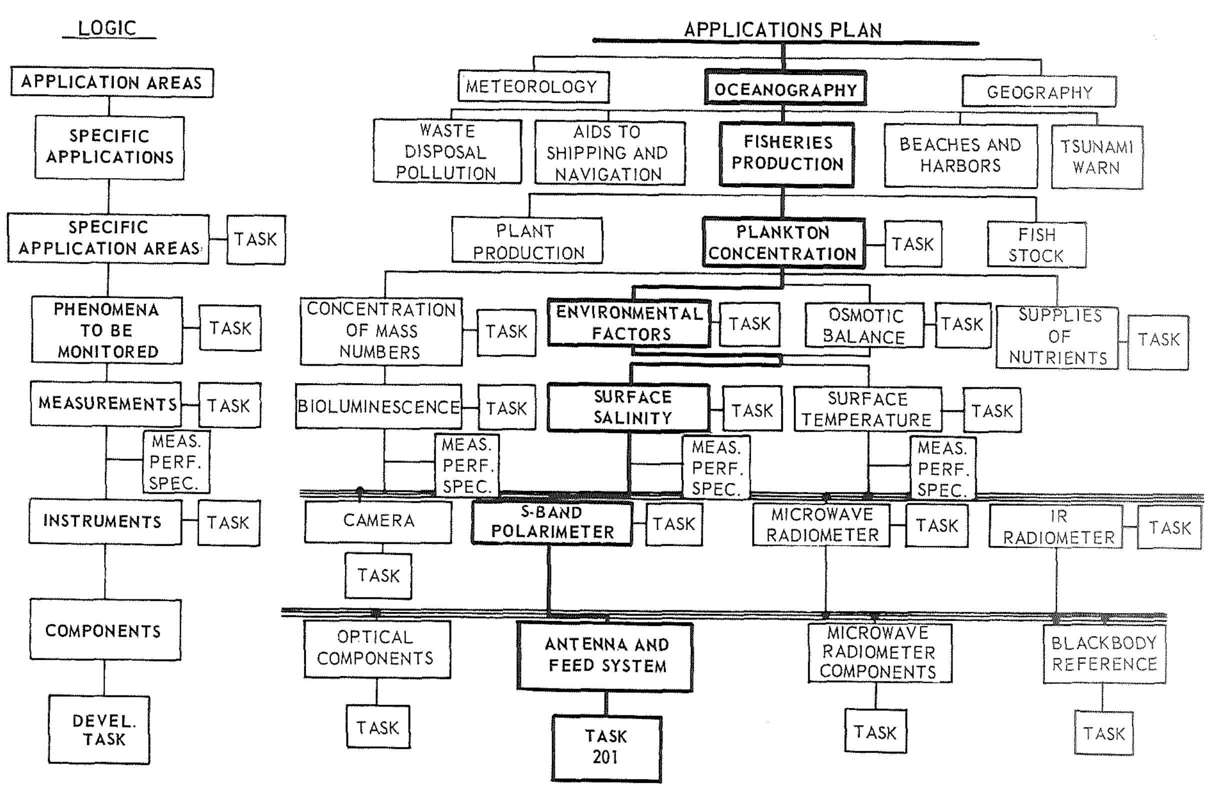

FIGURE 12.—Logic and application plan for a study of the distribution of life forms in the sea.

were analyzed for a dozen research objectives in oceanography and meteorology. This analysis might be likened to a program evaluation review technique (PERT) chart in that it portrayed or identified the critical research tasks necessary to accomplish a given research objective. For just these few areas, some 272 tasks requiring 222 635 man-hours in orbit would be necessary. This might be compared to the data bank that, as a sample of research, included 2150 man-hours of orbital activity devoted to oceanography and meteorology. This 100:1 growth ratio between the sampling and in-depth analyses cannot be projected indiscriminately across the spectrum of research. However, it does indicate the need to examine each research area in depth to identify all of the supporting R&D necessary to accomplish the end objective. Of more specific interest to this conference is the point that, in fact, hundreds of thousands or even millions of man-hours of significant research can and should eventually be accomplished in Earth orbit.

The development costs and support for one MORL-class vehicle for a 5-yr mission life averages out to be on the order of three-quarters of a billion dollars per year. Phrased differently, 1 man-hour of useful work will cost about $47 000.

At this cost, and with the tremendous potential for challenging research programs to be accomplished in orbit with their scientific, social, political, and economic payoffs, it is absolutely mandatory that man's time in orbit be used effectively. Man-hours will continue to be the most precious commodity or resource available in orbit. The role of the biotechnologist and the human-factors design specialist should be to optimize, not maximize, the utilization of man's time.

The desire to optimize man's use may at times give rise to significant changes in spacecraft design and in operational procedures. To illustrate, the procedures established for EVA operations are examined. Certain ground rules were established for the analysis. Among them were such considerations as the requirement for 45 min for denitrogenation before exit from the laboratory's 7-psi environment to a 3.5-psi, 100-percent O_2, pressure-suit environment; the requirement for a backup crewman, denitrogenated and standing by in an airlock, for immediate egress and assistance should an emergency arise; and the requirement for monitoring of the physiological condition of the external crewmen.

Table IV summarizes the operation times that were estimated for installing a small antenna assembly on the external shell of the laboratory. The nature of the operation was such that it required two crewmen for holding and mounting the unit. For comparison, the times required for this task with the antenna being mounted internally in a shirt-sleeve environment are also shown.

Analysis of the baseline experiment plan indicated 391 individual egress movements

TABLE IV.—*Sensor Assembly Time Comparison*

Tasks	Mounted externally		Mounted internally	
	Men	Man-hours	Men	Man-hours
Obtain equipment	3	1.75	2	1.00
Denitrogenate	3	2.25	0	0
Exit procedure	3	2.50	0	0
Install sensor	2	4.00	2	4.00
Monitor EVA	1	2.00	0	0
Entry procedure	3	1.50	0	0
Total	....	14.00	–	5.00

were required per year for experimental purposes and 30 for routine maintenance operations. Although some of these egress operations could be combined, it might be anticipated that EVA times will be limited to a 2-hr period and, therefore, the total number of egress requirements will remain significantly high. As a design change to reduce the number of required egress movements, the MORL configuration was altered to include an experiment bay illustrated in figure 13. The primary purpose of this modification was to allow access to sensor equipment in a shirt-sleeve environment and thus minimize the number of EVA events as well as the time required for assembly. Sensors are exposed to the environment by opening the bay door. The experiment bay also included a rigid beam on which sensors and other equipment can be mounted along with the attitude reference system. Thus, a secondary advantage of the equipment bay was the minimizing of alinement errors associated with sensors located at various stations on the laboratory as had been the case in the original configuration.

In work to date on experiment definition, Douglas researchers encountered many biomedical and behavioral research proposals that have seemingly ignored the basic fact that man is going into space as a working member of a complex and expensive man-machine system chartered to do useful and significant work that can be done in no other way. One example of such a proposal dealt with the study of vigilant behavior in stressful situations; the investigator proposed that, with use of a device similar to the Mackworth clock test, the crewmen spend up to 30 hr/week/man observing a panel of meters. Their task would be to report random movement on the meters, which could occur anywhere from 0 to 10 times/hr. Decrement in performance could then be plotted against time in orbit; however, the luxury of having crewmembers stare at a meaningless panel of meters for extended periods simply does not exist. Another proposal dealt with the effect of frustrating situations on subsequent psychological performance during prolonged space flights. In this test, troubleshooting of equipment mal-

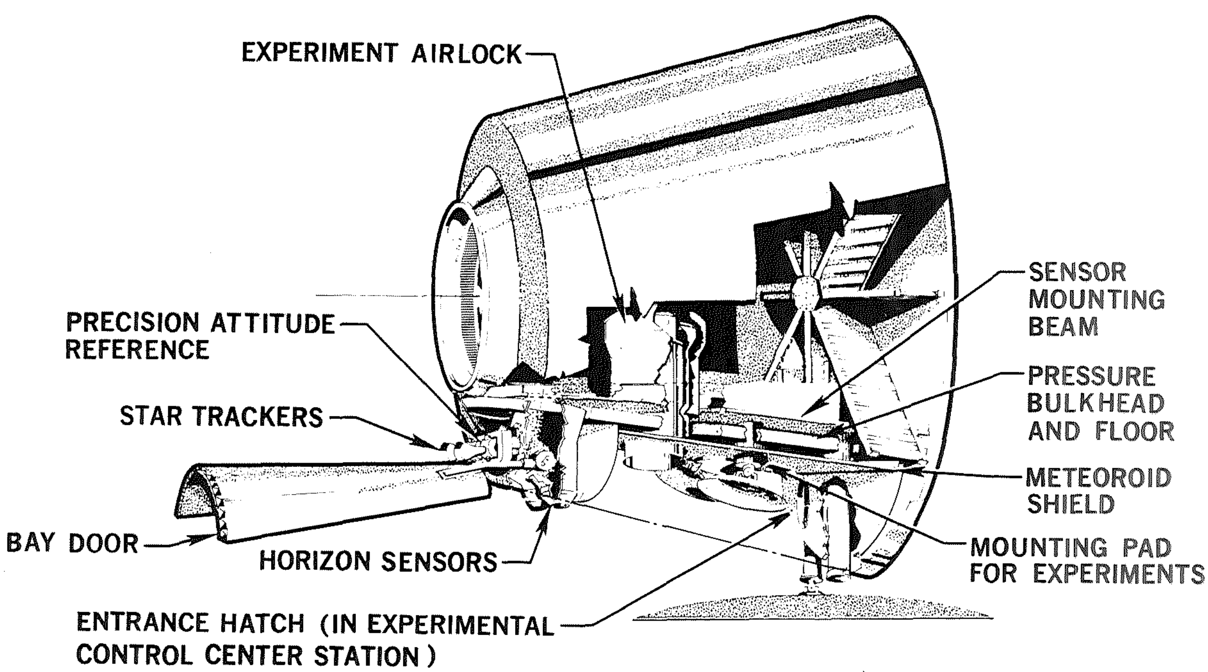

FIGURE 13.—MORL experiment bay.

functions was to be required, one example of which would be impossible to perform. The goal of this study was to evaluate the degree of behavioral disruption and disorganization that would appear on the part of the crew following their exposure to this frustrating situation.

Other examples of equipment evaluation dealing with the assessment of different oral hygiene procedures, development of helmet-mounted scalp electrodes, and so forth, could be cited as the types of tests that have no place in an operational vehicle. Each vehicle launched into orbit should represent the best facility that our combined ingenuity can achieve. As experience is gained, recommended improvements will be forthcoming for that equipment or those procedures that operational experiences identify as requiring change. The life scientists must break away from the classical college laboratory approach to experiment design. The concern is not with college sophomores in a general psychology course, but real people in a real-world operational situation where the success or failure of the missions and the life or death of the crew are at stake. An entirely new philosophy of biomedical and behavioral assessment on a non-mission-interference basis must be established.

Valid assessment techniques can be designed that are an integral part of the normal operational routine. As an example, suggestions have been made that harmonic and other forms of analyses of voice characteristics should be pursued to explore their promise as possible indicators of anxiety, depression, hostility, or other emotional reactions. Onboard operational tasks could be designed with built-in checklists or performance indicators. The crewmen could be scored or evaluated as they were actually performing useful work. Parity checks and associated performance-scoring techniques should now be developed and validated in ground simulation tests so that they may be ready for use when needed. In-flight biomedical measurements also must be continuously reexamined in light of their validity, the time required for their accomplishment, and the impact that they may have on crew comfort and mobility. As in other research areas, a priority system will be required to insure that only those measures deemed, by competent medical authority, to be significant and nonhazardous to mission success are implemented.

New or different statistical tests are required where events are analyzed as they occur. In developing a methodology for the statistical analysis and related decision procedures associated with biomedical and behavioral assessment programs, two factors must be considered: (1) the particular hypothesis being tested must be either accepted or rejected, utilizing the smallest feasible sample size and/or number of observations; and (2) economy of operation dictates the need for careful consideration of the depth of measurement or level of measurement scaling necessary or theoretically justifiable. The first factor suggests the use of sequential analysis in the testing of hypotheses, and the second factor suggests the consideration of nonparametric statistics.

The concept of developing and validating biomedical- and behavioral-assessment techniques that can function on a noninterfering basis with normal activities represents a challenging area of research in its own right. It will require the best minds, clear thinking, and a great deal of creativity to divorce in-flight assessment programs from the stereotyped approaches to experiment designs.

The most significant design safety problem of a biotechnological nature bearing on mission success encountered during Douglas' research was not that of weightlessness but that of radiation protection. Many guidelines for the radiation protection of astronauts have been suggested in the literature. None has been found completely applicable to the radiation-exposure situation anticipated for laboratory crewmen.

The operation of an orbital research laboratory will entail chronic radiation exposure of a small number of highly skilled individuals who will have limited careers in orbit but very essential assignments. Although protected from solar flares, a continuous low-level exposure will be encountered at 200-n.-mi., $\pm 28°$ inclination orbits. Also, the lower fringes of the geomagnetic belt will expose the crew to an intermittent, but almost daily, background of high-energy protons and electrons. However, an acute dose hazard will exist for missions at inclinations greater than $\pm 30°$. The radiation guidelines in table V were derived from a consideration of current radiation-protection guides, allowable sociological risks, and the known biological effects of exposure to radiation that are considered to be risk-limiting responses for the radiation environment and mission profile. To place these limits in perspective, figure 14 shows risks to human life from various socioeconomic endeavors. For example, the radiation risk for the late risk-limiting responses of leukemia and the life shortening are comparable to risks accepted by society in other lines of endeavor. Note that the risks of various human pursuits involve effects that would occur within 1 yr, while the radiation risks are for effects that would occur many years after exposure.

With use of the above values, it was found necessary to add 165 lb of shielding material to the aft dome of the laboratory to reduce the radiation dose received by the crew to an acceptable level on a 50° inclination mission. To provide the same protection on the polar mission, 1820 lb of shielding material is required. Presently projected launch capabilities would allow this amount of shielding and this material to be installed relatively easily by increasing the gage of the laboratory bottom, sides, and top dome. The most significant problem from a design standpoint, however, was the uncertainty in the amount of shielding required for a synchronous mission. More analysis and better data relative to the electron flux density and the generation of bremsstrahlung are required. Depending upon the assumptions made, the amount of shielding required for the synchronous mission varied from 4400 lb to 110 000 lb. Mission-success probabilities could be severely curtailed if excessive weight penalties of this magnitude were imposed on the spacecraft. Figure 15 summarizes the effect of allowable dose on required shield weight for a synchronous mission based on current, electron-flux density estimates.

In a short overview of the significant biotechnological factors in spacecraft design, it is not possible to discuss or even anticipate all of the potential problems that may arise in the development of vehicles capable of extended-duration space flight. Even so, it may be of value to list at least some of the potentially critical research and technology requirements that have been identified to date. A program of supporting R&D initiated now and based on these requirements would provide high confidence in the ability to solve the various system and subsystem development problems in timely fashion.

Suggested Areas for Research Investigations

Further research should involve the following investigations:

(1) Investigation of techniques for the

TABLE V.—*Proposed Guidelines for Protracted Radiation Exposures for MORL*

Critical organ or area	Maximum, 3-month exposure, rem	Maximum, 6-month exposure, rem	Maximum, 12-month exposure, rem	Maximum, single exposure, rem	Maximum, emergency, single exposure, rem	Acceptable integral exposure (lifetime), rem
Skin of whole body	300	350	400	100	400	1000
Skin of extremities	650	750	900	250	600	1500
Lens of eye	225	240	270	100	200	600
Bone marrow	50	80	150	25	150	750

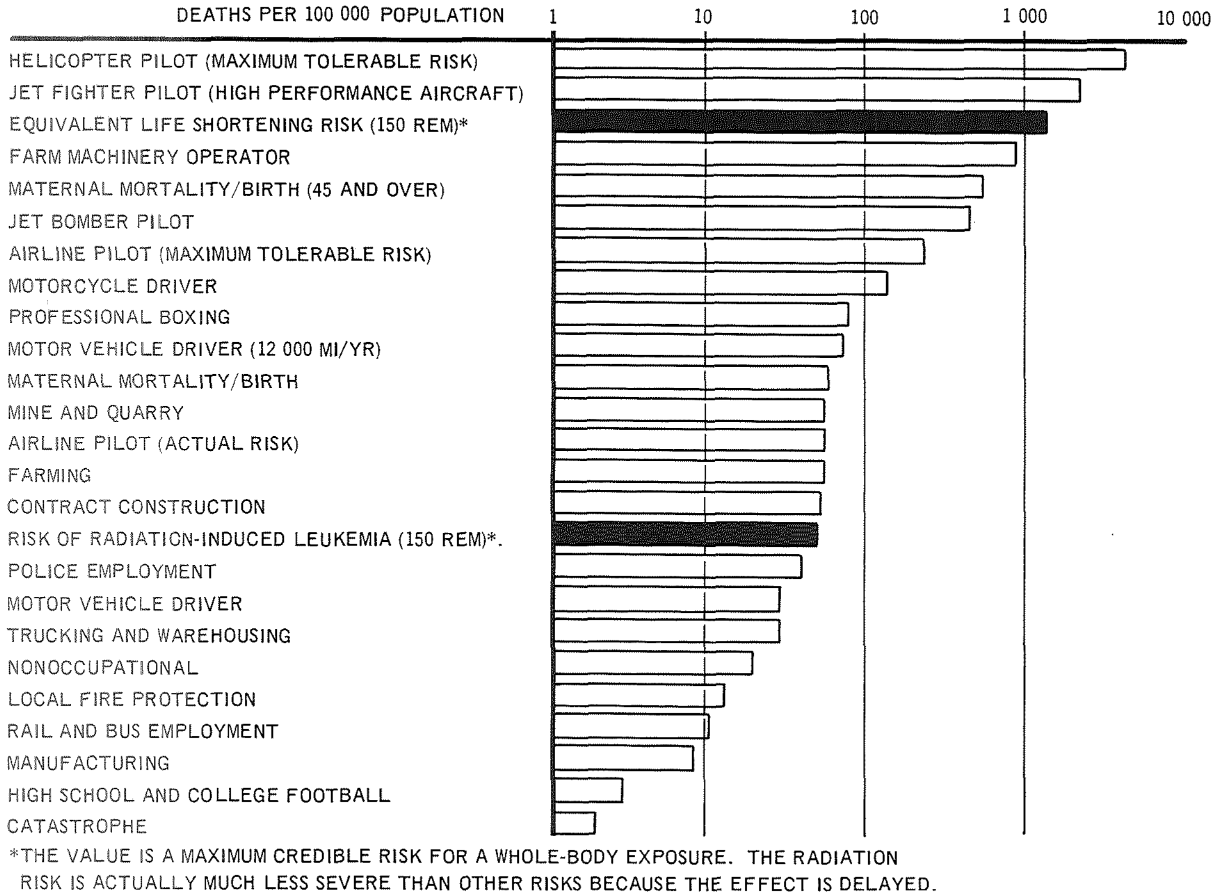

FIGURE 14.—Risk to life per person per year in various accepted human involvements.

noninterfering assessment of crew performance and behavior (for example, harmonic analysis of speech characteristics, body movement patterns)

(2) Investigation of radiation environment in all areas of mission interest; particular emphasis is required in establishing the electron flux at synchronous latitudes

(3) Investigation of micrometeoroid environment in all areas of mission interest

(4) Investigation of proposed orbiting research laboratory atmosphere for long-term habitability

(5) Investigation of aeroembolism effects upon decompression to pure-oxygen suit atmosphere

(6) Investigation of detrimental atmospheric contaminants and establishment of toxicity levels

(7) Investigation of methods of identifying and continuously monitoring all trace contaminants at levels significantly lower than ever attempted before

(8) Investigation of long-term exposure to modified (semisterile) bacteriological environment

(9) Investigation of biological and psychological effects of long-term use of recycled and reclaimed (urine) water

(10) Investigation of human requirements and operational parameters for spinning (artificial-gravity) mode of laboratory operation

Areas in Which Advances in Technology and Development Are Required

(1) Development of physiological/psychological testing equipment compatible with the orbital environment

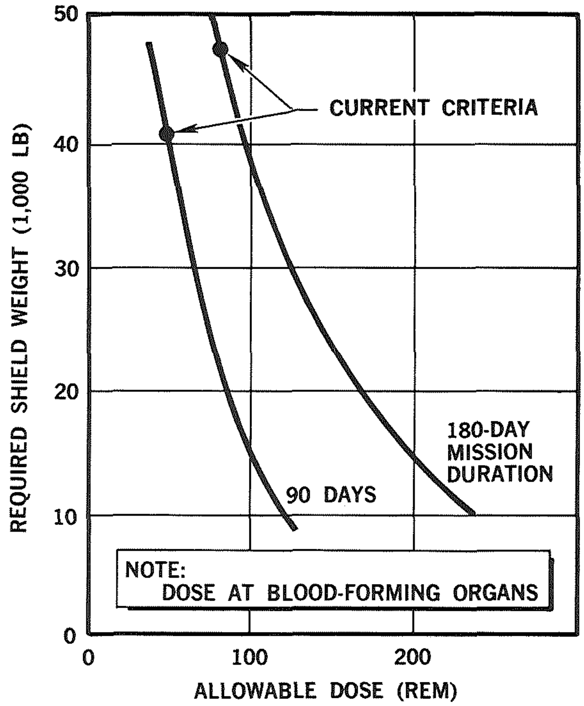

FIGURE 15.—Effect of allowable dose on required shield weight—synchronous mission.

(2) Development of physiological/psychological monitoring and conditioning criteria

(3) Development of techniques for integrating behavioral testing with routine station operation and maintenance procedures

(4) Development of automated biomedical measurements

(5) Establishment of realistic, long-term, radiation-exposure criteria (particularly critical for synchronous missions)

(6) Development of effective partial body shielding

(7) Determinations of accurate metabolic rates for various activity levels so that spacesuit airflow fans can be efficiently sized

(8) Determination of food wastes to be expected as a function of crew size, the density of wastes after freeze drying, and the long-term compatibility of fecal wastes with food and laboratory wastes and the collection or storage device

(9) Evaluation of decontamination and cleanup techniques in case of illness

(10) Evaluation of long-term, maximum, sound-tolerance levels for EC/LS rotating machinery and air ducts

(11) Determination of duct configuration for minimum sound propagation

(12) Evaluation of cabin ventilation in 0*g*

(13) Resolution of micrometeoroid-penetration leak-detection problems

(14) Determination of long-term physical and psychological effects of food packaging and processing methods

(15) Development and testing of onboard 0*g* laundry facilities

(16) Assessment of man's capability in 0*g* to perform station-keeping operations, maintenance, and experimentation

(17) Development of techniques for crewman positive motion control

(18) Identification of flightcrew procedures, with emphasis on communication requirements; need for restraints, special tools, and work aids; special requirements for controls and displays; and optimum layout of onboard equipment and facilities

(19) Assessment of man's performance capabilities in EVA spacesuit operations

(20) Determination of time and motion data for 0*g* operations to provide a more accurate baseline for evaluation of ground-based simulation activities

(21) Development of biomedical sensors that do not interfere operationally and do not violate the epidermal layers

(22) Evaluation of the long-term effectiveness of trace-contaminant removal techniques

(23) Development of flight-qualified ultraviolet lights used for control of atmospheric bacteria

CONCLUSION

It is clear that spacecraft sizing and operation depend upon the crew size and capability in several ways. Examination of a broad spectrum of Earth-orbital missions has confirmed the tremendously exciting potential of manned space laboratories capable of extended-duration flights. During the next 50 yr, the socioeconomic and political rewards of these missions will touch the lives of every person on Earth. Although the engineering and economic feasibility of accomplishing these missions has been established, available man-hours will continue to be the most critical resource available in orbit. It is absolutely mandatory that man's time in orbit be used effectively and that the right man in terms of required skill be available when needed. The man-machine interface must be designed to optimize the use of man's time, even at the risk of redesigning some experiment packages for operation by observers who are less well qualified. Far more sophisticated concepts of biomedical and behavioral assessment must be devised that give a maximum rate of information return for minimal operational interference. A crash program to develop and validate such techniques in Earth-based laboratories should be undertaken immediately if we are to be ready for the operational orbital laboratories of the 1970's. Better radiation data at synchronous orbits are required and more realistic long-term criteria for radiation risk levels established. Although many questions still need answers, no insurmountable problems have appeared. Man's accomplishments in space will be limited only by his own ingenuity.

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Man as an Experimenter and Operator in Space

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In this report an attempt has been made to identify and analyze man's role as an experimenter and operator in space and to resolve questions about the precise region of application of man's capabilities. The potential space applications for the exploration and exploitation of space are considered. Man's potential role in space is then identified to justify his participation in the space program. A philosophy of man's applicability in space is analyzed to assess his capabilities to contribute to space tasks. A review of simulation results is presented for some specialized areas of man's application. The prognostication of man's suitability is discussed to specify the areas of his utilization. Simulation is proposed to obtain hard numbers on man's performance and determine the best machine aid required for support.

SPACE POTENTIAL APPLICATIONS

Synopsis of ORL Study

Recent Government and industrial studies and forums have identified, defined, and analyzed the functional areas of application of Earth-orbital space.

The synthesis approach is based on the recognition that the Orbiting Research Laboratory (ORL) represents a platform for significant experiments, generated by a systematic analysis in terms of their contribution to the solution of national and international problems and to the illumination of crucial scientific questions.

Thirteen fields of activity, called scientific/technical (S/T) areas, were identified as potentially benefiting from the ORL. Functionally, these areas may be categorized as follows:

(1) *User-oriented applications*.—This category has the property that its benefits can be quantized in terms of dollars. It contains the areas of agriculture/forestry, geology/hydrology, oceanography, geography, atmospheric science, and communications/navigation and traffic control.

(2) *Science*.—The value of this category is dependent upon judgment and cannot be categorized. It contains the areas of astronomy/astrophysics, bioscience, and physical science.

(3) *Support for future space missions*.—This category can theoretically be quantized in monetary terms if an advanced mission were to be approved. It contains the areas of biomedicine/behavior, advanced technology, extravehicular engineering activities (EVEA), and operations techniques/advanced mission subsystems.

Major ORL Results

Analysis of each of the 13 scientific/technical areas identified by the ORL study led to individual requirements for payloads, orbits, and experiments. Synthesis of these areas by commonality led to the conclusion that the three orbiting stations (fig. 1)

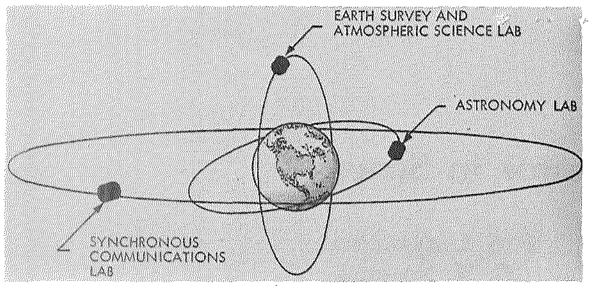

FIGURE 1.—Core of constrained program.

listed here are required to perform the entire program:

(1) High inclination station for Earth-oriented applications

(2) Low inclination station for astronomy

(3) Synchronous space station for communications and later applications

The analysis showed that one of the most critical problems is the handling of the large volume of data that this program will generate.

Data Transmission Problem

Data transmission from the spacecraft to ground represents the first facet of the data-handling problem:

	Bandwidth
Commercial TV, mc/sec	4.24
Unified S-band	1.25
SGLS	10.0
Advanced microwave systems, mc	100
Time to transmit 10^{16} bits:	
4.25 mc, yr	60
100 mc, yr	3.1

The time to transmit a photograph electronically depends upon the system bandwidth. Using the bandwidths of current transmission systems, the time required to send 10^{16} bits is seen to be prohibitive. Potential solutions would include survey techniques using only sampling, onboard selection of photographs of value, and data capsules for physical recovery of film.

Ground Data Handling

The second aspect of the problem concerns ground data handling. This involves the need for coordinating different requests for survey and the need for storing results in a form that can be used by photo interpreters expert in the various disciplines.

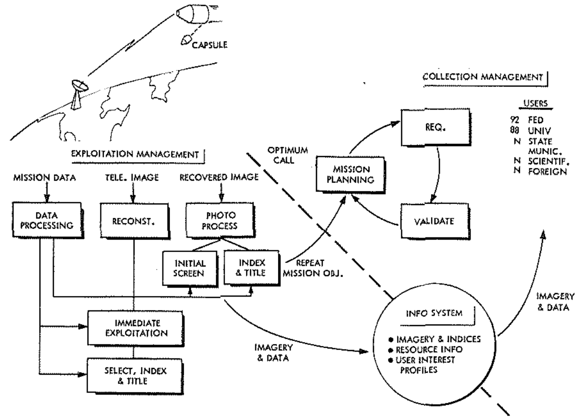

FIGURE 2.—Survey interpretation system elements.

Figure 2 shows the elements of a ground data management system that includes:

(1) Collection management for receiving requirements from users; checking them against an information system to determine whether information is already on file; and, if not, planning the missions to accomplish the requests.

(2) Exploitation management for receiving the information; checking it in quasi-real time to determine whether the photography meets acceptable standards and, if not, to order a repeat observation; and indexing.

(3) An information system that is essentially a large library of the photography. Through use of modern data-handling equipment, large and efficient libraries of this type have been built.

World Photo Completion Constrained by Weather and Illumination

An important consideration is the time of flight required as a function of comprehensiveness of survey.

The first step is to determine the positional opportunities, the number of times during a given flight period within which a given point on the Earth's surface falls within the field of view of the sensors. For the example selected, 300-n.-mi. swath width,

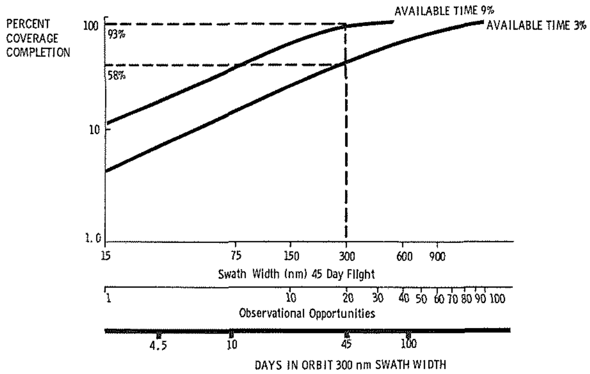

FIGURE 3.—World photo completion constrained by weather and illumination.

20 opportunities at the Equator occur for 45-day flights (fig. 3).

The next step is to consider the day-night cycle and weather on a worldwide basis, which yields an average available time of 9 percent. For the conditions of the example cited, namely 300-n.-mi. swath width and 45-day duration, this yields almost complete (93 percent) coverage of the Earth's surface.

In practice, particularly over the developed nations, the presence of manmade or man-induced haze further cuts the available time by a factor of 3 (ESSA); thus, over developed regions, a flight time of 45 days with 300-n.-mi. swath width would only allow coverage of 58 percent. Conversely, under these conditions, coverage of 90 percent would entail flight time between 120 and 150 days.

These considerations thus make a strong case for long-duration missions.

TABLE I.—*Economic Benefits of Spaceborne Survey Systems*

Application area and principal requirements	Estimated annual benefits (millions of dollars)			
	World		United States	
	Expenditures	Returns	Expenditures	Returns
Agriculture/forestry:				
Global crop survey; Crop yield and damage survey; Detection and location of forest fires; Wildlife migration; Range management survey; Assessment of ecological factors	130	11 000	26	840
Geology/hydrology:				
Global mineral and fuels survey; Earthquake and volcano damage assessment; Distribution of soils, moisture, erosion platters; Water pollution surveys and warning; Flood damage assessment	620	6 000	170	2 500
Oceanography/marine technology:				
Fishery surveys; Hazard warning to shipping; Coastal hazard warning; Sea-state prediction and tidal inundation	800	7 000	350	3 500
Geography:				
Global topographic mapping; Synoptic demographic survey	33	800	9	100
Atmospheric science and technology:				
Weather prediction and monitoring; Air pollution survey and warning; Warning of storm and climatic hazards	1 000	83 000	500	29 500

Estimate of Economic Benefits

The value of the user-oriented applications has been estimated by various industrial groups.

The benefits from space survey are of two categories:

(1) Reduction of the cost of current surveys

(2) Improvements in yield resulting from utilization of the new information

Shown here (table I) are estimated benefits for the Earth-oriented applications of Earth-orbital space.

If these benefit numbers are correct, a large advantage would accrue from operations in Earth-orbital space.

MAN'S ROLE IN SPACE

Man's Role as an Operator in Space

The earliest efforts in space compared man's capabilities with the capabilities of complex mechanized subsystems to justify man in space as something more than a scientific specimen or curiosity.

Gradually, a more mature, man-machine integration approach was developed that concentrates upon the optimal combination of man and machine to permit more efficient performance than either could produce alone. This has always been one of the primary goals of human engineering endeavors.

Following a system analysis approach for an effective man-machine system, man's role in the space mission should be defined by assessing human capabilities in the space environment and then determining whether, in a specific application, he can operate as shown here.

In summary, man's role as an operator in space is valuable for several reasons:

(1) He can provide a unique function that could be performed in no other way.

(2) He can perform functions efficiently as a substitute for costly and heavy equipment.

(3) He can operate in combination with machines to perform functions that neither alone could achieve satisfactorily.

Contribution of Man

The question of man's usefulness in space operations and of the exact region of his utility has been raised. Various studies have attempted to identify man's potential contributions to space systems based upon his inherent capabilities.

The contributions that man brings to a task are—

(1) Motivation, creativity, imagination, and foresight

(2) Highly selective, flexible, and extensive memory

(3) Inductive and deductive reasoning

(4) Sensitive manipulative ability

(5) Human sensory capabilities—discernment of fine detail and pattern

(6) Ability to be reprogramed easily

These contributions enable him to—

(1) Observe and act upon unforeseen events

(2) Evaluate complex data or situations

(3) Extract, compact, and communicate data

(4) Make judgments and decisions, even with incomplete data

(5) Translate items of research nature into routine elements for automatic programing

(6) Inspect, adjust, calibrate, and repair

There exist very little hard data defining quantitatively the scope and limitations of man's possible contributions.

Effect of In-flight Maintenance on Reliability

What is desired next is a numerical assessment of these capabilities. A search of the open literature shows that numerical indications and measurements are indeed available in certain areas.

Some data have been obtained through analysis and simulation.

Figure 4 shows the improvement in reliability (probability of mission success) resulting from carrying a single spare for each replaceable module. The data shown were developed during a simulation of a spaceborne data-processing run using the computer designed at IBM for the Saturn V rocket.

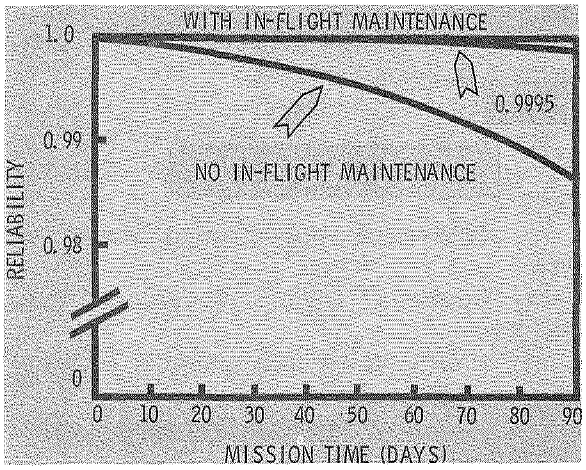

FIGURE 4.—Effects of in-flight maintenance on reliability.

Man's Application in Camera Operation

A typical example of suggested applications of man in space-experiment systems is shown in this block diagram of the operation of a single spaceborne high-resolution camera (fig. 5).

Shown are both the spacecraft equipment, such as the inertial subsystem, and the camera peculiar equipment, such as pointing and tracking subsystems.

The dotted lines indicate potential applications for man in loop to have data displayed and to control the individual subsystems.

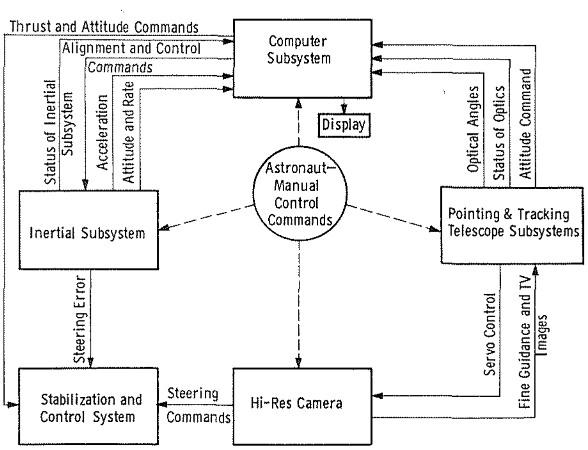

FIGURE 5.—High-resolution camera operation.

MAN'S APPLICABILITY IN SPACE

Man's Capabilities in Space

Except for sporadic and nonquantitative discussions, no real numbers, either simulated or real, are available for most of the potential areas that represent man's higher and most-touted capabilities.

This clearly represents a major gap. Not only would we like numbers to resolve the 10-yr-old question of manned versus unmanned, but we would also like to define the requirements for many assists that need to be given to man to perform his job better.

We do not have today the solution to this gap. The following are hopefully oriented toward filling this major hole in our knowledge:

(1) First, a philosophy of man's applicability to space tasks

(2) Second, a brief review of some in-house work pertaining to specialized areas of man's applicability

(3) Third, a prognostication as to what specific Earth-orbital applications are potentially suitable to man, and why

(4) And, finally, a proposed experiment designed to obtain "hard numbers" as to man's performance in space

Philosophy of Man's Applicability

The specific objectives of several studies are to provide figures for man's capabilities as

(1) A performer of pattern-recognition tasks in terms of his ability to discern fine detail and pattern:

(*a*) Complex pattern detection and recognition

(*b*) Decisionmaking on collection of data

(2) An evaluator of complex situations in terms of his ability to measurably increase image data yield and quality via adjustment to sensor equipment controls:

(*a*) Pointing and focusing of instrumentation to targets

(*b*) Tracking of critical pattern aspects

(3) A data extractor and compactor in terms of his ability to reduce data transmission requirements via selection and data compaction:

(*a*) Collection and analyses of data information

(*b*) Selection of information to be compacted, recorded, or transmitted

(4) A performer of EVA activities in terms of his ability to adapt to his environment and to use EVA equipment efficiently:

(*a*) Maneuvering and transferring cargo

(*b*) Assembling and erecting structures

(5) A performer of tasks to cope with unforeseen events in terms of the efficiency of his response to such events:

(*a*) Identify and correct malfunctions

(*b*) Identify unforeseen targets

Performer of Complex Pattern-Recognition Tasks

This would include the comparative analyses of performance using targets that will be presented well above detection/recognition thresholds and will be perceptually matched to the highest possible degree; i.e., size, color, contrast, illumination, etc.

The dependent variables would be time and number of errors for complex pattern detection, recognition, and decision on collecting data.

The end items include:

(1) Effects of luminance and contrast ratio on pattern detection and recognition (PDR)

(2) Effects of magnification factor on PDR

(3) Effects of various amounts of haze on PDR

(4) Effects of various amounts of cloud cover on PDR

(5) Effects of combinations of the above on PDR

(6) Each of the above with respect to category of patterns and types of cues

(7) Evaluation of go/no-go decision-making performance in real time versus postexperiment performance.

Evaluator of Complex Situations

This would include the ability of man to adjust his sensor equipment to increase image data yield.

The dependent variables would be time and number of errors for pointing of instrumentation to targets, tracking of critical pattern aspects, and focusing of instrumentation to moving surfaces.

The end items include:

(1) Effects of luminance and contrast ratio on pointing, tracking, and focusing (PTF)

(2) Effects of magnification factor on PTF

(3) Effects of various amounts of haze on PTF

(4) Effects of various amounts of cloud cover on PTF

(5) Effects of combinations of the above on PTF (time/errors)

(6) Each of the above with respect to category of patterns.

Data Extractor and Contractor

This task will study man's ability to select only those features that are of interest to the ground analyst. Thus, man will contribute to reducing the volume of data to be transmitted to the ground by rejecting duplicate data.

The dependent variables would be time and number of errors for collection of data, analysis of information, and selection of information to be transmitted.

The end items include:

(1) Assessment of the amount of data transmission that is saved via inclusion of man in the processing loop as a data selection and compaction tool (for each type of data tested).

(2) Trade analyses that evaluate volume of data collected with compacting as a requirement against total data volume that could be collected without data compaction and against loss of good data in real time due to cropping.

(3) Evaluation of compaction performance in real time versus postexperiment compaction performance.

Performer of EVA Activities

This would include the ability of man to use efficiently his locomotion equipment to perform EVA activities.

The dependent variables would be time and number of rest periods required for locomotion and transfer and for the assembly and erection of large structures in space.

The end items include:

(1) Effects of professional skill and training on locomotion and handling for EVA

(2) Effects of maneuvering unit characteristics on EVA

(3) Effects of various shapes and sizes of structures on the assembly and erection for EVA

(4) Effects of foot restraints and waist restraints on reaction forces and torques for EVA

(5) Effects of combinations of the above on EVA

(6) Evaluation of teamwork for the handling, assembly, and erection of large structures.

Performer of Tasks to Cope With Unforeseen Events

This task will study man's ability to make use of his sensors and equipment to cope with unforeseen events. These events will include system malfunctions and the appearance of unforeseen targets in the field of view.

The dependent variables would be time and number of events for identifying and correcting malfunctions and identifying unforeseen targets.

The end items include:

(1) Effects of skill and training on coping with unforeseen events (CUE)

(2) Effects of type of malfunction on CUE

(3) Effects of the size and type of targets on CUE

(4) Assessment of the degree in improvement of reliability by man's action to maintain and repair malfunctions

(5) Evaluation of coping with unforeseen events in real time versus postexperiment performance

SIMULATION RESULTS IN SPECIALIZED AREAS

Recognition Time of Landmarks

Some work performed at IBM-Owego simulated man's capability in specialized areas; i.e., in acquiring and tracking special phenomena, represented synthetically by point landmarks.

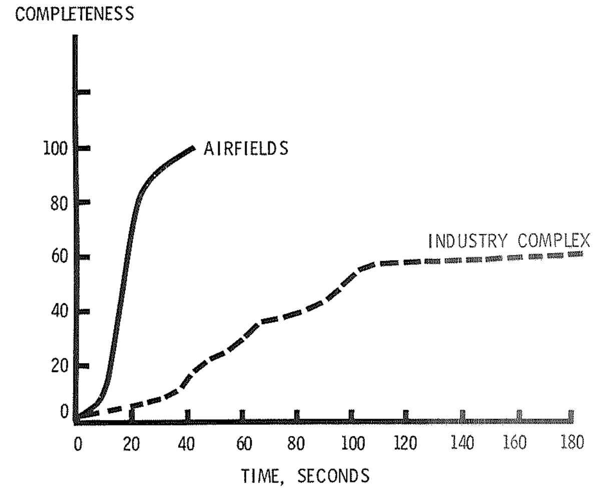

FIGURE 6.—Recognition time of landmarks.

Figure 6 is typical of the quantitative results that can be obtained for guiding the allocation of experiments among manned and unmanned space stations. It indicates the time man requires to recognize various landmarks from space. These data were obtained in the IBM Simulation Laboratory and are typical of data obtainable through use of simulation techniques.

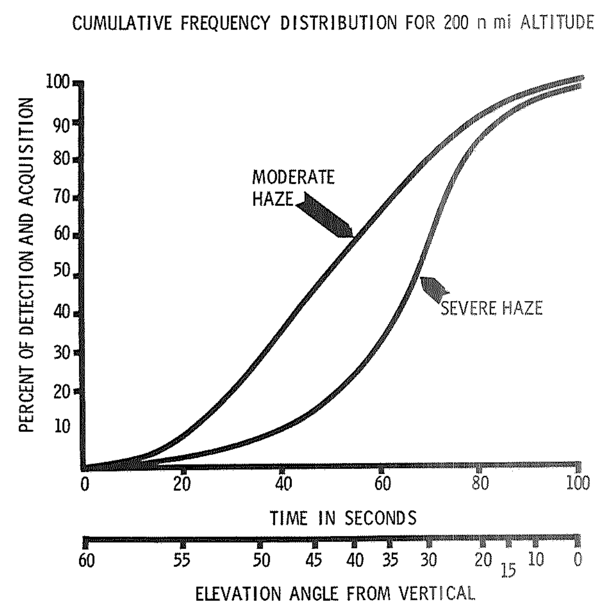

FIGURE 7.—Landmark detection and acquisition.

Landmark Detection and Acquisition

The time necessary to detect and acquire preassigned landmarks was assessed as a function of altitude, magnification, landmark type, and severity of atmospheric haze. (See fig. 7.)

High-contrast complexes were selected for landmarks that remained somewhere within the field of view during the experiment run that started at an angle of 60° from local vertical.

Acquisition requirements of wide field of view, 15–30°, low-power magnification, 5–20 ×, and pointing accuracy ±10 min of arc, were established.

It was shown that, with simple aiding requirements, man has the capability to acquire prebriefed landmarks at least 15 sec from the nadir point.

Tracking of Landmarks

In tracking, all image motion was compensated by means of hand-control signals.

The relationship between magnification and performance was investigated for high-contrast complexes selected for landmarks from an altitude of 200 n. mi.

Tracking requirements of narrow field of view (2°) and high-power magnification (20–100 ×) with zoom capability were established.

The experiments have shown man's ability to track better than 0.2 percent of orbit velocity and to point to better than 10 sec of arc.

However, the ultimate limitation of his performance will probably be the result of landmark type and size, color and texture, contrast ratio and illumination, equipment performance, and other environmental factors.

PROGNOSTICATION OF MAN'S SUITABILITY

Prognostication of Man's Applicability

As seen before, we have in the Earth resources area three types of surveys:

(1) *Those characterized predominantly by a fixed data base.* Examples: surveys of principal cities (geography), surveys of coastlines (oceanography).

(2) *Those having limited requirements for target-of-opportunity operations.* Example: high-resolution agricultural surveys where last-moment shifting of the sensor may be desired to insure a more appropriate sample.

(3) Those in which all targets are of opportunity. Examples: search for fish schools, search for sea ice.

Man is most desirable for (2) and (3), but is not strictly needed for (1). The specific actions where man may be useful are derived for a specific case of meteorological survey time-line analysis.

AAP Meteorology Payload

The AAP meteorology experimental program is designed to determine optimum instrumentation and operational techniques for meteorology, to provide, through the synoptic overview available from space, increasingly complete weather forecasting for Government and private agency users. It employs optical (through TV and multispectral photography), microwave, and infrared detection, and recording systems (including polarimetry) to provide penetrating surveillance of weather formations and movements.

Temperature, pressure, density, and velocity must be capable of being measured from orbit as well as cloud coverage now provided by Environmental Science Services Administration (ESSA) unmanned satellites.

The implementation of these experimental programs will define the most effective manned/unmanned instrumentation and utilization techniques for future operational missions.

Onboard and ground-based data-handling techniques will be tested to determine the best approach for timely data dissemination to users.

Astronaut participation in these experimental exploitations can provide effective surveillance to identify dynamic formation and evolution of weather phenomena through sensor pointing and tracking, instrument control, and the data-gathering process.

Tests both with and without man in the system will determine future human involvement and value.

Human Activity Requirements

Operations analysis shows that approximately 10 000 switching operations must be performed and 5000 display events monitored during an AAP mission for meteorology and survey of natural resources.

Table II shows the human activity requirements for a 14-day, three-man mission.

Systems analyses of typical experimental activities point very strongly to an increasing need for preprogramed, computer-assisted astronaut activities.

Experiment Operation Timeline

Based upon the experiment requirements analysis, an operations profile for a typical day was constructed (see fig. 8) reflecting the relative priority of the several mission activities in the following four steps:

(1) Astronaut rest
(2) Calibration periods
(3) Specified targets
(4) Targets of opportunity

An undisturbed quiet period of 8 hr was blocked out during the two orbits prior to U.S. coverage.

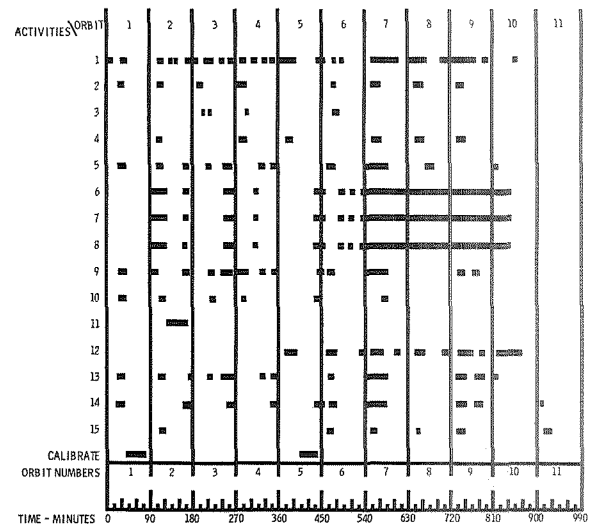

FIGURE 8.—Experiment operation timeline (typical mission day).

TABLE II.—*Human Activity Requirements for a 14-Day Mission*[a]

Experiment functions		Parameters	
Visual backup	Experiment control	Time, hr	Total time, hr
Spacecraft ground-point tracking	Monitoring, switching displays, computer programed	25.6 2.5	154
Visual sighting (assisted and unassisted)	Monitoring, switching displays, computer programed	7.5 2.5	84
Boresighting	Monitoring, switching displays, computer programed	1.25 3	10
Target-of-opportunity identification	Monitoring, switching displays, computer programed	31.7 3	443
Fixed target observation	Monitoring, switching displays, computer programed	1.67 3	5
	Recording voice tape and logbook	.7	10.5

[a] Experiment hr 710
Sleep hr (3 astronauts sleep 8 hr/day) 336
Astronaut mission 1046

Desirable periods for the calibration of the instrumentation were identified.

Those experiments requiring specific ground truth sites or for which there were specific areas (or targets) of interest were scheduled.

Potential targets of opportunity were randomly distributed along the ground track. An average of nine such targets per revolution were included.

Other constraints affecting assignment of an experiment to a specific orbital time included Sun angle (experiments 2 and 10), spacecraft attitude, and day/night periods.

Targets of Opportunity

Acquire targets of opportunity; dodge clouds—set filters on camera and other sensors to reflect illumination conditions; do not take imagery when clouds are present; filter the information. As to the latter, here is a potential situation of a typical function that a man can perform. Assume that the problem here was to locate cargo ships. By knowing where to look, such as along the shoreline in figure 9, man can rapidly recognize them.

Magnification Aid

Having located the target—a cargo ship—in the display shown in figure 9, using an automated system such as a light pen, an enlarged portion of the first display may be obtained as shown in figure 10.

If more detailed examination is required, further enlargement can be called for. These steps can be accomplished in a matter of seconds to identify portions of interest for rapid transmission to the ground, either in radio-image format or by voice. This provides both a rapid response and a major reduction in the data load for transmission.

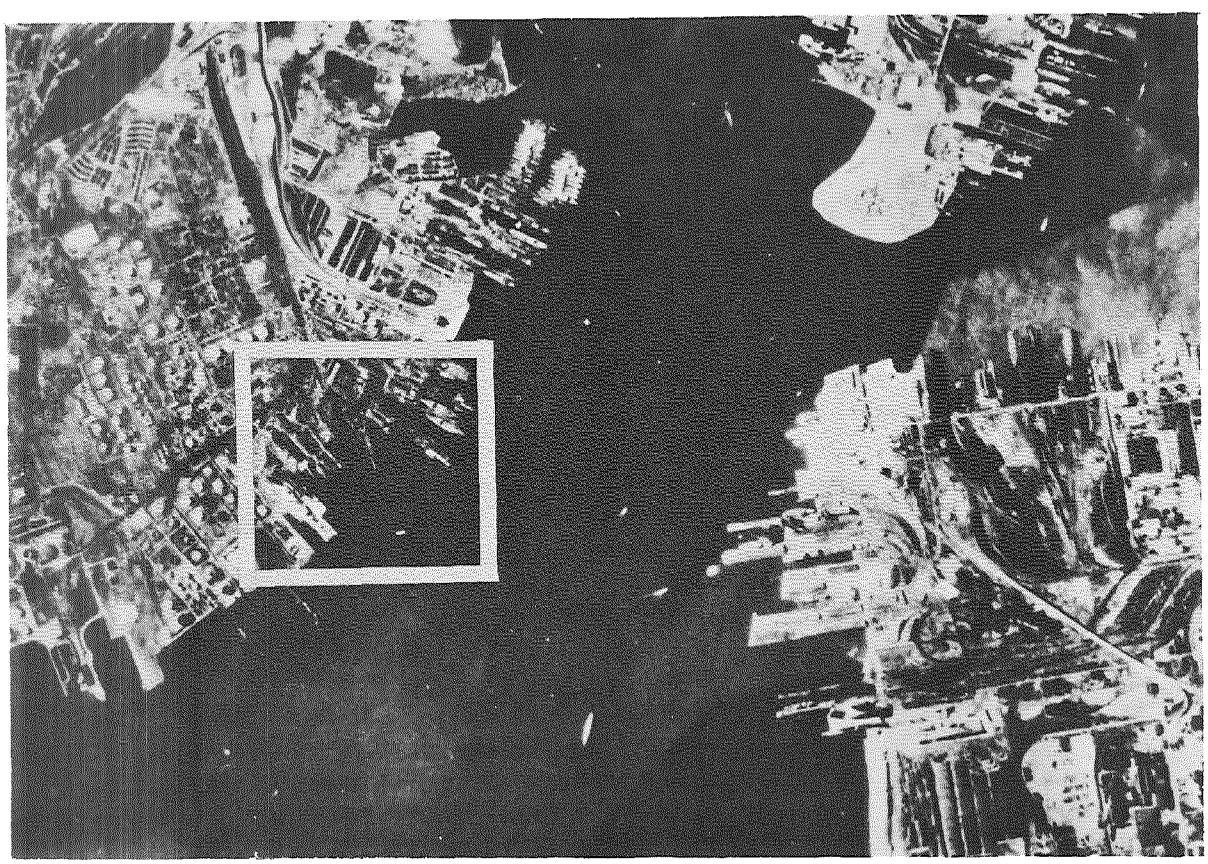

FIGURE 9.—Targets of opportunity.

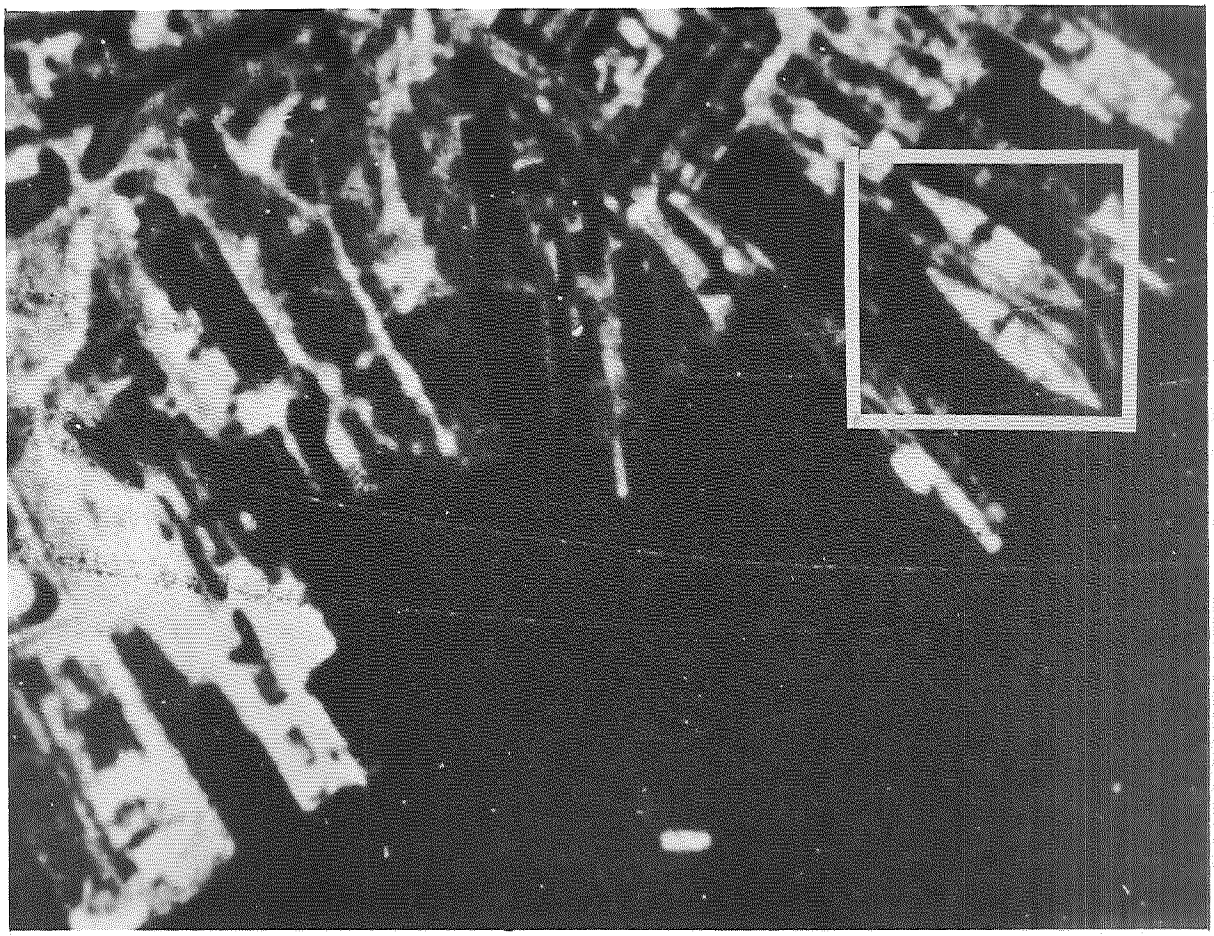

FIGURE 10.—Magnification aid.

PROPOSED SIMULATION

Astronaut Involvement

Data on the role and specific capabilities of the astronaut in both intravehicular and extravehicular tasks are lacking in areas such as degree of automation, experiment design criteria, ability to handle data, tasks to which man is best suited, motion and maneuvering, transfer of cargo, maintenance and repair, assembly and erection, and rescue of personnel. Simulation is the only method, short of actual space flight, of obtaining these data.

Advanced space system studies have identified the need for developing equipment concepts and operational procedures that will enable astronauts to perform various tasks in support of future space operations.

Initial data are required on the ability of man/machine combinations to perform tasks in the space environment. These data will be valuable in verifying the feasibility of equipment and procedures.

Simulation To Answer Basic Questions

Two basic questions are involved in the material presented thus far:

(1) Is man worthwhile?

(2) What can he do?

Simulation can provide hard numbers on certain of man's capabilities:

(1) Target acquisition and discrimination

(2) Fine adjustment of complex equipment

(3) Image motion compensation
(4) Equipment setup and calibration
(5) Team performance
(6) Time-line analysis
(7) Data compaction, including preselection filtering and postselection editing and cropping
(8) Sensor queuing and management
(9) Maintenance and repair
(10) Motion and maneuvering
(11) Assembly and erection
(12) Transfer and rescue

Some fragmented data have been obtained on portions of the problem—target recognition, etc., but the total problem has not been addressed.

The Earth-sighting simulator (ESS), developed and built by IBM, provides a tool with which to start a coordinated study of the problem. The ESS can be used to provide data in most of the areas listed in the previous paragraph.

The EVA simulators include:

(1) Zero-gravity flights in aircraft, which can produce weightlessness only for very short time periods, approximately 30 sec

(2) Water immersion tests, which have high damping effects

(3) Five- and six-degree-of-freedom "frictionless" platforms with high mass connected to the astronaut

(4) Computer-controlled complex simulators without the elements of temperature, vacuum, and weightlessness

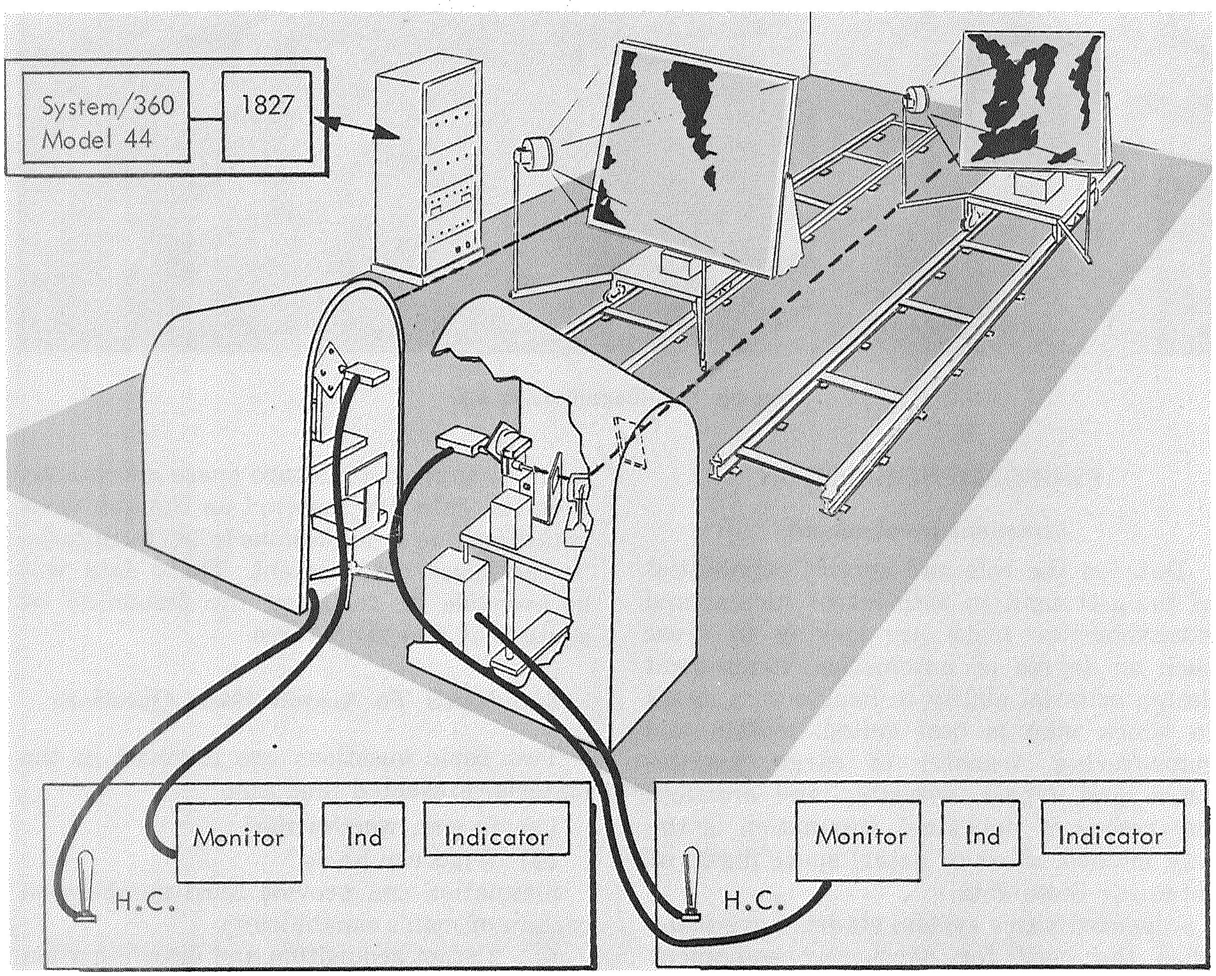

FIGURE 11.—Dual-station Earth-sighting simulator.

Earth-Sighting Simulator

Figure 11 provides a general view of the Earth-sighting simulator. The basic operating portion of the device consists of two optical sighting stations and two gimbaled mosaic holders mounted on tracks. The operator is provided with a view of a portion of Earth as seen from space with the proper Earth motion provided by moving the mosaic in response to precalculated computer commands.

Performance Obtainable on ESS and EVA Simulators

The Earth-sighting simulator has been used to provide numerical data on man's capabilities in target recognition and pointing and tracking. In addition, it has a flexibility that will allow it to be expanded to provide hard data on certain of man's capabilities:

(1) Equipment setup and calibration

(2) Target detection, acquisition, and recognition tracking (including interfering phenomena)

(3) Team activities

(4) Scheduling-time line analysis

(5) Training

(6) Multiple sensors

The EVA simulators provide data on man's abilities to operate required extravehicular equipment, for the evaluation of various techniques and equipment concepts, and for the establishment of astronaut training requirements to develop skills required for EVA.

Limitations of Earth-Based Simulations

Simulation has limitations; therefore, all of the necessary elements of the space environment cannot be combined in any single simulator.

The ESS is limited in that it includes no synergistic effects (vacuum, weightlessness, motion, etc.).

Zero-gravity flights in aircraft can produce weightlessness only for extremely short time periods of approximately 30 sec.

Water immersion tests are not time restricted, but the high damping effects produce unrealistic motions that normally would not be experienced in the vacuum of space.

In five- and six-degree-of-freedom "frictionless" platforms developed to study locomotion and maneuvering techniques, the additional mass of the simulator is connected to the astronaut and the resulting motions are seriously degraded from the expected motions in space. These complex simulators do not negate the ever-present $1g$ force on the astronaut's body, and when the man extends his arm, he still must support it against gravity, which would not be present in a true $0g$ field.

The computer-controlled simulators do not limit motions, distances, and orbital mechanics; however, they do not include elements such as temperature, vacuum, and weightlessness, nor the combined effects of long-term $0g$ on the man.

Although these simulators have their limitations, they do provide baseline data on astronaut performance, preliminary design requirements for equipment, and a means of training the astronauts in space operations.

Expected Results

The Earth-sighting simulator can directly provide the hard data on man's capabilities as a part of the data loop. Analysis of these data can provide a means for developing the specifications for technical requirements in improved man-machine interfaces: displays, controls, etc. In addition, data on optimal sampling rates for Earth survey missions could also be obtained.

Similarly, the EVA simulators will be used to provide data on man's capabilities to apply appropriate procedures to operate required extravehicular equipment. Analysis of these data will evaluate various equipment concepts and will identify design criteria for future spacecraft equipment that will simplify in-flight activities. In addition, data on assembling and erecting large structures in space will be obtained.

CONCLUSIONS

Man's Role in Space

Dynamic simulations are required to provide virtually nonexistent quantitative measurements of human perception capabilities and manipulative capabilities, under the constraints imposed by the space environment.

Although the astronauts have shown man's ability to perform some operational functions in space, man's ability as a perceptor and operator in space is still to be documented.

Sufficient operational data should be collected to evaluate equipment concepts and techniques for the best man-machine combination.

Man's capabilities can be used to perform unique functions and most efficient operations in space.

The value of the results expected from man's performance in space operations may be estimated in both economic benefits and scientific knowledge.

SESSION II

Life Support in Manned Space Flight

Chairman: **R. W. ENGEL**

Biological and Engineering Implications of Space-Cabin Atmospheres*

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Lovelace Foundation for Medical Education and Research
Albuquerque, N. Mex.

During the past several years, the selection of space-cabin atmospheres has become a major question in the planning of manned space programs. The severe limitation of weight and power available to the designer has made mandatory a detailed tradeoff study of the biological and engineering implications. Many of these considerations have already been covered in a series of studies for NASA (refs. 1, 2, 3, and 4). Only the more recent findings will be covered in this presentation.

The basic physiological and pathological factors in the selection of a space-cabin atmosphere are:

(1) Alertness and performance
(2) Communication
(3) Time of useful function
(4) Oxygen-toxicity syndrome
(5) Respiratory physiology:
  (*a*) Atelectasis
  (*b*) Hypoxia
  (*c*) Hypocapnia and hypercapnia
  (*d*) Hemoglobin control
(6) Decompression syndromes:
  (*a*) Baro-otitis and barosinusitis
  (*b*) Bends and chokes
  (*c*) Neurocirculatory collapse
  (*d*) Explosive decompression and aeroembolism
  (*e*) Ebullism syndrome
(7) Radiation sensitivity
(8) Fire and blast hazards:
  (*a*) Meteoroid penetration effects
  (*b*) Cabin fire control
(9) Bacterial flora changes and infections
(10) Water physiology
(11) Thermal control problems

The most prominent environmental and engineering factors to be considered are:

(1) Total pressure
(2) Partial pressure of oxygen
(3) Fire and blast hazard
(4) Diluent inert gas factors
(5) Humidity and temperature control
(6) Carbon dioxide control
(7) Toxic contaminants
(8) Dusts, aerosols, and ions
(9) Circulation of the atmosphere
(10) Leakage rate
(11) Decompression time after puncture
(12) Gravitational factors
(13) Weight, power, complexity, and cost

The absolute pressure chosen for a space-cabin atmosphere is determined primarily by the weight penalty for the cabin wall, although leakage, decompression time after puncture, and decompression sickness may be factors. The weight penalty is determined by the minimum structure required for flight loads as well as the consideration of hoop tension in the wall and meteorite puncture (ref. 4). These relationships are shown in figure 1 for a typical idealized space cabin.

The heavy line indicates that below 6 psia the wall thickness and weight may be determined by meteoroid penetration criteria in

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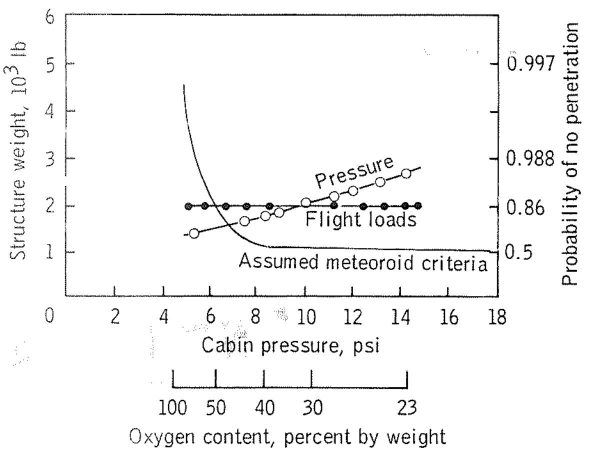

FIGURE 1.—Structural weight considerations for a vehicle having a volume of 2100 ft^3 and an area of 860 ft^2 for a mission of 1 yr and an O_2–N_2 system.[1]

the presence of atmospheres with high percentage of oxygen. From 6 to about 10 psia, flight loads may determine the weight penalty; above 10 psia, pressure considerations predominate. These curves may be shifted by different vehicle and mission constraints, especially those related to meteoroid and fire hazards. The curve below 6 psia is, therefore, most variable and uncertain.

The relationship between the pressure and percent of oxygen is determined by the partial pressure of alveolar oxygen required for normal function. This is seen in figure 2.

The curves are based on exposure for 1 week or more. To maintain the same degree of oxygen saturation in the blood as in air at sea level when total pressure is decreased, the percentage of oxygen in the atmosphere

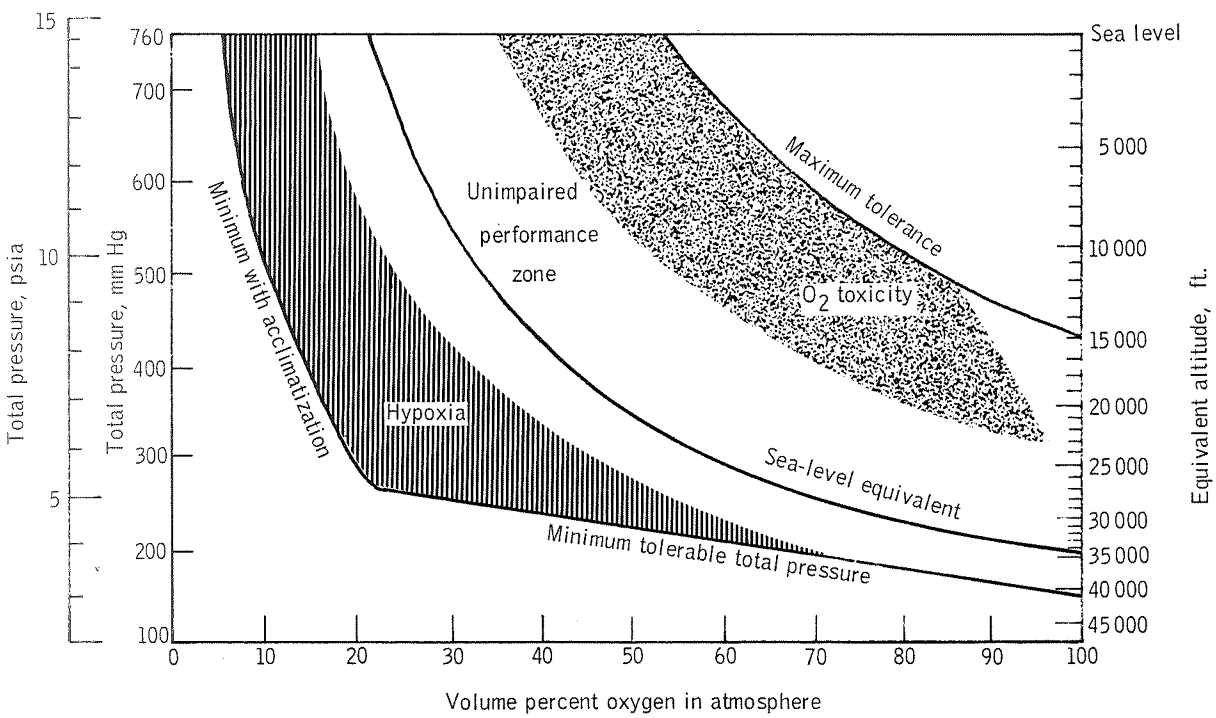

FIGURE 2.—Oxygen pressure effects[2] (ref. 5).

must increase as shown by the sea-level-equivalent curve.

The unimpaired performance zone (center clear zone) indicates the range of variation that can be tolerated without performance decrement. The maximum oxygen tolerance (definite pathology) for long periods is cur-

[1] BOEING COMPANY, ECS Flight Technology Group: Engineering Tradeoffs of Different Gas Systems Pertaining to the Selection of Space Cabin Atmospheres. Seattle, Wash., 1965 (unpublished data).

[2] U. C. LUFT: Oxygen Pressure Effects. The Lovelace Foundation for Medical Education and Research, Albuquerque, N. Mex., 1962.

rently under investigation. The role of nitrogen and trace contaminants on the symptoms of oxygen toxicity in the oxygen range of 90 to 100 percent is still open to question, as shown by the shaded right-hand area (refs. 1, 3, and 6).

Prolonged exposure to the low-oxygen levels illustrated to the left of the unimpaired performance zone requires special acclimatization. Acclimatization can be accomplished by continuous exposure to successively lower pressures, with little intermediate return to higher pressures. Optimal acclimatization to allow survival at 25 000 ft requires 4 to 6 weeks. The minimum tolerable total pressure is based upon the effective partial pressure of oxygen.

Oxygen toxicity is a fascinating problem that has received much consideration. Figure 3 summarizes the effect of the partial pressure of oxygen on the nature and time of onset of the symptoms.

Above 760 mm Hg, the central nervous system is the primary site of defect, with symptoms such as nausea, dizziness, convulsions, and syncope. In the range of 400 to 760 mm Hg, respiratory and nervous system symptoms predominate. These are substernal distress (bronchitis and probably atelectasis), paresthesias, and nausea. In the range of 200 to 400 mm Hg, reported symptoms are respiratory and, possibly, hematological and renal: atelectasis, oxidative hemolytic anemia, and protein and casts in the urine (refs. 1, 8, and 9).

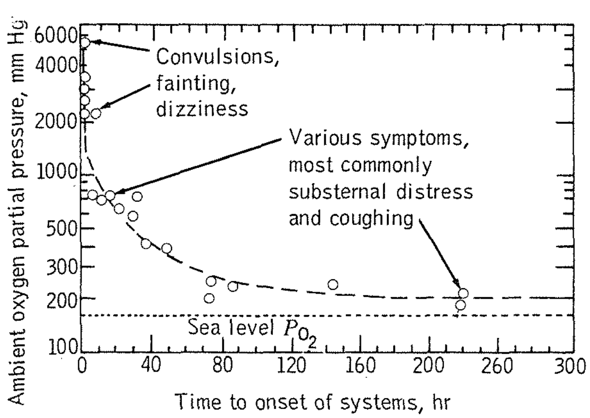

FIGURE 3.—Effect of partial pressures of O_2 (refs. 1 and 7).

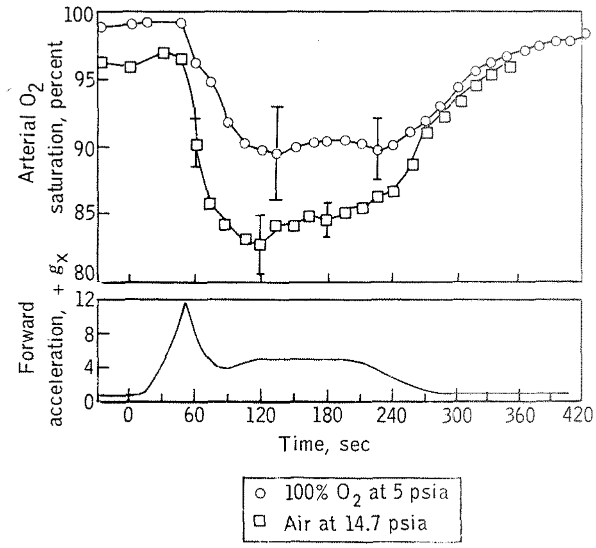

FIGURE 4.—Relief of hypoxia by 100 percent oxygen (ref. 10).

Early in the space program it was felt that aural and pulmonary atelectasis would be major problems associated with 100 percent oxygen. These have not proved to be significant in space flights to date. The high-*g* loads on takeoff and reentry have not aggravated the atelectatic tendency expected in 100 percent oxygen. Figure 4 indicates that during high-*g* loads the arterial unsaturation brought about by the expected alveolar ventilation-perfusion defect is somewhat alleviated by 100 percent oxygen. It is seen, however, that the resaturation rate in 100 percent oxygen is somewhat slower, probably because the reopening of alveoli is retarded in the absence of inert gas.

The alveolar collapse tendency is theoretically about 360 times greater in 5-psia oxygen than in air (ref. 11). Recent work suggests that persons susceptible to atelectasis under these conditions have bronchial systems with a much greater tendency to collapse during expiration (ref. 12). The ratio of pulmonary air conductance to lung volume appears to be a significant factor. This is seen in figure 5 where the curve for an atelectatic subject is compared with pre-

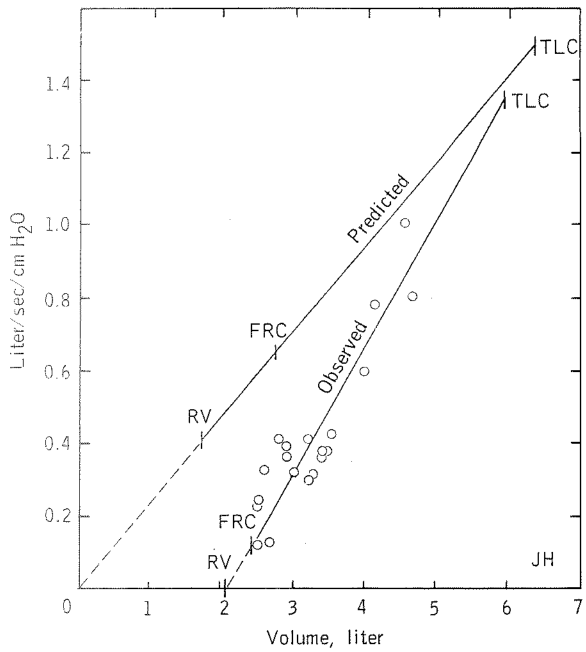

FIGURE 5.—Airway conductance measured at different lung volumes in a subject sensitive to atelectasis (ref. 12). Predicted values are shown by the line labeled "predicted." Residual volume, functional residual capacity, and total lung capacity, predicted and observed, are indicated on the graph.

dicted values. When this ratio, measured in (l/sec)/cm H_2O per liter of lung volume, is less than 0.13, atelectasis is seen after exposure to 100 percent O_2 at 5 psia. Fortunately, most normal subjects tested have ratios of greater than 0.14. This would suggest that selection of astronauts for resistance to atelectasis in 100 percent O_2 space-cabin environments may be practical. It is of interest that addition of only 5 percent nitrogen will alleviate the atelectatic tendency in the most susceptible subjects.

An atmosphere of 100 percent O_2 at 5 psia has a partial pressure of oxygen of 258 mm Hg, or 100 mm Hg greater than that of air at sea level. Use of this elevated oxygen pressure instead of the more normal 3.5 psia in the Mercury, Gemini, and Apollo programs has been dictated by the reliability and simplicity of atmosphere control and by the desire to maintain a pressure high enough to minimize the chance of pulmonary atelectasis, as well as to reduce the chance of decompression sickness early in the mission. Also, the selection of cabin pressure at 5 psia allows for a backup emergency suit circuit operating at 3.5 psia. This backup mode is automatically initiated when the cabin pressure falls below 3.8 psia. Another factor often mentioned in the choice of the higher pressure is the added safety factor of a longer decompression time in case of puncture of the sealed cabin.

Early studies on the toxicity of oxygen at 5 psia gave equivocal results. The oxidative hemolytic anemia and urinary findings reported by Helvey et al. (ref. 9) were not found in other studies (refs. 1, 7, 13, 14, 15, 16, and 17). However, there were slight decreases in hemoglobin attributed to decrease in exercise (refs. 18 and 19) and blood-letting. Recent findings in the Gemini program suggest that a hemolytic process was present during these flights. Figure 6 indicates the degree of loss of red-cell mass immediately postflight in Gemini 4, 5, and 7. In Gemini 7 there was a postflight overcompensation in plasma volume levels, but red-cell mass was still reduced. Hemolytic pat-

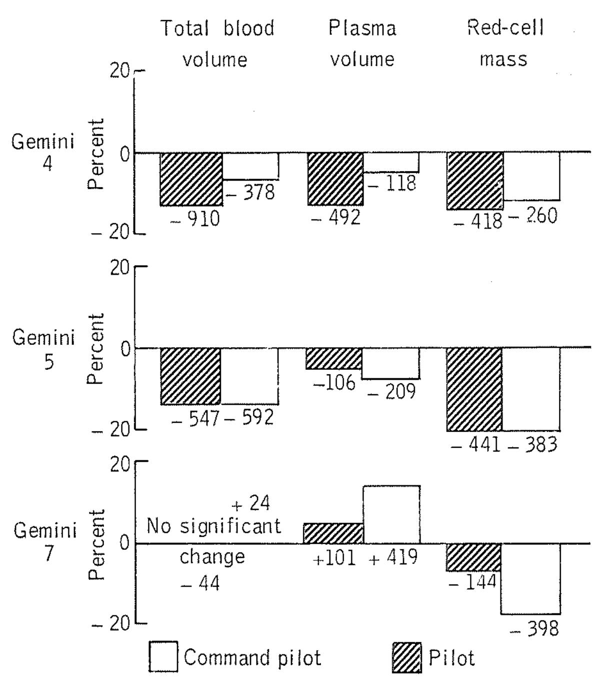

FIGURE 6.—Blood volume studies (ref. 20).

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terns are seen in table I showing little change beyond the 8-day mission.

TABLE I.—*Summary of Hematologic Findings From Gemini 4, 5, and 7 Missions*

[Ref. 21]

	GT-4	GT-5	GT-7
Days	4	8	14
Hematocrit	N	N	N
Reticulocytes		D	N
Total blood volume	D	D	N
Red cell mass, percent	D8	D20	D19
$T_{1/2}$ (^{51}Cr)		D	D
White blood count	I	I	I
Osmotic fragility			I
Serum bilirubin		N	N
Liver/spleen scan ratio, percent			I30

NOTE.—I means increasing; D means decreasing; N means normal.

Spiked red cells or acanthocyte-like cells were seen in the plasma of astronauts in Gemini 7 (ref. 8). In subsequent Gemini flights, a decrease of more than 50 percent in the antioxidant, tocopherol or vitamin E levels of the plasma were recorded, but no spiked cells were found (ref. 8). In these latter Gemini flights, changes in the plasma lipids suggesting, indirectly, the presence of lipid peroxides were also noted. These preliminary data suggest that the association of spiked cells, the degree of hemolysis, the decrease in plasma tocopherol, and lipid changes in the plasma or red-blood cells are not clear cut. Much more in-flight data are needed on the transiency of these factors and on the molecular processes involved in the decrease in red-cell survival.

Animal studies shed some light on the problem, but also indicate a vast species difference in this area. At the Aerospace Medical Laboratories of the USAF, monkeys, dogs, rats, and mice were exposed to 100 percent oxygen at 5 psia for 236 days, or 8 months (refs. 18 and 21). After about 2 weeks, a slight but significant fall in hematocrit, hemoglobin, and red-cell count was seen in monkeys. This stabilized rapidly so that at 90 days the average hematocrit and red-cell counts were essentially the same as at 2 weeks. No changes were seen in dogs. Both types of animals had a leukocytosis. After 8 months there were no changes beyond those seen at 3 months. Changes in the blood of rodents have been erratic, probably because of the species and strain differences often seen in oxygen toxicity studies of these animals (refs. 22, 23, and 24).

The possible mechanism of oxidative hemolysis has been discussed in detail (ref. 1). The recent studies of Pollack, George, and Crosby (ref. 25) have added to our knowledge of oxidative damage to the red cell. Mengel, Kann, Smith, Heyman, and coworkers (refs. 26 and 27) have demonstrated that the red blood cells on only tocopherol-deficient mice are sensitive to oxidative hemolysis with only high pressures of oxygen. In vitro, cells from these tocopherol-deficient animals are sensitive to hemolysis by hydrogen peroxide with the production of lipid peroxides. The red blood cells of dogs previously exposed to several atmospheres of oxygen are also sensitive to subsequent hemolysis by hydrogen peroxide in vitro with the elaboration of lipid peroxides (ref. 28). Even though the osmotic fragility was increased, there were no signs of Heinz bodies or elevated methemoglobin levels. Those studies suggest that absence of Heinz bodies or methemoglobin in the blood of space crews does not rule out a mild oxidative hemolysis. It is of interest that red cells of tocopherol-deficient humans show greater sensitivity to the in vitro hydrogen peroxide hemolysis test (ref. 29). It is also of interest that in the human congenital disease, acanthocytosis, spiked cells are present in association with a mild hemolysis (ref. 30). The disorder is caused by absence or deficiency of a plasma protein that binds tocopherol. The anemia is actually reversed by feeding of high levels of tocopherol. The marked difference in sensitivity of experimental animals and humans to red-cell changes after low overpressures of oxygen casts some doubt on the value of long-term animal experiments in evaluating pure oxygen atmospheres in man.

As previously mentioned, it is possible that the astronaut crews may have indeed been deficient in tocopherol. There is variation found in the levels of tocopherol in the Gemini diets.[3] When exposed to low levels of oxygen, they may have suffered from a mild form of oxidative hemolytic damage to the red cell with increased fragility as the only visible defect, giving a syndrome similar to acanthocytosis (ref. 30). High levels of tocopherol in the diet may also reverse these changes. The role of 0*g* and exercise in this syndrome is still not clear.

The role of peroxidation of lipids (refs. 25, 26, 31, and 32) and free radical peroxides (ref. 33) in this oxidative hemolytic process is now under study. Subtle changes in the oxidative or free-radical environment of red cells may have profound effects on the half life, on the function, and, less clearly, on the marrow production of these elements (refs. 1 and 21).

Effect of prolonged exposure to 100 percent O_2 at 5 psia on other organs of the body such as the lungs, liver, kidney, and gonads is under study (refs. 34 and 35).

In one report, altered renal function was found in man but no alteration of lung function was discovered other than atelectasis (ref. 9). Exposure of animals to 5 psia of pure oxygen for periods up to 8 months have led to interesting electron-microscopic changes in the liver and proximal tubules of the kidney (refs. 36, 37, and 38). The mitochondria of these organs proliferate, enlarge, and become distorted in shape with abnormal cristae. Less drastic changes in polysomes, golgi, and other organelles are also seen. After several weeks, these changes regress toward normal. Depending on the animal and the organ, minor residual alterations in the mitochondria and other cytoplasmic organelles do persist. It is not clear whether these are adaptive changes to the slight elevation of P_{O_2} within the cell or represent true pathological changes with altered function. Because air controls in these studies were not performed in chambers, there is a possibility that toxic contaminants in the chambers may have played a role. Studies of organ function under these conditions are presently underway. Mitochondrial changes of this type are seen most clearly with toxic agents that tend to uncouple oxidative phosphorylation. The most marked changes are seen with dinitrophenol and excessive thyroid hormone (ref. 38). No rise in protein-bound iodine (PBI) has been found in the serum of rats breathing 99 percent O_2 at 1 atm for up to 72 hr. In fact, a decrease in PBI was noted with no detectable microscopic changes in thyroid function (ref. 39).

It is possible that cells adapt to the slightly elevated P_{O_2} by uncoupling oxidative phosphorylation and that the mitochondrial changes are a manifestation of this response. With time, other antioxidant defenses may be brought to bear and the uncoupling is reduced. Liver mitochondria exposed in vivo to 100 percent O_2 at 5 psia do indeed show this uncoupling of oxidative phosphorylation (ref. 40). Studies of this uncoupling in mitochondria exposed to 100 percent O_2 at 5 psia are now underway.[4] The potential enzymatic targets for oxygen on the energy-generating cycles have already been reviewed (refs. 1 and 21). Recent studies by Chance (ref. 41) suggest that excessive conversion of reduced diphosphopyridine nucleotides to the oxidized form and the resulting interference with adequate function of the oxidative-phosphorylating mechanism is the most rapid and probably the prime defect that can explain the rapid effects of oxygen on cellular energetics. Study of the relationship of these findings to the subtle effects of low overpressures of oxygen appears to offer a fruitful area of research.

A parallel has been drawn with the mechanism of tissue damage seen in oxidation syndromes that follow radiation (refs. 1

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[3] D. CALLOWAY: Department of Nutritional Sciences, University of California, Berkeley, Calif., personal communication, 1966.

[4] B. E. WELCH: Chief, Environmental Systems Branch, School of Aerospace Medicine, Aerospace Medical Division, Brooks AFB, Tex., personal communication, 1966.

and 6). High pressure of oxygen has been used to sensitize tissue to radiation during X-ray therapy for cancer. Protective effects of antiradiation drugs against oxygen toxicity have also been shown. Synergism between low overpressures of oxygen and radiation is of great interest to space operations. At present there appears to be no requirement in future space cabin atmospheres for the alteration of shielding calculations because of the presence of 100 percent oxygen at 5 psia. However, several studies suggest that some synergism may be present. Benjamin (ref. 42) has shown that mice exposed to 750 R of gamma radiation from cobalt-60 given at 90 R/min have a survival about 10 percent lower in 100 percent oxygen at 5 psia than in air. At 900 R, given at a rate of 38 R/min, the synergism was much less. Kelton and Kirby (ref. 43), on the other hand, have exposed mice to 800 R of 250 KVP X-rays at only 14 R/min and have found no synergism with 100 percent oxygen at 5 psia. These data are shown in figure 7. The type, total dose, and the dose rate of radiation may be significant variables in these studies of synergism. Further study along this line is needed.

Presence of elevated partial pressures and percentage of oxygen does present a hazard to space operations as evidenced by the recent Apollo tragedy. A detailed analysis of fire and blast hazards in space operations is available (refs. 2 and 44). Both ignition

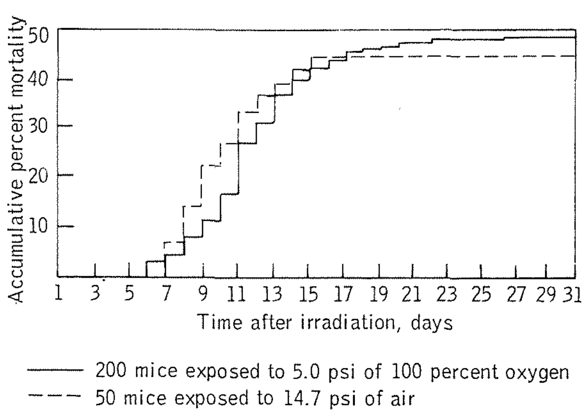

FIGURE 7.—Effect of 100 percent O_2 at 5 psi on radiation sensitivity (ref. 43).

and burning rates may be altered. The most dramatic change in ignitability is seen in the case of premixed hydrocarbon vapor or mist systems. Such would occur after the disruption of coolant or hydraulic lines. Figure 8 represents the effect of the percent of oxygen in an O_2–N_2 mixture on the ignitability and flammability limits of premixed propane systems. There are differences of several orders in magnitude between the ignitability of propane in air and in 100 percent oxygen at several different pressures.

Ignitability of solid materials under Earth gravity is seen in table II (refs. 46 and 47). There is surprisingly little difference between ignitability in air and in 100 percent O_2, or between equivalent N_2–O_2 and He–O_2 mixtures. The most significant anomalous points are those for O_2–He mixtures. It has been proposed that through high thermal conductivity, these atmospheres convect away the heat so rapidly that a wire embedded in the plastic must be raised to a higher temperature to ignite the plastic. This gives a high apparent ignition energy.

Flame-spread rates are significantly affected by atmospheric composition. Table III indicates that the differences between flame rates in air and in 100 percent O_2 at 5 psia vary up to several orders of magnitude. Addition of inert gas will decrease the rate twofold to threefold. There is little difference between He–O_2 and N_2–O_2 mixtures. On the whole, the rates are slightly faster in He–O_2 than in the corresponding N_2–O_2 mixture, but there are situations where the opposite is true.

The rate of flame spread is a complex function of the properties of the solid and such gas factors as molecular weight, thermal conductivity, heat capacity, and fraction of oxygen in the mixture (ref. 46). A critical gas factor in flame spread appears to be the heat capacity per mole of oxygen. The relationship is seen in figure 9.

This linear relationship holds for different materials, although slopes vary with material. The critical heat capacity per mole of O_2 above which there is no flame spread is the y-intercept of the curve and varies for

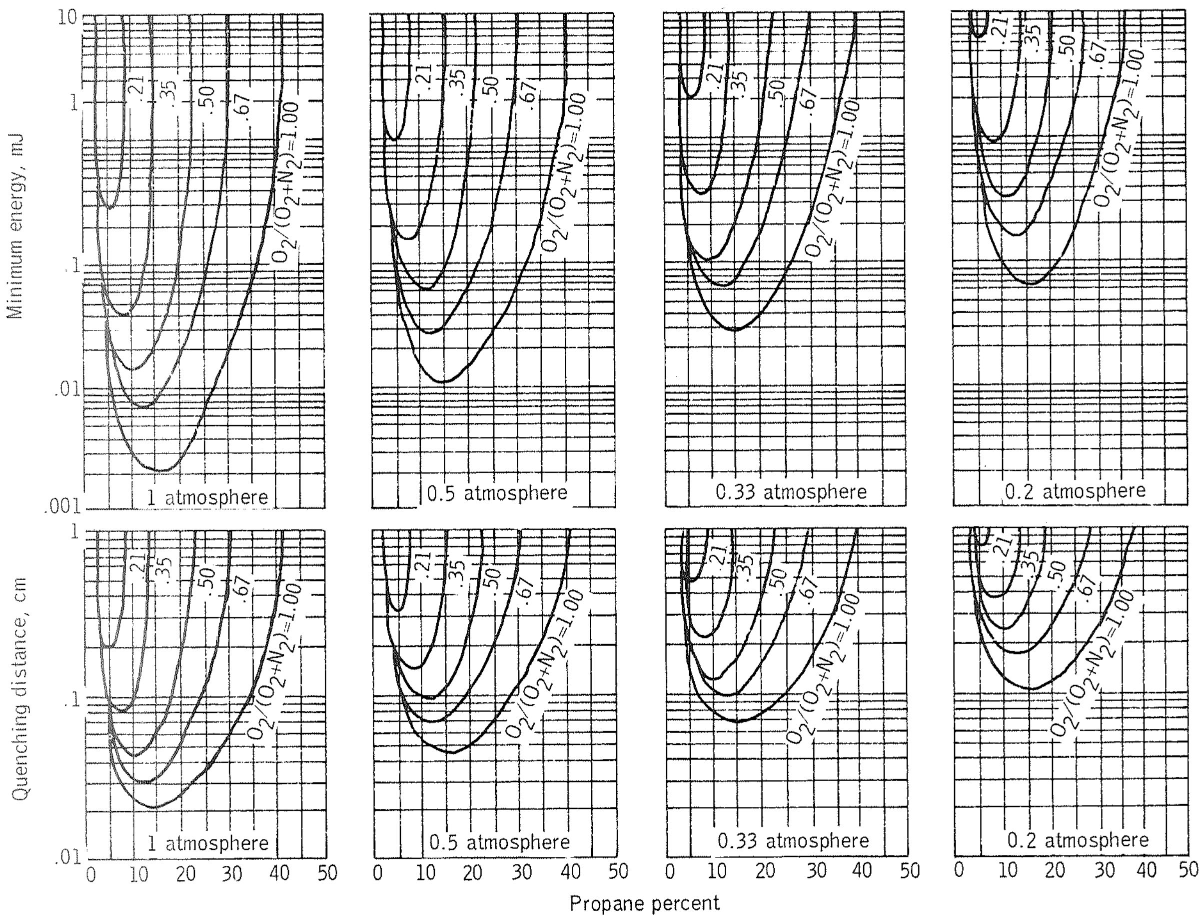

FIGURE 8.—Minimum spark-ignition energies and quenching distances between flanged electrodes for mixtures of propane, oxygen, and nitrogen (ref. 45).

TABLE II.—*Energy (cal/cm²) Required for Ignition of Materials in Various Atmospheres Using a Radiant Flux of 13.2 cal/cm²-sec*

[Ref. 46]

Material	Air, 760 mm Hg	20% O_2–80% He, 760 mm Hg	46% O_2–54% N_2, 380 mm Hg	46% O_2–54% He, 380 mm Hg	70% O_2–30% N_2, 258 mm Hg	70% O_2–30% He, 258 mm Hg	100% O_2, 258 mm Hg
Wood	[a] 25±1	109±11	25±2	24±0.5	25±1	22±1	23±1
Paper	32±1	39± 0.5	25±2	26±0.5	26±0.5	25±0.5	25±1
Cotton fabric	13±0.5	NI [b]	12±0.5	17±0.5	15±0.5	16±0.5	15±0.5
Plastic wire	20±1	NI	16±1	NI	17±1	46±1	16±1
Painted surface	30±1	NI	56±5	70±4	61±3	57±5	36±1

[a] Average deviation.
[b] No ignition of material.

TABLE III.—*Flame-Spread Rates (in. sec) for Materials in Various Atmospheres*

[Ref. 46]

Material	Air, 760 mm Hg	20% O_2–80% He, 760 mm Hg	46% O_2–54% N_2, 380 mm Hg	46% O_2–54% He, 380 mm Hg	70% O_2–30% N_2, 258 mm Hg	70% O_2–30% He, 258 mm Hg	100% O_2, 258 mm Hg
Wood	[a] 0.025 ± 0.025	0.04 ± 0.005	0.12 ± 0.02	0.18 ± 0.03	0.18 ± 0.03	0.27 ± 0.03	0.35 ± 0.03
Paper	0.08 ± 0.01	0.30 ± 0.06	0.42 ± 0.02	0.63 ± 0.05	0.55 ± 0.05	0.74 ± 0.06	0.90 ± 0.07
Cellulose acetate	0.008 ± 0.002	----	0.11 ± 0.01	0.15 ± 0.02	0.20 ± 0.03	0.18 ± 0.02	0.30 ± 0.01
Cotton fabric	0.10 ± 0.01	0.17 ± 0.01	0.9 ± 0.3	1.1 ± 0.1	1.8 ± 0.2	1.2 ± 0.2	3.2 ± 0.2
Foam cushion	0.14 ± 0.02	0	2.7 ± 0.8	2.1 ± 0.3	6.1 ± 0.5	6.0 ± 0.6	13 ± 1
Plastic wire	0	0	0.25 ± 0.01	0.35 ± 0.02	0.48 ± 0.01	0.60 ± 0.02	0.84 ± 0.03
Painted surface	0	0	0.21 ± 0.01	0.27 ± 0.01	0.32 ± 0.02	0.42 ± 0.06	0.45 ± 0.05

[a] Average deviation.

each material undergoing combustion. The rate of flame spread at constant atmospheric composition is approximately independent of pressure over the range of 258 to 760 mm Hg.

Studies of plastics burning in closed chambers containing 100 percent O_2 at 5 psia and in other gas mixtures during 0*g* parabolic flight maneuvers suggest that the 0*g* factor in suppressing flame propagation may more than compensate for the increased flammability in 100 percent O_2 (refs. 48, 49, and 50). However, the lack of forced convection in the closed system during simulation is somewhat unrealistic and may give a false sense of safety. On the other hand, it should be remembered that in actual space vehicles a nearly zero-convection state can be readily attained by merely shutting off circulation fans soon after the fire has been discovered. Future 0*g* studies are being planned to include forced convection at levels similar to those expected in operational space cabins. One must, however, always keep in mind the fire hazard during the positive-*g* phases of launch and reentry.

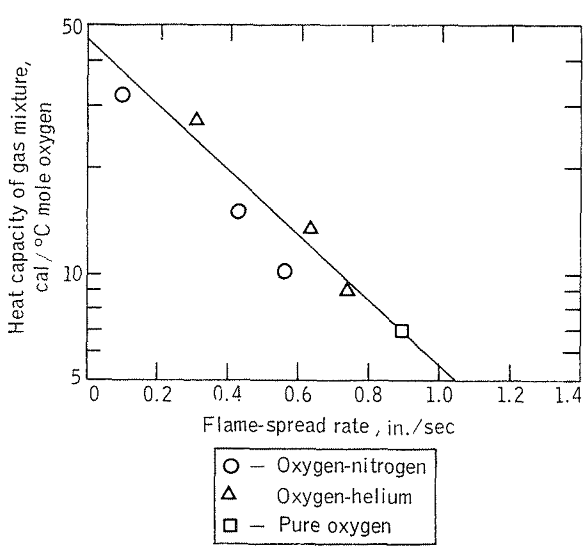

FIGURE 9.—Flame-spread rate for paper versus heat capacity of atmosphere (ref. 46).

In summary, presence of inert gas reduces the apparent ignitability and combustion rate for most solid and gaseous fuels. N_2–O_2 mixtures appear slightly more safe than equivalent He–O_2 mixtures. However, overheated wires have a significantly lower apparent ignitability in He–O_2 than in N_2–O_2. The overall choice between the two mixtures is difficult. The greater the percent of inert gas, the safer the mixture.

Presence of inert gas in the atmosphere raises the possibility of decompression sickness (ref. 3). One must consider the frequent but less serious bends, the less frequent but more serious chokes, and, finally, the very rare but very lethal neurocirculatory collapse syndrome. Several theoretical studies of the hazard of bends in space operations suggest that in the case of bends, Ne–O_2 would be slightly safer than either He–O_2 or N_2–O_2, but that the latter two would be of about equal hazard (refs. 3 and 51). These conclusions were approached independently from the point of view of rate of macrobubble growth as well as initiation of microbubbles. The other inert gases appear more hazardous. In the case of chokes or neurocirculatory collapse, Ne–O_2 appears, theoretically, far safer than the other two mixtures (ref. 3). Empirical data cover only He–O_2 and N_2–O_2 (ref. 51). The former gives a slightly higher bends incidence than does the latter in decompressions simulating the USAF MOL mission profile. These studies were performed in the unsteady state while the body still had significant amounts of N_2 in the slowly exchanging tissues and variable amounts of He and N_2 in the rapidly exchanging tissues. No empirical data on relative decompression hazard are available for steady-state gas conditions after 12 or more hours' equilibration in different gas mixtures. Such data are sorely needed.

Unfortunately, the halftime of tissue inert-gas exchange in rodents is measured in minutes and can, therefore, not be used to evaluate cabin atmospheres. Goats or miniature swine may be of value in this regard (ref. 3). Data are needed on the effects of Ne–O_2 in animals and man. Preliminary studies in the Royal Navy suggest that Ne–O_2 may be superior to N_2–O_2 in diving.[5] An attempt has been made to predict the incidence of bends following decompression from space-cabin atmospheres at equilibrium conditions (ref. 3). Analysis of limited World War II data and recent USAF studies suggest that these predictions are of the right order of magnitude (refs. 3 and 51). Prior equilibration with 50 percent O_2 and 50 percent N_2 atmospheres at 7 psia and subsequent decompression to spacesuit pressures of 3.5 psia should lead to less than 1.0 percent bends symptoms at rest and 7 to 10 percent symptoms with severe exercise. If 5-psia suits are used, there should be about one-third of this incidence. Prior equilibration to 30 percent inert-gas mixtures at 5 psia should lead to considerably lower symptoms than those quoted for the mixtures at 7 psia. Unfortunately, no data are available on the timed denitrogenation of astronauts who are older than the typical World War II pilots but are possibly in better physical condition. Such data would allow more realistic prediction. The use of new analog computer techniques in simulation of ascent schedules in diving suggest their use in predicting bends hazards in the many different mission patterns of space operations (refs. 3 and 52).

Another major factor determining the selection of inert gases in space cabins is the danger of explosive decompression. In addition to the external trauma that may befall a crewman following disruption of a spacesuit or cabin, damage to his lungs from explosive decompression is possible. The theoretical analyses of Haber and Clamann (ref. 53) and Luft (ref. 54) indicate that the mechanical effects upon the body are dependent upon the change in absolute pressure, the ratio of initial pressure to final pressure, and the rate of decompression. The pressure transients during the event can be defined in terms of the decompression-time characteristic of the cabin or suit and the lungs.

It has been demonstrated that if the time characteristic of the human lung and airway is greater than the time characteristic of the pressure suit or cabin in which an individual is confined during the decompression, a transient differential pressure will build up between the lungs and ambient atmosphere (refs. 54, 55, and 56). The mammalian lung may become disrupted by pressure differentials of over 80 mm Hg. If this pressure differential is exceeded during decompression, the lungs may be damaged. Because the volume of the lungs varies with phase of respiration, it is obvious that the time characteristic of the lungs may also vary accordingly. The pressure differential across a lung and degree of hazard would, therefore, be maximal with a narrow glottis in full inspiration. The volume/hole area ratio of the cabin relative to the lung volume/tracheal area ratio of the crewman determines the

[5] P. BENNETT: Royal Naval Physiological Laboratory, Alverstoke, Hants, England, personal communication, 1966.

critical pressure differential. These are called V/A ratios. Luft has reviewed the literature on critical V/A ratios and found that the maximum cabin ratios able to cause death were 3 m^3/m^2 (ref. 57). In studies with animals that have lower pulmonary V/A ratios than human beings, and can, therefore, tolerate lower cabin V/A ratios, the LD_{50} (the dosage lethal to 50 percent) occurs at cabin V/A ratios of 1.2 m^3/m^2 and the LD_{100} at 0.12 m^3/m^2. This would suggest that in the 50-cu-ft cabin of Project Mercury, a hole in excess of greater than 1.0 ft^2 in area would probably have to appear suddenly to incapacitate the crewman. Because the direct mechanical trauma by the agent causing the hole would probably kill the crewman, the lung factor will probably play a secondary role. Nevertheless, a comparison of the relative hazard imposed by different gas systems is of interest.

There appear to be two major factors: hemorrhage from the disrupted lung and introduction of gas emboli into the venous side of the pulmonary circulation with subsequent infarction or blockage of critical sites in the systemic circulation. It appears that an inert gas factor would play a role at two points in the overall sequence of events. The inert gas may determine the flow characteristics through the pulmonary tree or the glottic orifice as well as determine the size characteristic of the gas bubbles being sent to the peripheral systemic circulation. The flow of gas through the respiratory tree, as mentioned above, is a critical factor in lung damage during "explosive" decompression. A rigid analysis of the flow factor has been performed by Bowen, Holladay, Fletcher, and White (ref. 58) in their mathematical model of the fluid-mechanical response of the thoracoabdominal system to blast overpressure and "explosive" decompression. A review of the gas-dependent factors in their model leads to the conclusion that the rate of pressure change in the lung with respect to ambient pressure is a function of the product of the reciprocal of the square root of the average molecular weight of the gas MW_g and the adiabatic gas flow factor involving the specific heat ratio γ. The lower this rate of pressure change with respect to ambient, the more dangerous is the atmosphere. This same relationship would define the hazard from external blast overpressure resulting from meteoroid pene-

TABLE IV.—*Relative Hazards of Gas Mixtures at 7 psia, 50 percent Inert Gas, 50 percent O_2 in "Explosive" Decompression and Blast Overpressure*

[Ref. 2]

Factor	Gas mixture in cabin						
	$He\text{-}O_2$	$Ne\text{-}O_2$	$Ar\text{-}O_2$	$Kr\text{-}O_2$	$Xe\text{-}O_2$	$N_2\text{-}O_2$	O_2
$\frac{1}{(MW)_g{}^{1/2}}$	0.34	0.20	0.17	0.15	0.13	0.18	0.18
γ (50 percent adiabatic)	1.25	1.25	1.25	1.25	1.25	1.20	1.20
Isothermal expansion (γ=1) $\left(\frac{dP}{dt}\right)_{t=0}$	.34	.20	.17	.15	.13	.18	.18
Relative hazard index ($N_2\text{-}O_2$=1)	.53	.90	1.1	1.2	1.4	1.0	1.0
Polytropic expansion (50 percent adiabatic) $\left(\frac{dP}{dt}\right)_{t=0}$	.26	.15	.13	.11	.10	.13	.13
Relative hazard index ($N_2\text{-}O_2$=1)	.50	.87	1.0	1.2	1.3	1.0	1.0

tration or military action (ref. 2). Table IV presents an analysis of the relative hazard of explosive decompression and blast hazard for isothermal and polytropic expansions (50 percent adiabatic) of gas, thus covering the expected range of thermodynamic flow patterns (ref. 3). The gas mixtures were 50 percent inert gas and 50 percent O_2 at 7 psia. It can be seen that there is little difference in hazard determined by thermodynamic nature of the expansion. $He–O_2$ appears to be about 0.5 times as hazardous as $N_2–O_2$; $Ne–O_2$ about 0.9 times as hazardous. These are, of course, the maximum differences expected. A 5-psia cabin with only 30 percent inert gas would show far less difference between gases.

Most second-order factors would probably tend to decrease the relative molecular-weight dependence. For example, the rate of gas escaping from the cabin is also dependent on molecular weight. However, when one reviews the cabin V/A ratios required for lethality in animals, it is evident that the cabin pressure will have essentially reached ambient well before the flow of gas out of the respiratory tree has ceased. Any overlap of these flows would reduce the molecular-weight dependence. One would, therefore, predict that the smaller the cabin hole, the less gas dependent is the decompression hazard. Unfortunately, there are no direct experiments covering the inert-gas factors in explosive decompression.

Another problem to be faced in space operations is the ebullism syndrome (refs. 3 and 59). Exposure to altitude where the total ambient pressure approaches the effective vapor pressure of fluids at body temperature gives rise to the profuse evaporation associated with formation of vapor bubbles in tissues, blood vessels, and body cavities. In his excellent theoretical analysis of this phenomenon, Ward pointed out the physicochemical considerations that define the site and nature of vapor bubbles throughout the body (ref. 60). He recommended that the syndrome be named "ebullism," and this name has been accepted by the scientific community.

Body fluids begin to vaporize at 63 000 ft. Selection of vapor site is determined by such local factors as temperature, hydrostatic pressure, tissue elasticity, solute concentration (Clausius-Clapeyron factors), and presence of gas nuclei. As would be expected from these considerations, the large venous channels at the center of the body-temperature core are sites of early bubble formation resulting in vapor lock of the heart. Subsequently, vapor pockets forming in the loose subcutaneous tissue are often seen, as are vapor bubbles in the aqueous humor of the eye and in the brain.

The survival and functional capabilities of animals exposed to altitudes above 100 000 ft are currently being studied in great detail (refs. 61–65). Decompressions up to 130 000 ft (2 mm Hg) result in violent evolution of water vapor with swelling of the whole body of dogs. Preliminary results indicate that dogs kept as long as 90 sec at 2 mm Hg do not present a single fatality. The animals were unconscious, gasping, and had bradycardias down to 10 beats/min from the normal rate of 159 beats/min, possibly a vagal response caused by distortion of the mediastinal structures resulting from sudden expansion of the thorax. Most also had paralysis of hind limbs, but walked about normally after 10 to 15 min at sea level. In animals exposed beyond 120 sec, death did occur most frequently. Autopsy of surviving animals exposed less than 120 sec tended to show damage to the lung in the form of congestion, petechial hemorrhage, and emphysematous changes. Denitrogenation appeared to reduce the incidence and severity of lung damage. For the exposure of more than 120 sec, gross examinations of the brain and other organs showed increasing amounts of congestion and hemorrhage with time at altitude. Exposure of squirrel monkeys resulted in similar findings (ref. 65). Many of the survivors of 90-sec exposure showed various defects in locomotion, hearing, vision, and food retrieval, and lost more weight than the control groups. Of interest, however, is the fact that among the survivors there was no loss of proficiency in learning set. Koestler found that the chimpanzee can survive, without apparent central-nervous-system damage (as measured by complex task performance), the effects of decompression to a near vacuum for up to 2.5 min and return within approximately 4 hr to baseline levels of functioning (ref. 64). Further research in which the replication of longer duration is accomplished, perhaps with several different primate species, should determine the reliability of these findings and suggest the degree to which animal results may realistically be extrapolated to man.

What is the major cause of death during decompression to ebullism altitudes? From the animal studies, it can be inferred that cardiovascular collapse will be most precipitous. After exposure to subebullism altitudes, there is a dramatic fall in blood pressure, followed by rebound with subsequent anoxic failure. At ebullism altitudes one can expect vapor lock of the heart to result in complete cardiac standstill after 10 to 15 sec, with increasing lethality for exposures lasting over 90 sec (ref. 62). Vapor pockets have been seen in the hearts of animals as soon as 1 sec after decompression to 3 mm Hg (ref. 63). Analyses of the changing gas compositions of subcutaneous vapor pockets by different investigators have given equivocal results (ref. 3).

The initial water vapor cavity is filled after several minutes with CO_2 and inert gas. The inert gas does not return into solution after recompression and may pass to the heart, lungs, and brain to give infarcts. The greater the permeation coefficient or product of solubility and diffusibility of the gas mixture, the more rapidly the inert gas enters the bubbles (ref. 3). Ne would, therefore, have the least tendency to enter, with He and N_2 as close seconds. Empirical data on the relative hazard of the inert gases under ebullism conditions have yet to be obtained.

Man has been exposed for up to 56 days in an atmosphere of 70 percent O_2 and 30 percent He without significant metabolic defects noted (refs. 66 to 76). Minor respiratory alterations due to low gas density were reported. The effects of helium on animals and tissue preparations have been recently reviewed (ref. 3). There are no metabolic defects noted in adult animals that cannot be attributed to thermal conductivity factors and excessive heat loss. Embryonal, microbial, and tissue-culture responses appear to be related to as yet unknown enzymatic alterations brought about by exposure to He. These cellular changes may play a role in altering metabolism in man, but as noted above, there is no evidence of change under spacecraft atmospheric conditions of He–O_2 in man. Extension of human exposure to He–O_2 beyond 56 days in spacecraft should probably be preceded by day-for-day simulation on the ground. Less stringent ground-based simulation is required for O_2–N_2 mixtures. No data are available on chronic exposure of man to Ne–O_2 atmospheres. There is no reason to expect any significant metabolic changes.

Alteration of the thermal environment by addition of inert gases does require some consideration. Figure 10 represents the alteration of thermal conductivity by different oxygen and inert gas mixtures at sea-level pressures and shows the significant changes produced by addition of helium.

Other thermodynamic factors have also been recorded for proposed space-cabin atmospheres (ref. 4). The increased rate of heat loss in He–O_2 mixtures requires a review of the thermal comfort zones. Figure 11 compares the comfort zones in the range of mean skin temperature of 91° to 94° F for 50 percent inert gas and 50 percent O_2 at 7 psia under 1-clo insulation at different gas-flow rates. There is only very slight increase in comfort temperatures in the He–O_2 mixture over the N_2–O_2 mixture. Predictions of comfort zones under different clo values and gas compositions are available (ref. 4).

Empirical data obtained in the USAF space-cabin simulator by recording voluntary thermostat settings by subjects in different atmospheres under about 1/4 to 1/5 clo are noted in table V. Gas velocity was probably less than 50 ft/min.

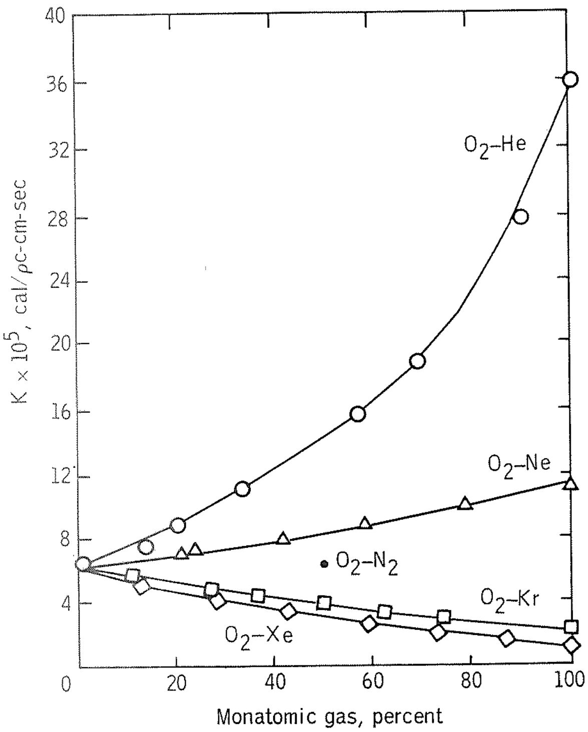

FIGURE 10.—Thermal conductivity of O_2–He, O_2–Ne, O_2–Kr, and O_2–Xe mixtures at 30° C (ref. 77).

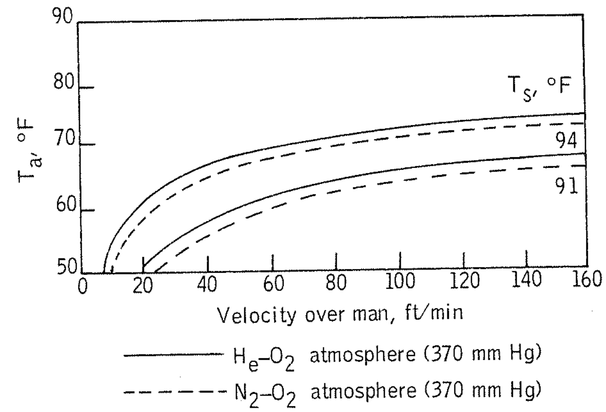

FIGURE 11.—Comfort lines for man seated at rest with 1 clo. The P_{O_2}=170 mm Hg and P_{N_2} or P_{He} =200 mm Hg (ref. 78).

Voice changes in the presence of helium do not appear to be a significant communication factor in space-cabin conditions because of the high percent of O_2 and low partial pressure of the gas system (refs. 3 and 79).

The engineer must consider several factors in comparing different gas systems as atmospheres in space cabins. These are summarized as follows:

(1) Weight:

(*a*) Structure of cabin wall

(*b*) Atmospheric leakage

(*c*) Tankage for gas

(*d*) Weight-power penalty for air-conditioning system:

(i) Cabin ventilation fan

(ii) Atmosphere processing fan

(iii) Equipment cooling fan

(iv) Cooling system pumps, reservoirs, tubes, valves, radiator, and heat exchangers

(*e*) Reliability factors

(2) Transient phenomena:

(*a*) Decompression time after puncture

(*b*) Transient overloads from environmental control system failure

(3) Power-system factors:

(*a*) Fuel cells

(*b*) Solar cells

(*c*) Nuclear systems

(4) Economic and operational factors:

(*a*) Development time

TABLE V.—*Temperatures Selected by Subjects in Space-Cabin Simulators*[a]

	3.7 psia, 100-percent oxygen	5 psia, 100-percent oxygen	5 psia P_{O_2}—175 mm Hg P_{He}—74 mm Hg	7.3 psia P_{O_2}—150 mm Hg P_{He}—230 mm Hg	7.3 psia P_{O_2}—165 mm Hg P_{N_2}—206 mm Hg
Selected temperature, °F	69.3	70.9	74.7	75.4	72.7

[a] See footnote 4, p. 60.

(*b*) Use of existing hardware and equipment

(*c*) Maintenance and convertibility

(*d*) Crew acceptance

(*e*) Contaminant buildup

(*f*) Qualification testing

(*g*) Environment for in-flight experiments

(*h*) Complexity of design and operation

(*i*) Cost

The more pertinent of these factors will be discussed.

The relation between pressure and the weight penalty for cabin-wall structure has already been covered (fig. 1).

Atmospheric leakage through small holes about seals has been reviewed by several investigators and found, on a pound basis, to favor the use of Ne and He systems over N_2 systems. This is seen in table VI where several independent calculations using capillary flow are recorded.

TABLE VI.—*Comparison of Mass Leak Rates*

[Ref. 4]

Mass leak rate, lb/day							Study
5 psia					7 psia		
100 percent O_2	70 percent O_2 30 percent He	70 percent O_2 30 percent Ne	70 percent O_2 30 percent N_2	50 percent O_2 50 percent He	50 percent O_2 50 percent Ne	50 percent O_2 50 percent N_2	
1.0	0.811	0.702	0.988	1.13	0.810	1.70	(Ref. 80)
1.05	.76	....	1.05	1.08	....	2.0	([a])
1.0	.72	....	1.00	1.02	....	1.90	Normalized to 5-psia O_2=1 lb/day [a]

[a] See footnote 1, p. 56.

A detailed review of tankage, power, and storage weight penalties for different oxygen and inert-gas systems is available but is beyond the scope of this presentation (ref. 4).

The time of useful consciousness available after acute cabin decompression may be a significant safety variable under many mission conditions (refs. 4, 79, and 81). Table VII compares the time to reach hypoxic levels of Po_2 in a specific cabin volume under different hole sizes and flow modes. The higher pressure systems and N_2 gas give the longest times of decompression. Graphic solution of this problem for other V/A ratios is available (ref. 4).

Power penalties for the air-conditioning system must be considered. Figure 12 is a schematic diagram of the three types of fans that must be considered. Presence of the suit in the loop has a significant role in the overall power weight penalty (ref. 4).

It can be shown that for the contaminant

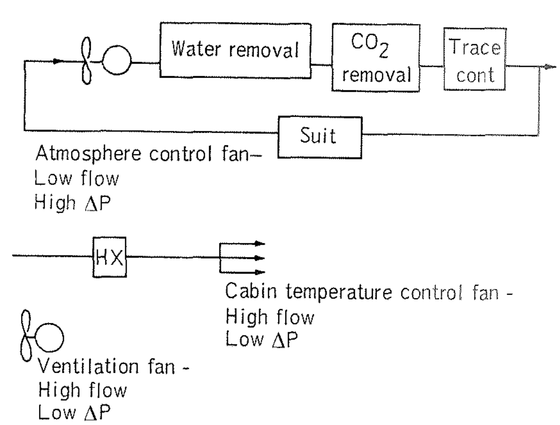

FIGURE 12.—Typical environmental control system. (See footnote 1, p. 56.)

TABLE VII.—*Decompression Time to Minimum Tolerable Total Pressure as Determined by Minimum Acceptable P_{O_2}*

[Cabin volume=770 ft^3; orifice coefficient=1[a]]

Leak mode	3.5 psia O_2 3.5 psia N_2 7.0 psia	3.5 psia O_2 3.5 psia He 7.0 psia	3.5 psia O_2 1.5 psia N_2 5.0 psia	3.5 psia O_2 1.5 psia He 5.0 psia	5.0 psia O_2
	Decompression time, min				
Isothermal—½-in. hole	6.17	4.72	2.25	1.93	5.42
Isentropic—½-in. hole	4.54	3.22	1.62	1.35	3.95
Isothermal—¾-in. hole	2.75	2.1	1.0	.86	2.41
Isentropic—¾-in. hole	2.03	1.42	.72	.59	1.75

[a] See footnote 1, p. 56.

TABLE VIII.—*Power Penalties for Thermal-Control Fan Assuming Equal Convective Heat-Transfer Coefficients*[a]

	O_2–N_2		O_2–He		O_2
	7.0 psia	5.0 psia	7.0 psia	5.0 psia	5.0 psia
k, Btu/hr-ft-°F	0.0153	0.0153	0.0386	0.0286	0.0155
ρ, lb/ft^3	0.0365	0.0268	0.022	0.0206	0.0279
$\bar{V}$, ft/min	47	64	12.5	25	60
Power, W	63	62	10	19	61
Relative power	1	0.98	0.16	0.30	0.97

[a] See footnote 1, p. 56.

removal fan of constant cubic feet per minute (CFM) output, the limiting horsepower is roughly proportional to the density ρ of the atmosphere. For the cooling fans (heat exchangers of low ΔP), the power is roughly proportional to the reciprocal of the square of the density and cube of the heat capacity ($\sim 1/\rho^2 C_p^3$) (refs. 4 and 78).

Assuming equal convective heat-transfer coefficients for the different gas systems, the relative power for the temperature-control system can be estimated as seen in table VIII.

It can be shown that the removal of water vapor from the atmosphere is the limiting factor for power utilization in the contaminant removal system. The power required to remove a given mass of water from the gas stream can be shown to be a proportional to the molecular weight of the gas mixture (ref. 4). If 100 W are required by an O_2–N_2 system at 7 psia, the power for water removal in the other gas systems of table VIII is seen in table IX.

TABLE IX.—*Power Required To Remove Water From a Gas Stream*

[Relative to 7-psia oxygen-nitrogen system=100 W[a]]

System	Power, W 7 psia	Power, W 5 psia
Oxygen-nitrogen	100	72
Oxygen-helium	60	53
Oxygen	....	72

[a] See footnote 1, p. 56.

TABLE X.—*Expendable Fluid Requirements and Total ECS Weight Penalties for a 30-Day, 2-Man Orbiting-Laboratory Mission*[a]

[All values in lb; ref. 83[a]]

Function	7 psia		5 psia		
	3.5 psia O_2 3.5 psia N_2	3.5 psia O_2 3.5 psia He	3.5 psia O_2 1.5 psia N_2	3.5 psia O_2 1.5 psia He	5.0 psia O_2
Oxygen tankage	42.7	42.4	41.0	40.9	46.3
Diluent tankage	89 (15.4)	93 (32.8)	76 (6.4)	48.5 (12.4)	—
Total tankage	131.7 (58.1)	135.4 (75.2)	117 (47.4)	89.4 (53.3)	46.3
Total O_2 system	372	367	357	355	402
Total diluent system	174 (101)	105 (44.6)	108 (96)	53 (17.0)	—
Total gas storage	546 (482)	472 (412)	465 (453)	408 (372)	402
Dehumidification	100	60	72	53	72
Ventilation	63	10	62	19	61
Total fan power	163	70	134	72	133
Controls	15	15	15	15	—
Total ECS penalty	724 (660)	557 (497)	614 (602)	495 (459)	535
ΔW	0 (−64)	−167 (−227)	−110 (−122)	−229 (−265)	−189
ΔW	+189 (+125)	+22 (−38)	+79 (+67)	−40 (−76)	0

[a] See footnotes 1 and 8, p. 56 and below.

Because of operational and design restraints, tradeoff studies for total environmental control system (ECS) weight penalties must be specific for each mission. Overall weight penalties for O_2, inert diluent, storage of these gases; ventilating power, dehumidification power, and control systems have been compared for different gas systems in a two-man orbiting laboratory and 30-day mission (ref. 4). Calculations of several independent studies have been compared[6–8] (ref. 82). Table X indicates the overall weight penalties using conservative and liberal (those in parentheses) values for He and N_2 diluent and storage penalties. Under the limitation of a 50 ft/min ventilation rate, the 5-psia O_2–He system appears to have the lowest weight penalty by as much as 200 lb. Figure 13 represents pressure sensitivity of total weight penalties assuming that the gas mixtures are set to give an alveolar P_{O_2} of 102 mm Hg. Flow rates are variable and optimized to give a minimum power penalty for each mixture. Under these assumptions, the O_2–He system at 7 psia gives a minimum weight by a factor of about 150 lb over the minimum weight of O_2–N_2 system.

The saving of several hundred pounds in

[6] See footnote 1, p. 56.

[7] LOCKHEED MISSILES & SPACE CO., Bioastronautics Division, Sunnyvale, Calif., private communication, 1965.

[8] J. MASON AND J. POTTER: AiResearch Mfg. Co., division of Garrett Corp., Los Angeles, Calif., personal communication, Mar. 1966.

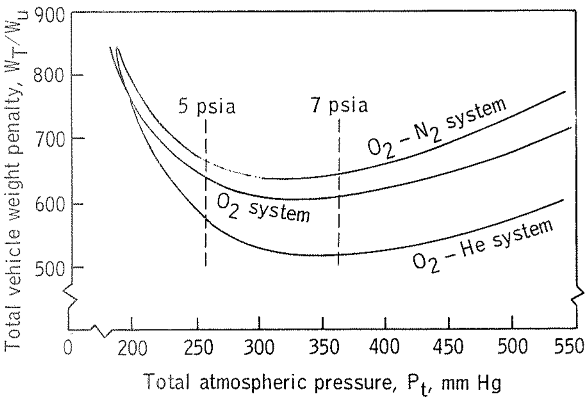

FIGURE 13.—Total vehicle ECS weight penalty for different gas systems with gas velocity optimized for each system in a 2-man, 30-day orbiting laboratory mission (ref. 82).

a 10 000-lb orbiting vehicle may or may not be significant in any given mission. One must, therefore, combine this weight savings with weighted factors of physiological and engineering hazards and mission constraints in choosing the ideal atmosphere for any space operation.

It must be emphasized that these total ECS penalties are for a specific mission type and cannot be directly extrapolated to other missions. Even the weight ratios for different gas mixtures cannot be used for other missions. These data have been presented only as an example of the interaction of biological and engineering variables in selection of space-cabin atmospheres.

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Atmospheric-Control Systems for Extended-Duration Manned Space Flight

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The subject of this paper is atmospheric control for manned spacecraft for missions of longer than 60 days' duration. Atmospheric-control systems may be defined as the hardware systems necessary to provide a habitable environment for man, including the following: carbon dioxide removal, water vapor removal, oxygen and nitrogen provision, contaminant control, and temperature control. This discussion is confined to the first three of these factors; namely, CO_2 removal, water vapor removal, and O_2–N_2 provision.

Man, existing in any near-leak-free vessel, such as a spacecraft, must be provided with certain environmental controls, so that the atmosphere will provide both comfort and support for his needs. Man in a living habitat may be pictured crudely as analogous to a hydrocarbon-fueled engine; he consumes O_2 by the oxidation of hydrocarbons, giving off both CO_2 and water vapor from this oxidation, as well as heat energy and contaminants. He operates best within a fairly narrow range of variables within this environment, but has a surprising capability of coping, especially for short periods, with variables of his environment. For example, man is most comfortable at a given temperature and relative humidity, the exact degree of comfort being dependent upon such things as wall temperature, air temperature, water-vapor partial pressure, gas composition, air circulation rate, clothing, and workload. He can cope with either increased or decreased cooling from this environment and has adaptive mechanisms that will allow continued functioning, for short time periods, depending on the extent of these changes.

In a similar fashion, man can tolerate both increases and decreases in other variables: O_2 partial pressure, CO_2 partial pressure, and water-vapor partial pressure. The greater the departure from normal in these parameters, however, the shorter is man's capability of coping with them without degradation in his abilities. In the design of environmental controls for manned spacecraft, therefore, prudence demands systems that minimize departures from these norms, while providing this control in a reliable and efficient manner.

The purpose of the present study is to indicate changes that must be made in atmospheric-control systems, because of the mission goal, as a result of changes in power penalty, and because of the considerations that must be made for reliability.

The simplest of all space missions is the Earth-orbital mission, because of the relative ease of rendezvous and resupply, and the relatively short abort times. The next most simple mission is the lunar base, wherein large, fixed installations utilizing nuclear power supplies and taking advantage of the $1/6g$ of the Moon's surface may eventually become feasible. Most difficult of the missions are the planetary explorations, wherein abort and resupply are difficult. For the first of these planetary missions, all materials and supplies that will be required must be provided in the initial vehicle, and unrepairable system failures cannot be tolerated because the presently envisioned booster systems would be unable to provide an abort capability that is significantly shorter than the length of time already elapsed.

In addition to mission orientation, the configurations of atmospheric-control systems are dependent upon power penalty. Regenerative systems utilize considerably greater quantities of electrical and heat energy than do the nonregenerative systems. Therefore, the equivalent penalty that must be assessed against these control systems for the power that they use will have an effect on the relative desirability of these systems. To cite an example, reduction of CO_2 to O_2 and carbon requires a given theoretical minimum amount of energy. This energy, plus any losses or inefficiencies, must be supplied to all processes that are expected to fill this function. In addition, certain techniques are more inefficient than others and thus require a greater penalty. Certain of these energies are more costly, in terms of weight of power supply, than others; heat energy, for example, can be provided at a lesser penalty than can electrical energy.

These power penalties are illustrated in figure 1. Shown are the estimated weights of two types of O_2 provision systems. Without going into details at this point concerning their operational methods, it is assumed that process A consists of a regenerative CO_2 removal system and cryogenic O_2 stores. System B utilizes a technique to reduce CO_2 to H_2O and CH_4, and the H_2O is subsequently electrolyzed to O_2 and H_2, which is reused in the CO_2 reduction. System A requires about 100 W of electrical energy, per man, and about 30 lb (13.6 kg) plus 2.5 lb (1.13 kg) per day of supplies to continue its function. System B requires about 400 W of electrical energy, and 100 lb (45.36 kg) per man plus 0.5 lb (0.23 kg) per man per day of supplies. Given two power-provision systems to provide this electrical energy requirement, one requiring about 200 lb (90.7 kg) of equipment to provide a kW of energy and the other, of 500 lb/kW (229 kg/kW), the effects of power penalty can be readily demonstrated. If the decision to utilize one or the other of these two systems rested solely on the basis of system weight plus weight of equivalent power required, the regenerative CO_2 removal and stored O_2 would be preferred over the O_2 reclamation system, at a power penalty of 500 lb/kW (229 kg/kW); for a penalty of 200 lb/kW (90.7 kg/kW), the opposite would be true.

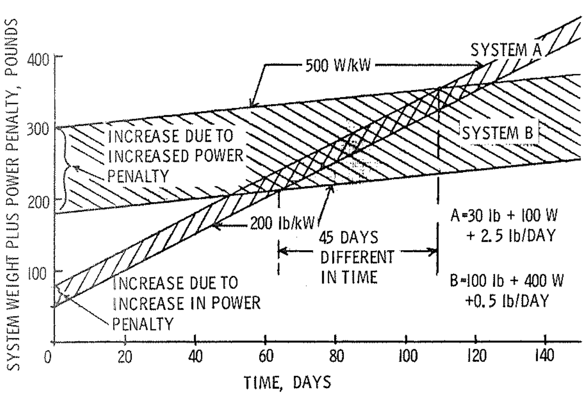

FIGURE 1.—Atmospheric control at different power penalties.

After the first successful lunar landings, lunar explorations will be undertaken for longer and longer times. Eventually, a permanent logistically resupplied lunar colony will be established. The life-support systems for such colonies will differ markedly from those presently envisioned for Earth orbit, in that longer term usage will be expected, with a periodic resupply of expendables, and additional reliability will be necessary. In the design of these systems, advantage can be taken of the $1/6g$ that is present on the lunar surface, so that many of the systems that now require $0g$ operation can be simplified.

Reliability, or failure-free operation, is not as easily quantified as are the variables of power penalty. Nevertheless, this consideration can result in modification of system selection simply on the basis of the degree of knowledge and experience with the candidate systems, as well as consideration of the relative complexities of the system.

The following three sections of this paper will deal with: (1) the control of humidity; (2) the removal and dumping of CO_2 and the provision of O_2 and N_2 from stores; and (3) the removal and concentration of CO_2 and the reduction of this CO_2 and some additional water to breathable O_2, with consequent reduction in the quantity of O_2 that must be supplied. The most attractive candidate techniques for fulfilling these functions will be discussed, and an attempt will be made to show the relative merits and disadvantages of these systems. In many cases, these techniques are undergoing fairly rapid changes because of the current research efforts. Certain of these efforts may uncover techniques that will ultimately prove to be better than the best shown here. One of the functions of the Langley Research Center is to encourage new research, to develop new techniques that have merit over presently known methods, and to reduce even further the weight and power requirements of presently known systems, while increasing their efficiency and reliability.

HUMIDITY CONTROL

If the engine analogy used in the beginning is again considered, man is an O_2-consuming system. To acquire this O_2, he respires about 16 volumes of air for each volume of O_2 that he takes up from this air. All the air passing through the lungs becomes saturated with water vapor. In addition, water is evaporated from the surface of the body. Therefore, about 2 lb (0.91 kg) or more of water are lost to the atmosphere per man per day, assuming about 50 percent initial saturation. If this water vapor is not removed from the atmosphere, and a comfortable environment maintained, the moisture level will increase to saturation, and will begin to condense on the coolest surfaces available. A high-humidity environment is undesirable as far as consideration of comfort, as well as for other reasons, and uncontrolled condensation is to be avoided. Therefore, humidity-control systems (in conjunction with temperature and air-moving equipment) that sustain a desired comfort level are a necessity. Further, the water condensed from the air is a valuable waste product suitable for reclamation for drinking water.

Chemical absorbers, such as lithium chloride, and other water sorbers become so costly, in terms of weight, in a short period of time that they have never been used in a manned spacecraft. All systems to date have been of the regenerative type; that is, the type that performs its function without loss of capacity with time. The only way that humidity control has been approached is to cool the air to some temperature below its dewpoint, condense a part of this moisture, and separate this moisture from the cooled airstream. Mercury, Gemini, and Apollo all use heat exchanges and regenerative separators. These systems have disadvantages, however, such as large pressure drops requiring large, power-consuming fans. A number of improvements have been proposed, including centrifugal separators, for use in the lunar module of Apollo. Presently, two concepts appear to be very attractive for future use: a technique utilizing a cooled, sintered metal plate; and a technique using hydrophobic screens to separate the droplets from the airstream, and hydrophilic surfaces to remove the separated water, free of air bubbles, to holding tanks. It should be emphasized at this point that the maintenance of air-free water from the humidity control system is most desirable, because any bubbles that are allowed to enter the condensed water stream may collect in the holding tank, under $0g$, and cause a failure of the system or subsequent systems.

The first of these humidity-control systems, shown in figure 2, was developed at the Langley Research Center and consists of a number of sintered metal plates that are exposed to the airstream. The plates are cooled to below the dewpoint of the airstream by circulating cold water. The moisture, condensed from the airstream by this cooling, is drawn through the sintered metal plate by maintaining the pressure within the circulat-

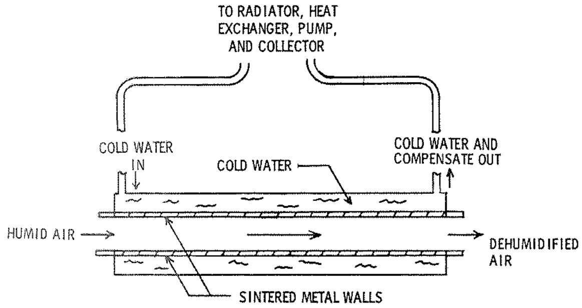

FIGURE 2.—Humidity control by the use of porous-metal heat exchanger.

ing fluid loop at a pressure lower than the airstream pressure. The condensed water is thus added to the volume of cooled circulating water and may be removed continuously or periodically for storage or further treatment. Care must be taken with this unit to prevent the differential pressure across the face of the plate from becoming so great as to break the capillary forces that tend to keep the pores of the metal plate filled with water. If the pore size of the plate is made small, these pressure differentials can be surprisingly high; in this case, a differential pressure of about 7 psi (4.8×10^4 N/m^2) is required before air is forced through the plate. Sintered metal plates can be fabricated in a number of configurations, and the concept possesses the desirable characteristics of simplicity, lack of moving parts, and a capability of operating under conditions of 0*g*, as well as any orientation under conditions of 1 or more *g*'s.

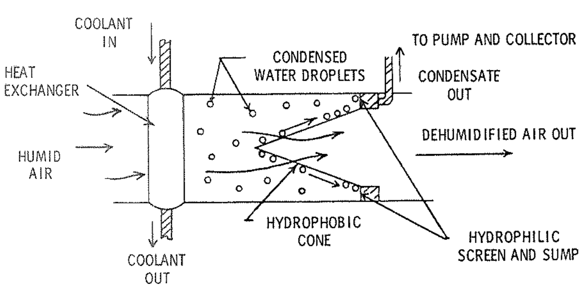

FIGURE 3.—Humidity control and water separation by use of hydrophobic and hydrophilic materials.

The second of these promising techniques is that in which hydrophobic and hydrophilic surfaces are used to separate entrained water droplets downstream from the heat exchanger. Figure 3 shows, in cross section, how such a device operates. The airstream, moving through the separator and carrying the entrained water droplets, passes through a fine-mesh conical screen that is coated with a hydrophobic material, such as Teflon. The surface tension of the water and the contact angle of the air-water Teflon interface result in the prevention of the passage of the water droplets, and because of the angle of the hydrophobic cone, these droplets are forced to migrate into the sump. In this region these water droplets collect and encounter a fine-meshed hydrophilic screen, constructed of material such as stainless steel. This screen and the tubing downstream from it will remain filled with water and will retain its resistance to air passage with a differential pressure of about 0.3 psi (2.07×10^3 N/m^2) between the air at the surface and the water within the screen. As water from the hydrophobic cone comes into contact with the screen, it passes through with only a small resistance (again because of the surface tension of the water, and the contact angle of the air-water–stainless-steel interface) and is eventually routed to a holding tank for reprocessing.

The major advantages of a humidity-control device of this type are its low pressure drop, and consequently low fan power, and the lack of moving parts. Tests at the Langley Research Center and research under contract to the Lockheed Missiles & Space Co. have confirmed the operational advantages of this separator, and long-term testing of the unit is planned in manned test chambers. Some of the significant operational parameters of this system are:

(1) System weight: 1½ lb/man
(2) Power requirement: 8 W/man
(3) Pressure drop: 2 in. H_2O at 75 CFM
(4) Removal capacity: 1.08 lb/hr
(5) Capacity: 12 men

CARBON DIOXIDE REMOVAL AND OXYGEN-NITROGEN SUPPLY

The removal of CO_2, as given off by man in spacecraft environment, requires a removal capacity of about 2.24 lb (1.02 kg) of CO_2 per man per day, with a flow rate through the removal system of some 3 CFM (0.085 m^3/min) to maintain a concentration of 0.5 percent of carbon dioxide in the cabin atmosphere, assuming near-100-percent removal of carbon dioxide per pass. If the removal efficiency per pass is less than 100 percent, the airflow rate must be increased proportionally, to maintain this partial pressure of CO_2.

There are many techniques for removing CO_2 from spacecraft atmospheres. CO_2 removal can be accomplished by chemical means (lithium hydroxide), or be regenerative means of several varieties: water-sensitive sorbers (molecular sieves), water-insensitive sorbers (modified resins, among others), and other means, such as the carbonation cell. The first of these techniques, lithium hydroxide, has been demonstrated to be successful on the Mercury and Gemini flights and is scheduled for use in the Apollo mission. Its chief drawback, when used for long missions, is its weight and volume, because it is expended rather than regenerated. Molecular sieves also possess an affinity for CO_2 and, furthermore, the affinity is not as strong as the chemical bond formed with lithium hydroxide so that the application of moderate amounts of heat energy, or reduction in the CO_2 partial pressure, or both, will cause this adsorbed CO_2 to be desorbed. Therefore, the molecular sieves (or other regenerable sorber) can be made reusable by removing the previously collected CO_2.

Because molecular sieves possess a preferential affinity for water over CO_2, it is necessary to protect the CO_2 sorption beds by predrying the airstream containing the CO_2 with another sorber such as a different molecular sieve, a silica gel, or some other sorber that removes water, rather than CO_2. This predrying system must also be made regenerable, and thus, by the application of heat energy, or a reduction in water-vapor partial pressure, as by exposure to space vacuum or both, the water is removed from the sorber and its predrying function capability restored. For continuous operation, it is necessary to have one set of beds adsorbing water and CO_2 while the other is desorbing. A minimum of four beds are necessary for predrying and for CO_2 removal. As indicated, water can be removed from the predrying beds by exposure to space vacuum; however, this process results in the loss of this moisture, and, unless a low penalty source of water is available, such as a fuel cell, the penalty for this water loss is excessive. For longer duration missions wherein fuel cells for electrical power are not an economical choice from a weight standpoint, most studies have utilized a heat-regenerated desiccant bed and a vacuum-regenerated CO_2 sorber. Heat regeneration allows the return of the moisture that the bed has adsorbed in protecting the molecular sieve beds.

Before a discussion is given of the numerous ways in which these molecular sieve, desiccant sorbers can be operated, some brief mention will be made of two additional concepts that are capable of removing CO_2. These concepts have their most promising application in the CO_2 concentration mode, that is, in the removal and collection of metabolic CO_2, so that subsequent reduction of this carbon dioxide can be performed and so the stores of oxygen supplies can be reduced. In one of these concepts a modified resin shows a capability for sorbing CO_2 in the presence of water vapor. In fact, water of hydration within the resins is essential for their proper operation.

These resins have shown a capacity for the adsorption of CO_2 that is slightly greater than the adsorption capacity of molecular sieves and have the capability of being completely regenerated at temperatures of about 212° F (100° C). The total quantity of heat energy that is necessary to regenerate these resins is about the same as that necessary for molecular sieves. The CO_2 that is desorbed from these resins has a high water content, however, and if these resins are to provide CO_2 for O_2 reclamation systems, care must be taken in the integration of these two processes to accommodate the wet CO_2.

The third type of sorption system is the carbonation cell. This system consists of three cells—the first two produce increasingly concentrated CO_2, which is absorbed from a cabin airstream by the first cell, together with some oxygen, and the third cell provides the separation of the CO_2 from the O_2. This process operates on an electrolysis principle, the electrolyte in the first two cells being a potassium carbonate solution, and the electrolyte in the third cell being an aqueous sulfuric acid solution. This process, like the resins, has its application in the providing of CO_2 for further reduction, as a part of an O_2 reclamation system.

The use of molecular sieves, in combination with predrying beds, has had the most intensive study and testing of all of the regenerative CO_2 removal methods. The concept is capable of being used in three separate and distinct ways: all-vacuum desorbed, wherein both the water and CO_2 are removed from the cabin airstream, and desorbed to space vacuum; CO_2 vent, water conservation method, wherein the adsorbed CO_2 is vented to space vacuum, but the water that was adsorbed is conserved and returned to the cabin; and an all-conservation method wherein the adsorbed water and CO_2 are retained, the water being returned to the cabin and the CO_2 collected for reduction as part of an O_2 reclamation process. These operating methods are shown in table I as "vent H_2O & CO_2," "vent CO_2, conserve H_2O," and "conserve H_2O & CO_2." It should be noted that these three methods are in order of increasing mission duration. The venting of both CO_2 and water has its best application on vehicles that use a fuel cell, and the water can, therefore, be lost without penalty. This desorption technique requires the least power. The intermediate case, the venting of CO_2 and conservation of water, has its application on spacecraft that do not use fuel cells, but at the same time are not of sufficient mission duration to warrant the reclamation of O_2. In this case, the conservation of water adds to the complexity and power requirements of the system. The case of the conservation of both water and CO_2 results in the most complex and power consuming of these operating concepts, in that the water vapor is returned to the cabin, and the CO_2 is collected and stored, usually with the aid of a pump, for subsequent reduction.

TABLE I.—*Regenerable* CO_2 *Removal*

	Increasing mission duration					
	Vent H_2O & CO_2		Vent CO_2; Conserve H_2O			Conserve H_2O & CO_2
	MOL	AAP	Conventional	GE	ESSO	ILSS
Adsorption:						
Isothermal	...	H_2O	...	...	...	...
Nonisothermal	H_2O & CO_2	CO_2	H_2O & CO_2	...	H_2O & CO_2	...
Desorption:						
Temperature change	...	...	H_2O	H_2O & CO_2	...	H_2O
Temperature and pressure change	...	H_2O	...	H_2O & CO_2	H_2O & CO_2	CO_2
Pressure change	H_2O & CO_2	CO_2	CO_2	...	H_2O & CO_2	...

On the vertical scale of this table are shown different operating modes for both adsorption and desorption; the isothermal and nonisothermal mode for adsorption, and the pressure change, temperature change, and both pressure and temperature change, for the desorption mode. The adsorption of water and CO_2 by these materials results in the liberation of heat energy, the heat of adsorption. The capacity of these sorbers decreases with increasing temperature. The sorbers may be operated in the constant temperature mode (isothermal) by removing the heat of adsorption, or may be allowed to "free-run," with the heat of adsorption raising the temperature of the bed, thus decreasing its capacity and raising the temperature of the airstream leaving the bed. In the desorption mode, two methods for removing the water or CO_2 may be used, or a combination of both: increased temperature, supplying the heat of desorption and decreasing the capacity of the sorber; or decreased partial pressure of the sorbate, CO_2 or water vapor. The latter can be accomplished by purging the bed with sorbate-free gas, or reducing the total pressure within the bed by means of a pump or exposure to space vacuum.

Currently, at least five different approaches are being studied. The first of these is the all-vacuum desorption case, as envisioned for the Manned Orbital Laboratory (MOL) and in the Apollo Applications Program. The MOL system concept adsorbs water and CO_2 in a nonisothermal mode, and desorbs these gases by vacuum only. The Apollo Applications Program concept uses active cooling of the water sorber to increase the capacity of this bed, and active heating of the bed, on desorption, to aid in its regeneration, as well as the application of space vacuum.

The second approach is the best known of the molecular sieve concepts, wherein water and CO_2 are sorbed, nonisothermally, and the water is desorbed by the application of heat to the process air entering the bed to be regenerated, while the CO_2 is vented to space vacuum.

The third approach is one in which active cooling and heating of both the water and CO_2 sorbers are used, plus a pump for the collection and storage of the CO_2. This system is in use at the Langley Research Center as the CO_2 concentration unit in the integrated life support system (ILSS).

The fourth approach is currently under study by contract from Langley. This study involves the isothermal sorption and heat-assisted desorption of both water and CO_2 for molecular sieves, silica gel, and other materials. The study is being carried out using heat-exchanger surfaces coated with the sorber materials. Very high heat-transfer rates are being studied from the standpoint of increasing the adsorption capacity and decreasing the desorption time.

The fifth operating method is the adiabatic, or "heatless," desorption, wherein the heat of adsorption is conserved within the bed, and the loading of the bed is confined to the linear portion of the capacity-loading curve. The heat of adsorption is, therefore, available to supply the energy requirement for desorption. This operating method depends not on changes in bed temperature, but on increased volume flow rate of sorbate-free air through the beds to regenerate them. Both of these last two methods show some advantages over the more conventional approaches, and may apply both to the conservation as well as the venting of CO_2.

In addition to the removal of CO_2, it is necessary to provide O_2 for man's consumption, as well as O_2 and N_2 to make up for vehicle leakage, and other losses such as airlock cycling. Cryogenically supplied O_2 and N_2 appear to hold the most promise for the mission duration wherein O_2 is not reclaimed. Depending on power penalty and the time for which the cryogenic stores are to be used, the electrolysis of water may be used to supply part or all of the O_2 supply. The differences in these two techniques may be seen in an estimate of the weight, power, and storage penalties: cryogenic O_2 can be stored on a one-man basis at a weight penalty of about 2 lb (0.91 kg) plus about 2.4 lb (1.09 kg) per day, whereas water storage and electrolysis may be accomplished for about 30 lb (13.6 kg), 260 W, and about 2.3 lb (0.94 kg) per day for storage and container. Depending on the power penalty, these two are about equal for longer term missions. If some water can be derived from the water reclamation cycle, at no storage penalty, this will increase the attractiveness of the electrolysis method. For very long-term storage, and with little continuous usage to account for the boiloff losses, the storage and electrolysis of water are probably advantageous.

OXYGEN RECLAMATION SYSTEMS

As mission length increases, the use of systems to reduce or eliminate the O_2, either cryogenically or as water, becomes feasible. These concepts, as shown in table II, involve the collection of CO_2, its reduction to H_2O and CH_4 (Sabatier), H_2O and C (Bosch), O_2 and CO (solid electrolyte), or O_2 and C (molten carbonate). In the case of the first two, the water produced must be electrolyzed to O_2 and H_2, and the H_2 reused in the process. The minimum theoretical electrical power necessary to reduce CO_2 and water to the required quantity of O_2, C, and H_2, to balance the O_2 cycle is about 125 W per man on a continuous basis. The relative efficiencies of these processes are calculated on the basis of the actual amount of power required to accomplish the overall task, including the collection of CO_2 if necessary, and the electrolysis of water as required.

In the later two cases shown in table II, a small amount of water electrolysis must be performed separately from the basic reduction of CO_2. (The Sabatier and Bosch processes produce water from H_2 and CO_2, all of which must be electrolyzed, along with some additional water, to achieve balance in the O_2 cycle.) In the case of the solid electrolyte, the CO must undergo a disproportionation reaction and the resulting CO_2 must be recycled to the solid electrolyte unit. Of these processes, the molten carbonate process is unique in that it is capable of sorbing CO_2 directly from the cabin airstream, rather than requiring a nearly pure feed stream of CO_2 from a concentration system.

These processes vary considerably in their efficiency, complexity, and ease of reduction to practical flight hardware. As might be suspected, the CH_4 dump Sabatier, the simplest reaction requiring the lowest temperature, is the easiest to construct in a reliable operational unit, but possesses, at the same time, the greatest penalties for losses. Figure 4 shows this concept as a part of an overall O_2 reclamation process. Because CH_4 is vented in this process, some H_2 must be stored to allow continued operation with a balanced O_2 cycle. In addition to the loss of

TABLE II.—*Oxygen Reclamation Techniques*

	Resupply to make up losses, lb	Requires CO_2 concentration	Requires water electrolysis	Requires phase separation	Requires carbon deposition	High-temperature operation, °F	Efficiency (125 W/man theoretical), percent
Sabatier:							
CH_4 vent	0.4	Yes	Yes	Yes	No	400	30
CH_4 crack		Yes, pure	Yes	Yes	Yes	2000	25
Bosch		Yes, pure	Yes	Yes	Yes, $CO_2+2H_2O \rightarrow C+2H_2O$	1250	21
Solid electrolyte		Yes	No	No	Yes, $2CO \rightarrow C+CO_2$	1800	19
Molten carbonate		No	Yes, 15 percent	Yes, high temperature	Yes, on cathode	1100	32

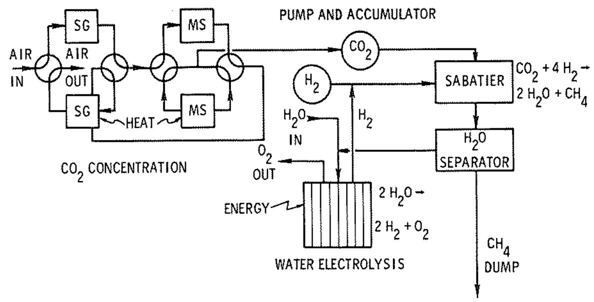

FIGURE 4.—Sabatier oxygen reclamation.

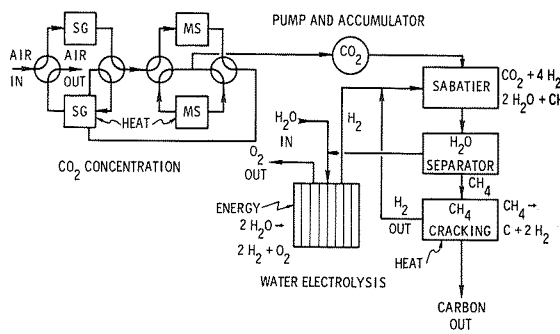

FIGURE 5.—Sabatier oxygen reclamation: methane decomposition.

CH_4, some water vapor is lost, adding to the inefficiencies of the unit. By the incorporation of a CH_4-cracking subsystem, as shown in figure 5, many of these drawbacks can be eliminated. Unfortunately, the problem of CH_4 cracking is very difficult and this addition adds greatly to the base weight and the problem of the system.

The Bosch reaction shown in figure 6 is accomplished at a somewhat higher temperature (1250° F (680° C)) than the Sabatier 300°–500° F (150°–260° C). It is, however, a closed system and losses are minimized. The losses in this system come about principally because of the inclusion of N_2 in the CO_2 feed stream, so that purging the system is required to maintain a constant pressure. The purge gases consist of those that exist in equilibrium in the reaction cycle, unreacted hydrogen and CO_2, CO, water vapor, and other hydrocarbons. Both the Sabatier and the Bosch reactors are fed from a CO_2 concentration unit, and both require water electrolysis to complete the process of O_2 reclamation.

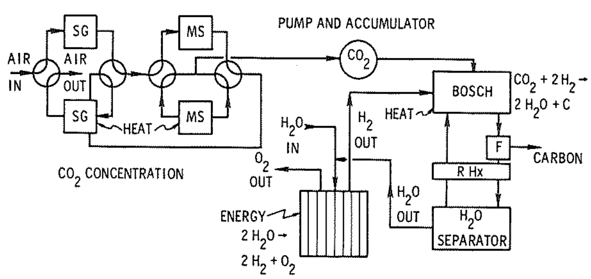

FIGURE 6.—Bosch oxygen reclamation.

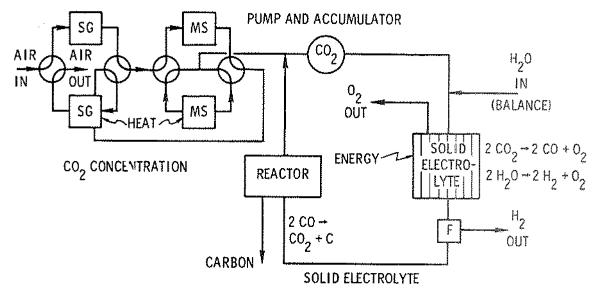

FIGURE 7.—Solid electrolyte oxygen reclamation.

Figure 7 shows the solid-electrolyte process, which is currently under investigation by several research laboratories. It differs considerably from the Bosch and Sabatier processes in that, although it requires a nearly pure CO_2 feed stream, the products that result from this high-temperature electrolysis process are O_2 and CO. This CO is made to undergo a disproportionation reaction that, in the presence of a catalyst, results in the deposition of carbon, and the formation of CO_2, which is recirculated back to the solid electrolyte. There is evidence that this process is capable of reducing water concurrently with CO_2, and there is also reason to believe that the reduction of CO_2 is enhanced by the presence of water vapor. Thus, by separating proper amounts of H_2 from this process, and feeding a stream of CO_2 and water vapor to the process, it may be possible to achieve a balance in the O_2

cycle, without resort to a separate water electrolysis.

The molten carbonate process, shown in figure 8, is being investigated by the Hamilton-Standard Division of United Aircraft Corp., under a research-and-development contract from Langley Research Center. This process shows promise of reducing weight, power requirements, and complexity of the overall oxygen reclamation process. It is unique in that it is capable of sorbing CO_2 directly from a cabin airstream and, in a one-step process, of reducing this CO_2 to carbon, which is deposited on the cathode, and O_2, which is liberated at the anode and leaves the system along with the cabin airstream. The O_2 and N_2 in this airstream are unaffected and do not enter into the process in any way. There is evidence to show that large amounts of water vapor may be detrimental to the process, and it is planned to minimize the quantities of water vapor entering the molten carbonate system by reversibly adsorbing and desorbing this water by the use of silica gel or other predrying beds in much the same manner that molecular sieves are protected by predrying beds.

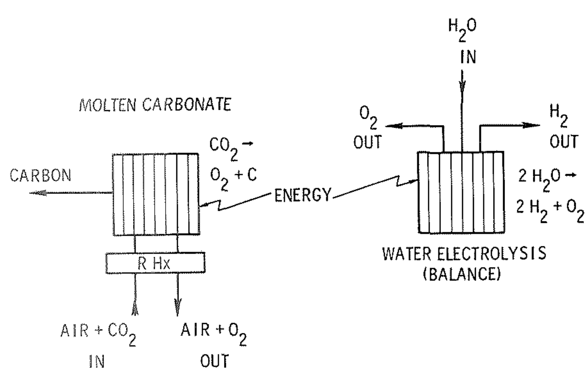

FIGURE 8.—Molten carbon oxygen reclamation.

The molten carbonate process takes place at relatively high temperatures, some 1100° F (600° C) and the process operates by the electrolysis of a molten mixture of lithium carbonate and lithium chloride. Some problems are still to be overcome in the application of this process; however, there is no reason to believe that these will not be solved. Laboratory demonstrators are now operating for relatively long time periods, and the inherent high electrical efficiency of this process is reflected in these demonstrators. Current efforts are centering around the design of a 1/6*g* prototype system, and subsequent efforts will include the construction of this system and the design and construction of a 0*g* system. In the application of this technique to O_2 reclamation in spacecraft, it will be necessary to provide for a balance in the O_2 cycle, by electrolysis of some water, which, according to present indications, must be accomplished separately from this process.

These system processes that have been discussed represent what is believed to be the most attractive candidate processes for O_2 reclamation in spacecraft. They are all capable, with some water input (0.33 lb per man per day) of achieving a balance in the O_2 cycle. Certainly some additional O_2 must be stored, along with N_2, to make up for leaks and possible air-lock cycling. However, dependent upon a number of considerations, such as power penalty, reliability considerations, and the like, they are capable of being utilized to reduce greatly the amounts of stores that are necessary for atmospheric provision and the support of man. The use of O_2 reclamation systems for long-term orbital spacecraft and lunar colonies will show logistic advantages by minimizing the resupply of O_2.

Some mention should be made concerning bioregenerative systems for manned spacecraft. Several candidate systems that are believed to be capable of removing CO_2 and supplying O_2 have been proposed. If this were the only capability of these bioregenerative systems, they would not be competitive with the electrochemical systems on the basis of weight and power requirements. They are potentially capable, however, of also providing all or part of the nutritional requirements of man, and of utilizing all or part of the waste products of man. When these factors are taken into consideration, it is apparent that for very long missions, or for permanently established planetary or lunar colonies, these bioregenerative systems will ultimately be the processes of choice. A much longer development time will be required for these processes, however, than is necessary for the physical-chemical and electrochemical processes that have been discussed here.

CONCLUSIONS

Several general problems can be noted from examination of the physical-chemical and electrochemical systems for application to long-term manned spacecraft. These problems can be separated into two types, the first of which is operational problems, or those that can be overcome by experience, further knowledge of the process, and more knowledge of materials and the way they react to the environment in which they are applied.

Carbon deposition, as required for the successful operation of the Bosch process, the CH_4-cracking Sabatier process, and the disproportionation reaction of the solid electrolyte, appears to be a common difficulty. The trouble-free continuous deposition and removal of this carbon in a $0g$ configuration has not been successfully demonstrated for long time periods; however, there is no reason to believe that this cannot be done. What is necessary is further attention to the problem, further knowledge of the details of the process, and perhaps the utilization of new materials.

In the past, the separation in a $0g$ system of mixtures of gases and liquids has presented much difficulty. This difficulty appears to be successfully overcome, at least for small quantities of nearly pure water in air at moderate temperatures. Further attention and effort will undoubtedly result in success for other liquids and gases at higher temperatures. These kinds of problems present no insurmountable difficulties; time and effort will provide an acceptable solution.

Aside from operational problems, the second problem area to be overcome is one of long-term reliable operation. Here again, knowledge of the exact nature of the failures and provisions to prevent their recurrence will aid in reducing failures. Systems can be made to operate with a high degree of freedom from failure for a specified time; but the more complex the system and the longer the mission duration, the more difficult the task becomes. Research is in progress to deal with both of these problems; for longer missions, more complex systems will replace the more simple systems, and the resultant requirement for failure-free operation becomes many times more difficult. The only escape from this dilemma is the allowance of maintenance and repair by the crewmembers, as well as applying strenuous effort to the final flight hardware. Provision for this repair and maintenance must be incorporated into the design of these systems and spares must be provided. The crewmembers must be familiar with the operation and maintenance of these systems, and they must be skilled in the diagnosis and repair of this hardware.

SUMMARY

In this paper, in order of increasing complexity and mission duration, candidate processes and techniques for atmospheric control of manned spacecraft have been discussed. The processes and techniques have been briefly described, and some estimates have been given as to their weight, power requirement, and required supplies. Factors that affect the use and attractiveness of such systems have been discussed, and the influence of such factors as power penalty, mission objective, and so forth, have been shown. The intent of this paper is not so much to acquaint the readers with the detailed working of these processes or to provide enough knowledge to allow selection of these systems on the basis of the variables stated, but rather to give an overall view of candidate processes for atmospheric control systems and to show the important factors that influence selection, power penalty, mission goal, and mission duration.

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Man's Tolerance to Trace Contaminants

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In September 1958 at the First International Symposium on Submarine and Space Medicine, I was asked to present a paper on threshold limit values for hydrocarbons and ozone in confined spaces (ref. 1). At that time it was quite obvious that the duration of the space trip would be of prime importance in deciding how much of various contaminants a man could inhale. I stated that we would have no problem from chemical stress, assuming that everything goes well with the life support system, as long as the exposures are at a relatively slow rate and that the mission duration does not exceed 2 weeks. Based simply on a dose-effect relationship, I also suggested that in this 2-week continuous-exposure period we could use the industrial threshold limit values (TLV) and probably be safe. (The TLV are based on a threefold increase in dosage and an 8-hr interrupted exposure experience.)

The chemical toxicants were arbitrarily divided into four categories according to probable responses to low-level continuous exposure:

(1) Equilibrium (intake = excretion)

(2) Adaptation, desensitization, cross-tolerance

(3) Cumulative damage (summation of interest)

(4) "Non-or-all" (carcinogens, sensitizers)

Category (1) includes all those agents that at low concentrations will equilibrate within the organism very quickly. If equilibrium is reached in a matter of hours, and at a level where physiological compensation is still effective, continuous exposure should be of little consequence. Category (2) includes those materials to which a certain tolerance or adaptation can be developed. It was found with many chemicals that short exposures to relatively high concentrations can increase tolerance considerably up to several months' duration. Category (3) (which I thought was the largest group) includes all materials that exhibit slow clearances or cumulative properties, and in this category are most of the hydrocarbons. Category (4) includes materials that could be placed on an all-or-nothing basis. These are materials that are carcinogenic, or materials where even trace quantities could be hazardous during continuous exposure, however short the duration of such exposure might be. These predictions were made without the benefit of any experimental data.

The presentation taught me that we would have to start doing some continuous exposures in animals to get some basis to prove or disprove what I had said. Following that meeting, we started doing research on continuous exposure, by exposing animals for periods of up to 90 days in atmospheric environment to various "typical" chemicals (table I). These typical chemicals were propellants that could be aboard the spacecraft, such as hydrazine, unsymmetrical dimethyl hydrazine (UDMH), nitrogen tetroxide, and pentaborane; typical industrial chemicals for which we have quite a bit of toxicity data, such as carbon tetrachloride

TABLE I.—*Summary of Mortality Rates*

Compounds	Monkeys		Rats		Mice	
	Number dead/Number used	Deaths, percent	Number dead/Number used	Deaths, percent	Number dead/Number used	Deaths, percent
Controls	1/10	10	0/50	0	1/100	1
N_2H_4	2/10	20	48/50	96	98/100	98
UDMH	1/10	10	3/50	6	6/100	6
Decarborane	6/10	60	25/50	50	82/100	82
NO_2	0/10	0	9/50	18	13/100	13
Controls	0/19	0	2/50	4	38/200	19
Indole	2/10	20	5/50	10	22/100	22
Methyl mercaptan	4/10	40	5/50	10	43/100	43
H_2S	0/10	0	12/50	24	26/100	26
CCl_4	1/10	10	0/50	0	0/100	0
Phenol	0/10	0	0/50	0	0/100	0
Mixture of indole, H_2S, skatole, and Me•SH	16/20	80	32/50	64	99/100	99

and phenol; some chemicals that are the end products of metabolic processes, such as indole, hydrogen sulfide, and methyl mercaptan; and a mixture of indole, methyl mercaptan, hydrogen sulfide, and skatole. These exposures were performed at the appropriate industrial TLV for each chemical, that is, the value that is thought to be harmless for daily 8-hr exposure, 5 days per week, for at least 30-yr duration, in an industrial situation. As expected, we found that this concentration was detrimental to the health of animals in many instances, causing nearly 100 percent mortality with some—notably hydrazine; decaborane; and the mixture of indole, skatole, methyl mercaptan, and hydrogen sulfide. It then looked as if the basic assumption of dividing chemicals into major categories was right.

Hydrazine, decaborane, and the mixture of indole, skatole, methyl mercaptan, and hydrogen sulfide appeared to produce strongly cumulative toxicity. Looking at the rate of mortality during the exposure (fig. 1), one can see that the majority of deaths occurred during the first month, which clearly indicates that continuous exposure at the TLV concentration had an early and overwhelming toxic effect.

In my presentation at the Symposium on Toxicity in the Closed Ecological System (ref. 2), I also pointed out that all the experimental data on continuous exposures were at ambient pressure air environments; this was fine for the Navy, but it left a big gap in knowledge as far as toxic effects during altitude flights were concerned. Obviously we would have to study these chemicals in the proper environment because the effect of 100 percent O_2 atmosphere at 5 psia might cause undesirable pulmonary reaction, and such a reaction could greatly reduce the tolerance to certain toxic agents. On the other hand, the rate of absorption of toxic gases and vapors may be retarded at lower pressures and may lower the magnitude of the inhalation exposure.

Therefore, we designed an inhalation facility to study these atmospheric contaminants in a space-cabin environment (ref. 3). As of this date, we have had the opportunity to study continuous exposure to contaminants for 90-day durations, in space-cabin atmospheres of 100 percent O_2 at 5 psia and in 5-psia mixed-gas atmospheres, such as 68 percent O_2 and 32 percent N_2. To keep the information disseminated as fast as possible, we began to sponsor an Annual Con-

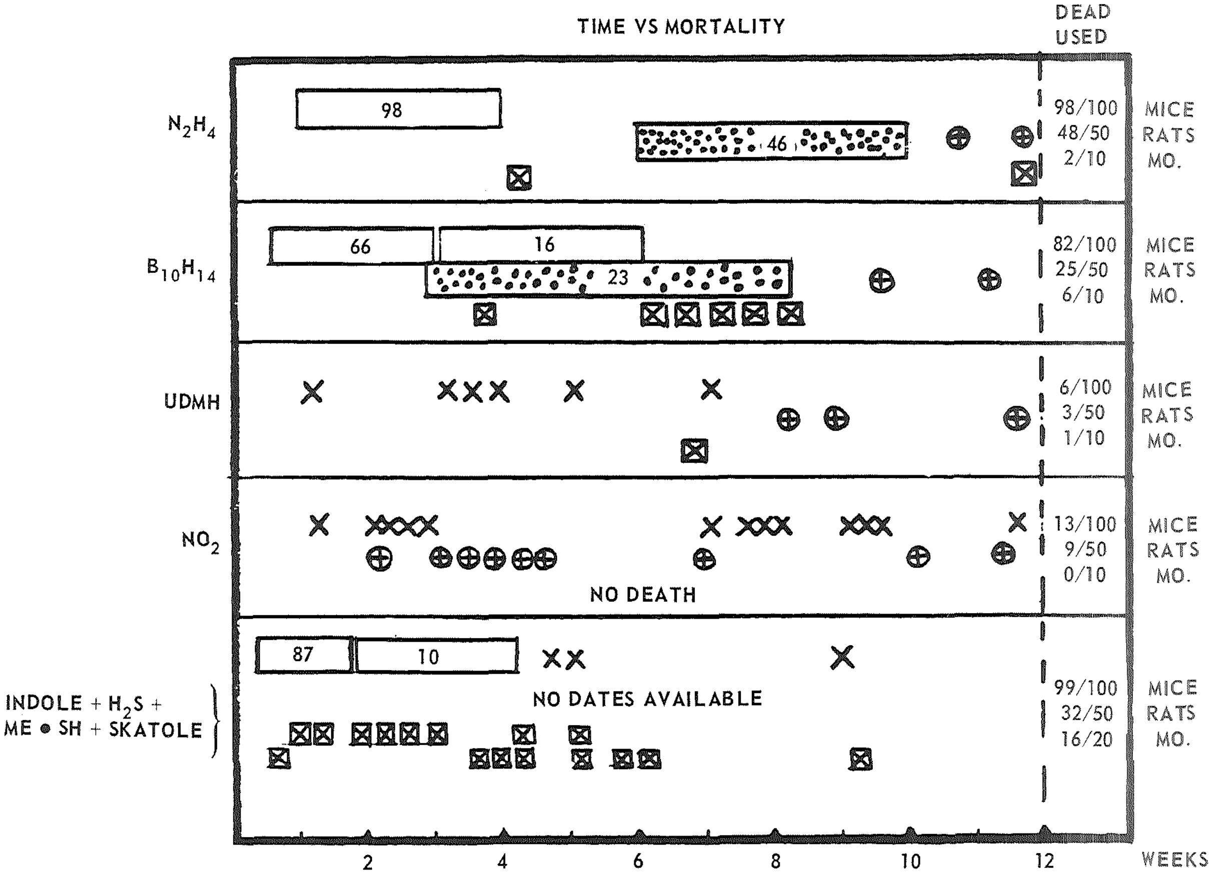

FIGURE 1.—Rate of mortality during exposure to various toxicants.

ference on Atmospheric Contaminants in Closed Spaces in 1965. If you read the proceedings of these past three conferences (refs. 4, 5, and 6), you will agree with me that we are far from knowing enough about continuous exposure, and far from knowing enough about the effects of space-cabin atmospheres on continuous exposure to toxic chemicals. One has not only to define tolerance and no-effect levels, but also to consider adaptation. And, last but not least, one must consider comfort levels, and levels that not only do not cause reversible pathology, but also do not affect the performance of the crew.

To highlight our knowledge, as of now, we can say that we are still uncertain about the significance of physiological and morphological changes that we are observing with the basic atmospheres of 100 percent O_2 at 5 psia and mixed gas at 5 psia without contaminants. We see changes, and we will have to decide whether they are adaptive in nature, or whether they are deleterious as a result of very long exposures. Our longest exposures to space-cabin atmospheres have not exceeded 8 months. An 8-month exposure is a far cry from a 1000-day mission. We yet have to validate by animal experiments the 1000-day tolerance to the basic cabin atmospheres.

DEFINITION OF MAJOR PROBLEM AREAS

The Trace Contaminant Problem

The four major sources of equal importance of contaminant generation in closed atmospheres are (1) man and his activities, (2) materials and outgassing, (3) equipment and processes, and (4) malfunctions

TABLE II.—*Gas-Off Products—Velvet Coating No. 104–C 10 Black*

Storage time, days	Atmosphere	Weight of component, mg per 10*g* candidate material						
		Ethanol	Acetone	Methyl-ethyl ketone	Toluene	CO	Methane	Naphtha [a]
30	Air	0.3	0.1	0.4	0.02	2.8	0.04	1.0
60	Air	.3	.3	.5	.02	3.6	.06	1.0
90	Air	.1	.1	.4	.02	4.5	.10	1.0
30+30	Air	.05	.1	.3	.02	.7	N.D.	.4
30+30+30	Air	.04	.08	.2	.01	.6	N.D.	.4
30	5-psia O_2	.4	.5	.3	.2	4.9	.16	1.0
60	5-psia O_2	.2	.1	.6	.02	4.0	.08	1.0
90	5-psia O_2	.08	.3	.5	.01	5.4	.12	1.0
30+30	5-psia O_2	.09	.09	.3	.02	1.2	N.D.	.5
30+30+30	5-psia O_2	.07	.09	.3	.01	.9	N.D.	.4

[a] Estimated from group of GLC peaks characteristic of C_5 to C_7 hydrocarbons.

TABLE III.—*Gas-Off Products—Class H Silicone-Impregnating Varnish No. 997*

Storage time, days	Atmosphere	Weight of component, mg per 10*g* candidate material					
		Ethanol	Propionaldehyde	Benzene	Toluene	Xylene	CO
30	Air	0.2	0.7	0.1	0.05	0.2	2.3
60	Air	.3	.5	.02	.004	.01	2.4
90	Air	.2	.4	.04	.05	.01	2.7
30+30	Air	.4	.2	.01	.03	.1	.3
30+30+30	Air	.4	.1	N.D.	N.D.	N.D.	.2
30	5-psia O_2	.04	.5	.02	.2	.3	2.0
60	5-psia O_2	.05	.2	.02	.5	.2	2.6
90	5-psia O_2	.05	.4	.02	.9	.7	2.9
30+30	5-psia O_2	.03	.1	.02	.6	1.0	.7
30+30+30	5-psia O_2	.04	.2	.04	.7	2.0	.5

and emergencies.[1] Conkle (ref. 7) reviews the complex contaminant picture found in a space-cabin simulator atmosphere in the manned and unmanned portions of a 27-day manned experiment. A total of 97 compounds were identified, out of which 21 compounds were noted only during the manned portion of the study. Most of these compounds have been found by us also, in outgassing studies on space-cabin materials, where individual materials are placed in a sealed atmosphere of ambient-pressure air, on one hand, and O_2 at 5 psia, on the other, for periods of 30, 60, and 90 days, after which the atmosphere is removed through a cryogenic trapping system and analyzed for contaminants (ref. 8). Tables II through VII clearly illustrate that the gas-off rates are not uniform, and that repeated gas-off studies on the same materials, subjected to three consecutive outgassing periods of 30 days each, do not result in a reduction of contaminant generation rates in many instances, or, if generation rates are reduced by such pretreatments, they still remain at a very significant level. Other salient points demonstrated in these tables are a substantial amount of carbon monoxide production and significant amounts of hydrocarbons in the qualitative composition of these mixtures.

[1] See pp. 107–112.

TABLE IV.—*Gas-Off Products—3614 Gray Coating, XA-194*

Storage time, days	Atmosphere	Weight of component, mg per 10*g* candidate material					
		Ethanol	2-Propanol	Methyl ethyl ketone	Toluene	Xylene	Saturated hydrocarbons
30	Air	1.5	1.1	0.4	7.1	2.9	0.3
60	Air	1.4	.7	.7	13.5	13.4	1.1
90	Air	1.0	.3	.3	7.6	13.8	.4
30 + 30	Air	1.1	.8	.5	12.1	5.8	.5
30 + 30 + 30	Air	.6	.5	.3	8.1	4.2	.2
30	5-psia O_2	3.7	3.0	.9	12.2	5.7	.6
60	5-psia O_2	.8	.9	.3	6.3	5.7	.4
90	5-psia O_2	.6	.7	N.D.	3.3	4.8	.4
30 + 30	5-psia O_2	.7	.4	.1	2.9	2.0	.1
30 + 30 + 30	5-psia O_2	.5	.3	.2	2.1	1.5	.1

TABLE V.—*Gas-Off Products—Silver Marking Ink No. 1448 (Cresylic Acid)*

Storage time, days	Atmosphere	Weight of component, mg per 10*g* candidate material			
		2-Ethoxyethanol	2-Ethoxy ethyl acetate	Acetone	CO
30	Air	0.3	7.0	0.1	0.08
60	Air	.9	6.8	.2	.2
90	Air	.6	12.5	.7	.2
30 + 30	Air	.4	15.0	.4	.06
30 + 30 + 30	Air	.5	11.8	.3	.09
30	5-psia O_2	.7	10.8	.2	.1
60	5-psia O_2	.5	9.5	.2	.1
90	5-psia O_2	.3	9.2	.2	.1
30 + 30	5-psia O_2	.1	9.0	.1	.08
30 + 30 + 30	5-psia O_2	.2	7.1	.1	.09

TABLE VI.—*Gas-Off Products—Latex Foam Rubber*

Storage time, days	Atmosphere	Weight of component, mg per 10*g* candidate material	
		Carbonyl sulfide	Carbon disulfide
30	Air	0.03	0.002
60	Air	.05	.002
90	Air	.09	.004
30 + 30	Air	.03	.001
30 + 30 + 30	Air	.04	.001
30	5-psia O_2	.07	.002
60	5-psia O_2	.10	.002
90	5-psia O_2	.12	.004
30 + 30	5-psia O_2	.12	.002
30 + 30 + 30	5-psia O_2	.13	.002

TABLE VII.—*Gas-Off Products—Silicone Primer, EC-1694*

Storage time, days	Atmosphere	Weight of component, mg per 10*g* candidate material			
		Ethanol	*n*-Butanol	2-Propanol	Toluene
30	Air	4.6	14.2	26.4	2.7
60	Air	4.6	6.5	29.6	3.4
90	Air	8.2	10.0	18.9	7.9
30 + 30	Air	1.8	15.5	15.3	.7
30 + 30 + 30	Air	.4	13.8	8.3	.1
30	5-psia O_2	4.1	11.1	21.7	3.3
60	5-psia O_2	4.6	10.4	27.9	4.2
90	5-psia O_2	7.2	12.6	25.4	6.5
30 + 30	5-psia O_2	2.3	10.7	14.8	2.9
30 + 30 + 30	5-psia O_2	.8	9.6	10.5	1.1

Carbon monoxide thus is produced by cabin materials, and is also produced by man. Conkle (ref. 7) reports a steady increase of carbon monoxide from 1 mg/m³ to 25 mg/m³ during the 27-day experiment. Obviously, we know that we will have a problem with exposure to carbon monoxide and hydrocarbons, if nothing else.

Cabin materials are usually classified as metallic and nonmetallic components. At the present time, nobody seems to be worried about metallic components. Nonmetallic cabin construction materials are very much varied and depend upon each system, but about 600 various materials have been identified so far. Research performed in the past 4 yr has clearly shown that many of these construction materials will gas-out various volatile components at an accelerated rate in the reduced pressure of the cabin.

Another large group of contaminants is generated by life support equipment, functioning properly or malfunctioning. By processing the cabin air, many of the original contaminants will be changed, oxidized, reduced, hydrolyzed, pyrolyzed, etc. One should also keep in mind that, with this very complex mixture of gases or volatile contaminants, interaction between these in the atmosphere is not only likely, but a certainty. So, the final spectrum of species that will be found in a cabin under operational conditions might be quite different from those that we observe in bench-scale laboratory tests.

There are, in addition to these contaminants, many nonpermanently incorporated materials in the cabin. There are large numbers of chemicals used during the construction and checkout process that can accidentally be turned loose in a life support system. Examples of this are materials such as mercury used for checking out and calibrating pressure gages, and many solvents and degreasers used in the final assembly process.

That accident can play havoc with equipment is well illustrated by a life support simulator mishap that was discussed by Saunders at our second annual conference. As usual, one malfunction can trigger a chain reaction of other malfunctions, resulting in a truly vicious circle, and, ultimately, in an acute health hazard to the crew. This has actually happened and led to abortion of a manned environmental system simulator mission. A catalytic hopcalite burner was used to purify the atmosphere from contaminants. During the actual manned trial, humidity increased in the chamber because of occupancy by people. This caused moisture from the atmosphere to condense in an aluminum canister containing sodium superoxide. Now, the vicious circle began. The moisture generated sodium hydroxide from the sodium superoxide. Sodium hydroxide generates hydrogen when in contact with aluminum. To get rid of the hydrogen, the crew increased the flow rate through the hopcalite burner to a faster rate than that specified, hoping to burn off the excess. By increasing the flow rate, the temperature of the catalytic bed dropped; it became inefficient to combust organic materials in the atmosphere. The chamber had been cleaned prior to use with a relatively harmless solvent, trichloroethylene. Residual trichloroethylene vapors, passing through the catalytic bed at a low temperature, were incompletely combusted to dichloroacetylene, which produced a marked clinical sickness in the crew and resulted in mission abortion on the third day.

This experiment has typically relied on control by remote sampling equipment and trapping out samples from the life simulator, which, after being collected, had to be carried to an analytical laboratory for testing. It was only many months later that some elegant detection work discovered the nature of the toxicant giving clinical illness to the crew. In a real flight situation, assuming a 1000-day mission, there is no leeway for such post facto diagnosis. When a crew is actually confronted with some troublesome contaminant, it will be their job to identify it as soon as possible. Without knowing the resulting toxic product, it would be very difficult to correct any abnormalities in the life-support-system function to make safe processing of contaminants possible. This, in turn, points out the need for onboard, continuous flow-monitoring devices with great sensitivity and great analytical specificity for identifying various atmospheric contaminants.

Another major source of atmospheric contaminants comes from the excreta of human occupants. At the last count, there were over 150 identified by analytical data, although not from a functional cabin atmosphere. The actual positive identification of the various components is an immense problem, even under laboratory conditions here on Earth. Many of the life-simulator runs have been sampled for atmospheric contaminants and the samples have been sent out to various laboratories for analysis. Depending upon the instrumentation used, the type of column materials employed in gas chromatography, and the circumstances under which the sample was obtained, laboratory results have come up with widely disagreeing results. As a consequence of this low credibility of analytical data, many of the engineering personnel have felt that the toxicity problem is overamplified. Their argument is based on the successful completion of manned missions so far. A word of caution is in order here. Talking about a 1000-day mission is basically different from the present flight experience of 1 or 2 weeks' duration. Logistic problems dictate that oxygen will have to be preserved and reprocessed, and leak rates will have to be tightened to prevent the loss of oxygen.

The Problem of Exposure to Complex Mixtures

When man is exposed to a multitude of contaminants simultaneously, each component of this mixture, depending on its concentration, may or may not exert a physiological effect. The effects of mixtures of toxic agents may be:

(1) Independent
(2) Potentiative
(3) Additive
(4) Synergistic
(5) Antagonistic

The TLV for additive components is

$$\frac{C_1}{\mathrm{TLV}_1}+\frac{C_2}{\mathrm{TLV}_2}+\frac{C_3}{\mathrm{TLV}_3}+\ldots\frac{C_n}{\mathrm{TLV}_n}=1.0$$

The problem of exposure to mixtures is not new and has been encountered frequently in industrial hygiene control of toxic materials. The listing of threshold limit values (ref. 9) devotes a special chapter to exposures to mixtures. To quote their philosophy:

> . . . when two or more hazardous substances are present, their combined effect, rather than that of either individually, should be given primary consideration. In the absence of information to the contrary, the effects of the different hazards should be considered as additive. That is, when the sum of the following fractions

$$\frac{C_1}{T_1}+\frac{C_2}{T_2}\ldots\frac{C_n}{T_n}$$

exceeds unity, then the threshold limit of the mixture should be considered as being exceeded. C_1 indicates the observed atmospheric concentration, and T_1 the corresponding threshold limit. Exceptions to the above may be made when there is good reason to believe that the chief effects of the different harmful substances are not in fact additive, but independent, as when purely local effects on different organs of the body are produced by the various components of the mixture.

Thus, the burden of proof rests on the toxicologist, and all of you who are familiar with biological research will agree that proving experimentally that components in a highly complex mixture do not have additive effect is an almost impossible research task. To oversimplify this matter, let us take a theoretical situation where 100 contaminants are present in an atmosphere, and all of these contaminants happen to have the same TLV: 100 mg/m³. According to the book, the equation can be balanced to unity only if each of these individual components is present at 1/100 of its TLV concentration; that is, 1 mg/m³. This would imply, then, that any of the components known to be safe at 100 times this concentration cannot be tolerated in a mixture if any of them is present at the TLV level.

Table VIII illustrates a case where there

TABLE VIII.—*Additive Anesthetic and Narcotic Effects From Hydrocarbons, Ketones, and Alcohols*

	Airborne concentration, mg/m³	TLV, mg/m³
Butadiene	2000	2200
Ethyl ether	1000	1200
Propane	1600	1800
Acetone	2200	2400
Ethyl alcohol	1700	1900

$$\frac{2000}{2200}+\frac{1000}{1200}+\frac{1600}{1800}+\frac{2200}{2400}+\frac{1700}{1900}=4.4$$

is positive proof of additive (anesthetic and narcotic) effects from hydrocarbons, ketones, and alcohols. By having these present as a mixture, and each of them at below its TLV, a definite decrement in performance could exist.

The Contaminant Buildup and Exposure Profile Problem

In a sealed cabin with a nominal leak rate and a constant generation of contaminants, the buildup of contaminant concentration is quite rapid and can be expressed by

$$C=\frac{w}{b}\left(1-e\,\frac{-(bt)}{a}\right) \tag{1}$$

where

c = contaminant buildup, mg/m³
w = contaminant generated per day, mg
b = atmosphere leaked per day at x psia, m³
a = total effective gaseous volume of cabin, m³
t = elapsed time, days; e = 2.718

Another equation that is useful to us defines the time required to reach 99 percent of the final equilibrium concentration under conditions of equation (1):

$$t=4.6\ a/b \tag{2}$$

where

t = time, days
a = total effective volume, m³
b = leak per day at x psia, m³

Using equations (1) and (2), and substituting some realistic values for effective volume of the atmosphere in a present-day spacecraft, for proper pressure and temperature, and an unrealistically low constant contaminant generation rate, table IX shows

TABLE IX.—*Contaminant Equilibration Rate*

Typical Cabin Values	
Effective volume	8.5 m³ (300 ft³)
Pressure	253 mm Hg (5 psia)
Temperature	26° C (78° F)
Contaminant generation	0.26 mg/m³/day [a]
Leak rate	1.0 to 0.1 lb/day

Leak rate, lb/day	Equilibration	
	Time, days	Concentration
1.0	30	2.1 mg/m³
0.1	250	21.0 mg/m³

[a] If molecular weight is 64, 0.26 mg/m³=0.1 ppm.

that with our present leak rate, which is approximately 1 lb/day, the contaminant concentration would equilibrate as soon as the 30th day of the mission, at about 2 mg/m³. If the contaminant should be a highly toxic material, such as ozone, although it is generated in quantities not exceeding its TLV for a 1-day exposure, at the end of 30 days it would be present at 10 times this concentration, and there would be severe lung irritation and death. We will be capable of 100-day missions in the coming years and we are projecting ourselves into the most distant future 1000-day mission area. Most likely, leak rates will have to be tightened for logistics reasons. Assuming the same parameters and the same very low contaminant generation rates, but a tenfold decrease in leak rate, 0.1 lb/day, the equilibration would occur at over 20 mg/m³, which means that even a less toxic contaminant could present a serious health hazard.

Because nothing illustrates the point better than a good visual aid, figure 2 recapitulates the rate of exposure of the crew, with the present 1 lb/day leak rate. It can be seen that even on a short 100-day trip, the crew will be exposed to a rapidly increasing concentration during the first 30 days and to a steady concentration during the remaining two-thirds of the trip. From a biological standpoint, if the area under the curve is taken as a measure of exposure, their exposure will be fairly constant for the entire mission duration. Of course, you could live with this situation for 1000 days if your final concentration stays below the limit of undesirable physiological response.

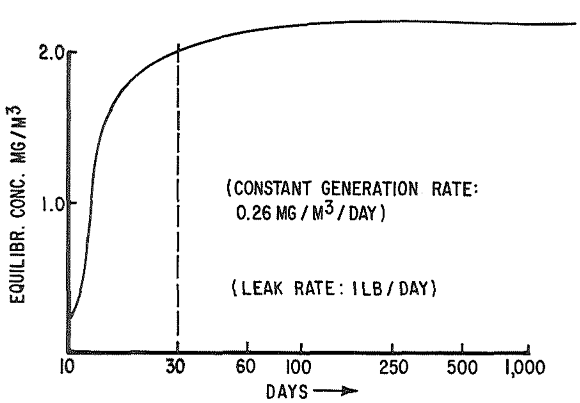

FIGURE 2.—Contaminant profile.

The exposure profile during the 1000-day mission, illustrated in figure 3, assumes a tenfold decrease in leak rates as a logistical necessity, and shows again, from a biological standpoint, that the exposure will be fairly uniform, as related to the area under the curve, because equilibrium will be reached within the first quarter of the mission duration. The great difference, however, is the tenfold increase in the contaminant level, indicating that compounds of moderate toxicity can play a significant role in determining limiting factors for mission duration.

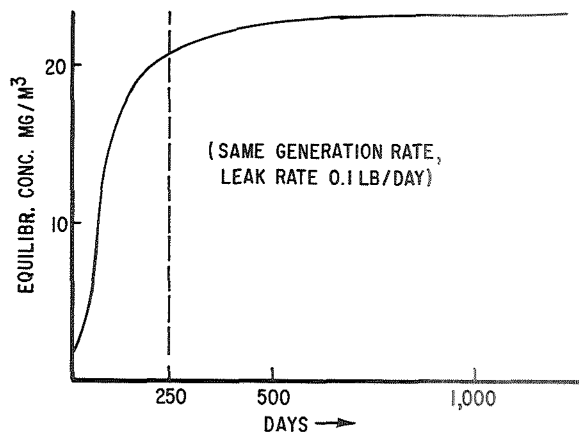

FIGURE 3.—Contaminant profile.

How serious this limitation can be becomes clear from figure 4. This is a distribution graph of the toxicity of industrial chemicals that are listed in the compilation of threshold limit values. For the sake of simplicity, they were categorized by TLV's falling into four major ranges, from 0 to1, from 1 to 25, from 25 to 100 mg/m³, and those in excess of these values. Out of a total of approximately 370 materials, more than 50 percent are in the range of 0 to 25 mg/m³, and these should be considered highly toxic. Almost two-thirds of these chemicals have a TLV not exceeding 100 mg/m³. Notwithstanding that these are chemicals that had to be controlled in the

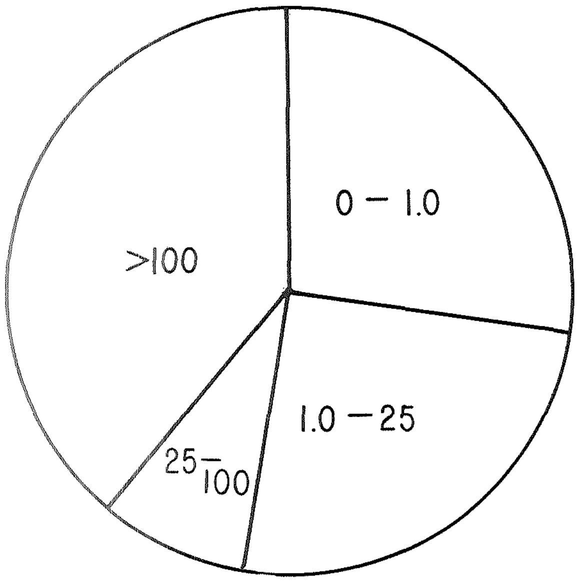

FIGURE 4.—Distribution of TLV's, mg/m³.

industrial environment, there is a valid analogy to control problems in cabin atmospheres. An overwhelming proportion of our gas-off products from cabin materials are industrial chemicals, and the likelihood of a similar percentage of "bad actors" among all the gas-off products is not too remote. Thus, we can conclude that with a 1000-day mission, and a minimal leak rate, even moderately toxic products that must be assumed to have additive effects should be removed from the atmosphere.

The Prediction of Tolerance Problem

Prediction of tolerance to a single toxic compound alone is quite difficult. Some extrapolations can be made from existing animal exposure data and human tolerance; Haber's law, i.e., concentration $\times$ time^n $=$ constant effect, works fine with limited time durations, but in long-term continuous exposure, the value of the exponent n is uncertain, and may vary from compound to compound, and with different lengths of exposure.

Introduction of mixtures to space-cabin environments, together with the artificial atmospheres, causes further complications. At the previously cited Symposium on Toxicity in the Closed Ecological System, Dr. Herbert Stokinger, from USPHS, presented a paper entitled "Validity and Hazards of Extrapolating Threshold Limit Values to Continuous Exposures" (ref. 2). In his paper, he pointed out that all the environmental factors must be taken into consideration, and he introduced the following equation, which, using the basic TLV's and correcting for such changes in environment as the dosage factor from ambient-pressure change to 5-psia pressure change, toxicity from continuous dosage, toxicity from temperature change, toxicity from restricted motion, toxicity caused by the 100 percent oxygen atmosphere, toxicity caused by fatigue, and toxicity resulting from interaction of all these factors, could possibly give an eyeball figure, or a target figure, to be used in setting continuous exposure limits for submarines and spacecraft:

$$TLV_{space}=\frac{TLV_{ind}\times F_{press}}{F_{cont}\times F_{temp}\times F_{decond}\times F_{O_{2_{tox}}}\times F_{fat}\times F_{interact}}$$

where

$$F_{interact}=f_1\times f_2\times f_3\ldots\times f_n$$

f_1 = threefold dose (8 to 24 hr) excess toxicity

f_2 = additive toxicity of O_2

f_3 = fatigue + O_2 toxicity

While this is certainly a very attractive approach, the individual factors must be assigned numerical values if we want to solve this equation. More often than not, these values must be determined experimentally because there is not much known about them. To further complicate the matter, many of the gas-off products that were identified in the analytical studies are not listed in the threshold limit values list, but, by chemical structure, resemble some of their relatives that we can find in the listings. Toxicity information on these materials is nonexistent and must be obtained by animal experimentation.

VALIDATION OF HUMAN TOLERANCE TO TRACE CONTAMINANTS FOR THE 1000-DAY MISSION

Admittedly, the previously listed problem areas are serious and quite discouraging. The present state of the art is centered around some experience with 90-day continuous exposure to certain toxic agents in ambient air environment and in single- and mixed-gas 5-psia cabin atmospheres. Looking at the 1000-day mission, we are not yet certain that man could tolerate any of the 5-psia basic atmospheres for that duration. Much less can we speculate about tolerance to toxic chemicals in such artificial environments.

Every toxicologist can set some limits with a reasonable approach, having a reasonable potential of success, just on the basis of intimate knowledge of toxicity of that chemical. However, even if his predictions are valid 999 times out of a 1000, the one instance where he missed may hurt the whole crew. So we are talking, really, in the case of these lists, about forecasts and educated guesses.

Suppose we should have to submit these values to an Approval Board that would ask: How valid is your estimate? Establishing space threshold limit values for man's tolerance to a contaminant during a 1000-day mission will require the same amount of experimentation, justification, and documentation as required today for qualifying a new drug or a new food additive, or a new pesticide for use in the community. For example, in qualifying a new drug, the following questions are asked: What is the effect of the drug itself on the central nervous system, on the autonomic nervous system, on the cardiovascular system, on the respiratory system, and on the gastrointestinal and excretory system? What is the effect on special senses, on taste, on smell, on auditory, or optic function, or the composition of the blood?

The next big question asked is what is the effect of the new drug on the activity of other commonly used drugs? The duration of action or potency of selected common central-nervous-system depressants and excitants? The effect on the duration of blood levels or the rate of urinary excretion of common acidic or basic drugs? After all, we may have to use drugs during the flight. The effect upon the absorption of essential minerals and vitamins from the gastrointestinal tract? Obviously, these last questions are directed toward potentiation and synergistic effects. As far as the matter of qualifying a new pesticide is concerned, some other questions are also asked. What is the acute toxicity? What is the subacute toxicity? What is the chronic toxicity? A subacute toxicity study, in this instance, is a 90-day study. In the chronic study, the time of elapsed observation is 2/yr. Serial sacrifices, of course, are required during this period, at 6-, 12-, and 18-month intervals. During the whole experimental period, each animal is considered as an individual, and observations are made of every change that affects the individual. You have to take into consideration the dietary effects on the toxicity of that chemical (just as the effects of an artificial atmosphere must be considered). You have to observe satisfactory growth and longevity. You have to know the target organs, and you have to know the mode of action. You have to know the intermediary metabolism, you have to know any adaptive processes going on, such as drug metabolizing enzymes. Of course, you also have to do reproduction studies and paired-feeding studies.

After all this experimentation is completed, it must prove conclusively that whatever pesticide residue remains on foodstuff is a negligible quantity. "Negligible residue" for pesticides has been recently defined by the Food and Drug Administration as—

> any amount of a pesticide remaining in or on a raw agricultural product that would result in a daily intake regarded as toxicologically insignificant on the basis of scientific judgment of adequate safety data. Ordinarily, this will add to the diet an amount which will be less than 1/2000 of the amount that has been demonstrated to have no effect from feeding studies on the most sensitive animal species tested.

Finally, after all this expensive research, the question is: How valid is your extrapolation to humans? I would like to quote Dr. Harry Hays, the former Director of the Advisory Center on Toxicology, from his speech at our First Annual Conference on Atmospheric Contamination in Closed Spaces, where he expounds on the problems of extrapolation and interpretation of animal data to man.

The subject I have been asked to comment on is one on which, I think, can be found no general agreement. There are some, who feel that the risks involved in attempting to extrapolate animal data to man are too great, and that man himself must become the experimental animal. In order to set the stage for this discussion, I think a brief review of the evolution of animal experimentation and predictability of toxicity in man lends some justification for the pessimism that has prevailed on the value of animal studies.

In the beginning, it was customary to use a rat or two, an odd rabbit, and a few mice. Before long, it was clear that toxicity in man could not be readily predicted in this way. So the number of rats increased, and before long, someone started statistics—so the number of rats increased still further. Dogs came in, rabbits went out. Cats became scarce. Well, predictions improved, but still there was a long way to go. So the number of rats increased again, so did the dogs; so did the mice. More species were added—monkeys, chimps, marmosets, quail, frogs, and pigs. Longer tests were required, 10 days, 2 weeks, 6 months, 2 years, 1 whole lifespan. Still no closer to predictability in man. Once it was just toxicity and then it was multigeneration tests. Carcinogens came in, and cocarcinogens; and if you couldn't find a carcinogen, you looked for a mutagen. If you couldn't find a mutagen, you looked for a teratogen. We used not one species, but many species. Not one strain, but many strains. Out-bred, in-bred, brother-sister mated, random mated. Still no better predictability. Once you counted just the dead. This procedure was charged with fallacy, so everything that could be weighed was weighed, and everything that could be removed was sliced and examined histologically. The function of every organ was looked into. From the cellular, we went to the subcellular. Radioisotopes became a must. Physiology gave way to psychology. And now, not even the rat doubts the results!

This may sound humorous, but it is also a very serious and sad aspect in validating tolerance criteria for a 1000-day mission. Compare these things with our present experience. For example, 8 months' continuous exposure to 100 percent oxygen at 5 psia alone seems to be definitely toxic to the dog, but there is practically no change in the monkey and in the rat. The question is, Will the other species also show changes if this exposure were extended to 1000 days? And the ultimate question is, Will man show any changes? And if he does, will we be astute enough to observe them? Will we look at subcellular morphology? Will we do punch biopsies after the flight? There might not be any gross clinical changes. Our animals did not show any abnormal clinical laboratory tests. To observe these changes, you have to look at the cellular level in the tissues. But this is exactly the requirement in qualifying a drug in animal toxicity tests—the cellular changes, the subcellular changes are the earliest indication of any effect, good or bad. You may well ask, then, even if you go through these animal studies, how do you extrapolate to man, ultimately?

From many pharmacological studies leading to the qualification of a drug, taking the no-effect value in an animal, some extrapolations from animal to man have been developed. It is always assumed that man is about 6 times as sensitive as the dog, 10 times as sensitive as the cat, and 10 times as sensitive as the rat. The next philosophical question is, Will we take the no-effect level in animals and then put this 6 to 10 times safety factor on it? Or will we settle for a level that causes no irreversible pathology, coupled with no change in performance? This, obviously, is a decision that we will have to make. It is a decision that is both philosophical and mission oriented, and still, we must consider that man is not expendable.

Considering these great difficulties, it becomes fairly obvious that the chemical insult perhaps could be spared the crew during the long mission. There are other insults that cannot be avoided. The chemical insult most probably could be avoided by engineering methods or by proper handling of the atmosphere. If it cannot be avoided, it should certainly be minimized to the greatest possible extent. We should never engineer to a given tolerance limit; we should try to get zero concentration of a particular contaminant in the atmosphere.

This, then, should be our general approach in developing man's tolerance to cabin contaminants. There is a great danger of being overconfident based on present experience in manned space flight. This overconfidence is multiplied by the apparent safety of nuclear submarine atmospheres. Table X points out the basic differences between submarine and space-cabin environments that aggravate the atmospheric contamination problem during the long space mission. We should also remember that all these ventures are new, and that not enough time has elapsed yet to evaluate objectively the true occupational medicine significance of prolonged confinement to a closed atmosphere on the crew.

TABLE X.—*Important Factors Influencing Atmospheric Contamination*

Aggravating	Beneficial
Continuous generation and exposure	Leak rate of cabin
Reduced pressure [a]	Materials selection
Volume/man ratio [a]	Preconditioning of materials
Power and weight limitation [a]	
Filter characteristics	
Complexity of contaminants	
Mutlistress environment [a]	
Escape leadtime [a]	

[a] Not significant in nuclear submarines.

The same overconfidence in validity of data has resulted in many tragedies in the drug development area—at one time we thought thalidomide was safe! Our margin for error is very small. In a 1000-day mission, the point of no return is reached quickly and dramatically. Choices for corrective action to control contaminants may be limited, or only partially effective.

TRADEOFFS IN EXTENDING HUMAN TOLERANCE TO TRACE CONTAMINANTS

By now it should be pretty clear to everyone that we are hamstrung by two major obstacles in the quantitation of human tolerance. The first one is in the area of experimental verification of tolerance and extrapolation of animal data to humans; the second is that even if we would have a better grip on man's tolerance to long-term exposure to trace contaminants, we probably would find in the process of our attempt to fully exploit his tolerance (whatever magnitude it might be) that we would be taking an unreasonable amount of calculated risk.

Tradeoffs in Biological Research

How can we proceed relative to the toxicological studies on space-cabin material and atmospheric contaminants in the cabin? Obviously, we are talking now about the biological research leadtime area, which is a real bottleneck. If we assume, as we did previously, that we will have to set some tolerance limits with a reasonable degree of validity and safety, we will have to do animal experimentation. Moreover, we will have to do this experimentation in the proper basic cabin atmosphere, which is characteristic of the mission. It is bad enough that we cannot simulate readily many of the other stresses present, such as weightlessness, psychological stress, and so on, although there are some hopeful signs of simulating psychological stress in animals by utilizing conflict techniques in performance measurements. Clearly, then, with the present state of the art, if we would like to set fairly valid tolerance limits for a 1000-day mission, we would have no choice but to run the animal experimentation for at least the full 1000-day duration. Depending on our success at picking the right concentration (or dose) of the chemical at which we would run the experiment, we might find an effect level that is marginal, and then we would have to find the no-effect level. So, we are talking here of at least two or possibly three or four 1000-day runs.

Frankly, this is unrealistic, simply because the facilities for such volume of work in this country, or anywhere else in the world, are just nonexistent. Whatever capability we have now cannot be tied up indefinitely in 1000-day runs because the rate of progress will be so slow as to be useless to the engineering people who are designing these systems. Clearly, the state of the art needs rapid advancement. Presently, there is a great degree of uncertainty in the overall experimental approach to delineate the effects of multiple contaminants on the overall human tolerance, primarily because of the potential synergistic and additive effects. Predictive equations are needed that can extrapolate the integrated toxic effect of a certain concentration of a single toxic agent or a fixed concentration ratio of multiple toxic agents from a minimum-duration animal exposure capable of causing typical chronic effects. Otherwise, the medical authorities cannot predict the ultimate compounded summation of toxic damage with progressive increments of exposure time. Also, to avoid toxic effects, such equations should predict a reduced level of concentration that, for a certain length of exposure, although longer than that used in animal experiments, would be without adverse biological effects.

This clearly puts us into the area of mathematical model design. The equations previously discussed, if interrelated, are a good start. Careful analysis of animal experimental data, with the aid of regression equations and advanced probability statistics, applied to all of the criteria of toxicity (death, growth curves, laboratory data, gross and histopathology findings, and the performance data from trained animals) will certainly lead to a dose-dependent proportional increase in the magnitude of the exponent power of time in Haber's law. Once this relation of the exposure length to toxic effects has been defined mathematically, and verified experimentally over and over again, the model should be further widened by the inclusion of Stokinger's equation. This will require experimental verification of the upper and lower limits for each factor in the equation. Thus, the development of the mathematical model, aside from being the only tool to shorten the leadtime involved in the biological experimentation, will also eliminate the human error that is introduced by the judgment factor in assigning numerical values to a great number of "fudge" factors. On the basis of such a mathematical model, a computing device must be designed, first for test purposes to enable more economical and expedient planning of sequential and comparative toxicological exposure studies in the laboratory, and, ultimately, to be used in decisionmaking on mission abort, should an unexpectedly high contaminant concentration develop during flight.

Tradeoffs in Engineering Design

The greatest potential tradeoffs are in the areas of life support system design. Moreover, these tradeoffs are inherently more effective than biological tradeoffs.

Testing of Life Support Systems

Because it is clear that we must make every effort to supply the purest possible atmosphere for our crew, this implies that our air-purification equipment should be not only oversized but also redundant. Coupled with that, we must have a quick diagnostic capability for malfunctions and their effects on the constitution of atmospheric contaminants in the cabin.

Fortunately, malfunctions can be simulated and studied during the development cycle. Therefore, it is absolutely imperative that each life support system (with its complete assembly of subsystems) undergo a "mode of failure" analysis that detects the implications of one malfunctioning subsystem on the functions of the other subsystems. This should be verified by experimental studies during which complete information must be collected on atmospheric contaminant composition, both quantitatively and qualitatively. This is the only way that the crew will be able to predict the effect of various malfunctions during the trip, and will be able to find the correct procedures for repair, which will not result in the production of unknown or unexpected atmospheric contaminants.

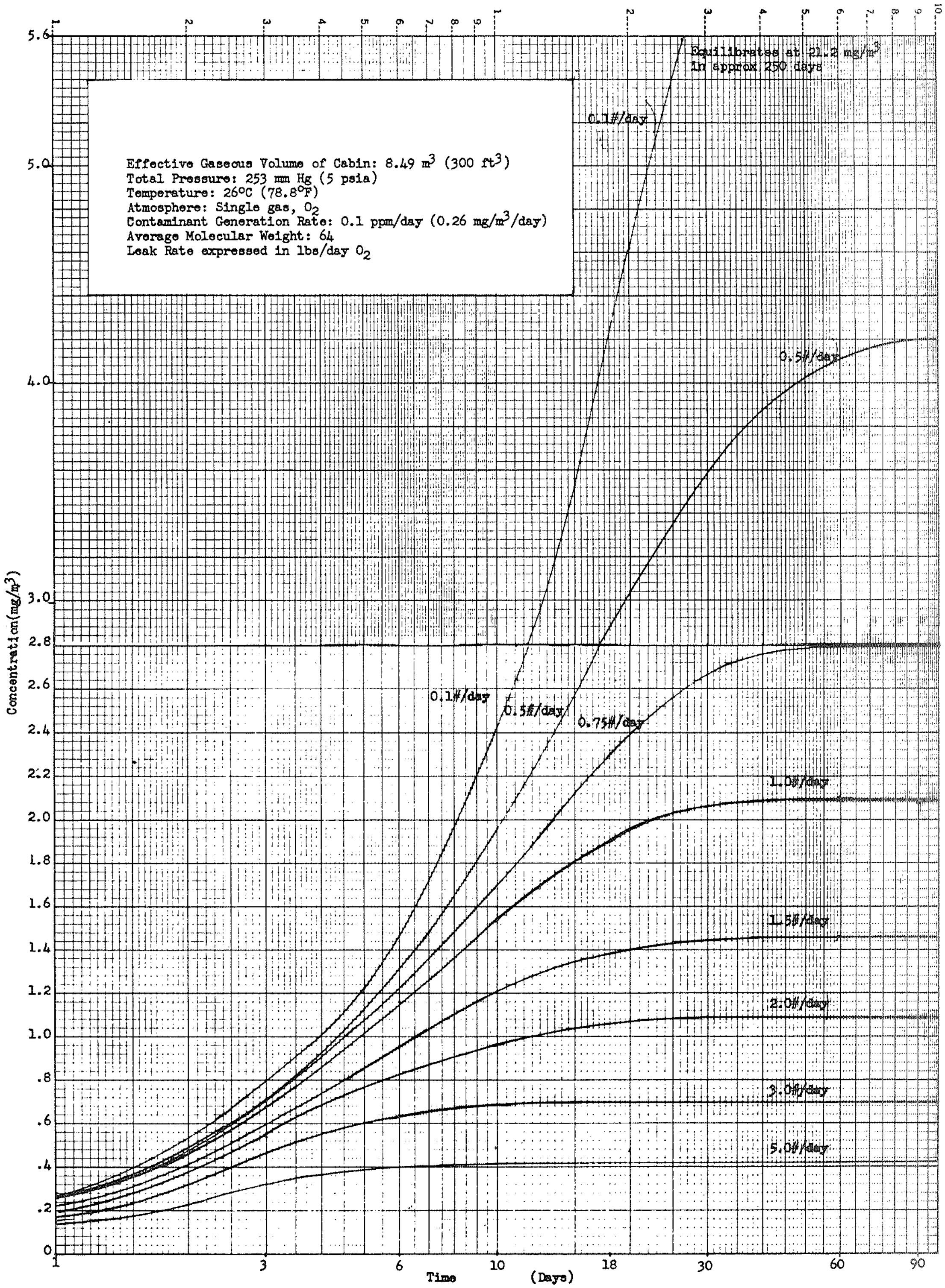

FIGURE 5.—The effect of leak rate on contaminant equilibrium times and levels in sealed cabins without air-purification equipment, assuming constant contaminant generation rate.

Leak Rates

In the previous discussion, the effect of cabin-atmosphere leak was demonstrated to have a major effect on equilibration time, level of equilibration of contaminants, and thus on the overall exposure profile of the crew. Figure 5 illustrates graphically the tremendous decrease of the contaminant problem as the leak rate is increased to 5 lb per day, and the dramatic increase in contaminant concentrations as the leak rate is decreased to 1/10 lb per day. The tradeoff in leak rates is a very attractive contaminant-control procedure that can be designed into the system from the very beginning. It is a far more convenient and a safer procedure than a forced emergency measure of dumping the entire cabin atmosphere and repressurizing during the mission. This latter procedure, of course, requires interruption of the shirt-sleeve condition. Depending on the number of EVA's planned, an optimum cabin leak rate could be selected that would keep the contaminant concentrations low enough between depressurization periods. (It is questionable whether such complete vehicle depressurizations will be performed in the multicompartment, sophisticated vehicles planned for the 1000-day mission.)

Filtering Devices

Filtering devices have two basic problems:

(1) They all reach a saturation point and, to be useful on a long mission, they either must be replaced or regenerated. Figure 6 illustrates the contaminant concentration along the bed and the contaminant concentration on the atmosphere leaving the bed as time of the filter usage increases.

(2) As the composition of the atmospheric contaminant mixture changes (and it will change during the mission), the lower boiling-point materials, which were generated at a slower rate from cabin materials, will increase in concentration and will replace the more volatile materials from the filter bed, thus returning them to the cabin atmosphere. Regeneration of such filter beds, if feasible during such a long trip, must be

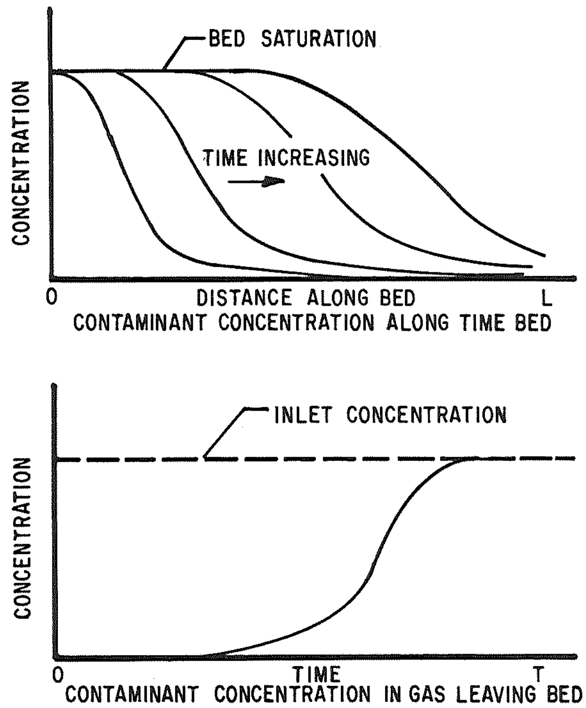

FIGURE 6.—Contaminant concentration.

performed with extreme care, so that contaminants stripped off from the filter do not reenter the atmospheric circulation.

Very likely, there are extraterrestrial sources for absorbents for toxic chemicals. Many of the materials found on extraterrestrial bodies, which have been in vacuum, should be able to absorb quite a considerable quantity of gaseous or particulate contaminants. Processing such materials to increase surface adsorption characteristics and maximize absorbent capacity is within the state of the art. Most likely, materials can be found that are of geological origin and can serve as trickling media or filtering beds for process vessel fillings. This would immensely aid our solid- and liquid-waste disposal.

Replenishment of Oxygen Supply and Power Sources

There is even distant hope that, by some process, water or oxygen can be extracted from extraterrestrial material. This would mean an increased atmospheric supply of fresh, uncontaminated oxygen. Another area where extraterrestrial supplies could become useful is in power generation for the life support system. (Power is required to operate our pumps, compressors, gas exchangers, and even our instrumentation.) It is entirely plausible that materials may be found that are combustible, or that materials could be found that may be directly used for batteries and fuel cells. And, one step further, the existence of radioactive materials has been frequently postulated. Even solar energy might be useful. Farfetched as they may sound, resupply en route might be the only solution to solve atmospheric contamination problems on a 1000-day mission when the point of no return has been reached.

Tradeoffs in Human Tolerance in Emergencies

The final question of course is: Given a set of unfavorable circumstances and unforeseen problems, can we extend man's tolerance itself in an emergency situation? I think the most obvious, and maybe partial, solution to the problem would be to remove man from the contaminated atmosphere, to interrupt his continuous exposure. Perhaps this could be accomplished by supplying absolutely clean atmosphere for the duration of his rest and sleep cycles. Perhaps the crew quarters should be isolated into operational and rest areas. In the rest area there would be a minimum volume of sleeping space and the atmosphere would be clean. Perhaps the airlock, after each EVA, with its fresh atmosphere, could be used for such a purpose. This would mean that we have interrupted the vicious circle of continuous exposure and reduced it to an exposure of 12 hr a day, rather than continuous 24 hr a day. With all the adaptive processes and repairability of the human body, such a break might be lifesaving and might mean the difference between failure or success of the mission. Other ways to accomplish such abruption of continuous exposure would be to use gas masks, filters, oxygen masks, etc.

CONCLUSIONS

The state of the art for predicting man's tolerance to trace contaminants for the 1000-day mission is not here. It must be developed so that it will be present within the next 10 yr. It will take an all-out effort of our scientific talent and of our research facilities. Suitable mathematical models of chronic toxicity during long-term continuous exposure must be developed for single and mixed contaminants to increase the prophetic value of animal experimentation and subsequent extrapolation to man.

Because we are dealing with unknown quantities, both in the toxicological stress and in the combined stress areas, our design philosophy must be that we will not impose a chemical health hazard by contamination of the cabin atmosphere.

We should set tolerance limits only for those contaminants that we cannot eliminate by any method at our disposal, assuming a best effort on the part of our engineers. Examples for such contaminants may very well be carbon monoxide and volatile hydrocarbons.

If we are to set group tolerance limits for a multitude of similar contaminants (e.g., hydrocarbons), we should remember that we must assume that their toxic action is additive, unless we are willing to accept the burden of experimental proof to the contrary.

The types of limits that will be needed are (1) ceiling limits that are valid for the entire mission duration, and (2) two types of emergency limits: the alert limit, which should have sufficient latitude in time duration so that maintenance and repair work can be accomplished without overexposure; and an abort limit, which is clearly applicable only within the initial phase of the mission.

Tolerance to trace contaminants should be studied in a combined stress environment. Mission equivalent length biosatellite programs, where animals could be exposed in the atmosphere of an orbital station to actual contaminants in a cabin atmosphere, simultaneously with all the combined stresses that cannot be simulated in our earthbound laboratories, are highly desirable to advance our knowledge. The state of the art to maintain these animals by only periodic visits of scientists and technicians from Earth is clearly here. Without this type of animal testing, any tolerance limit set for 1000-day missions will remain a highly speculative figure. If a separate program is not feasible, the manned orbital laboratories should consider animal complement to the crew. By leaving the animal population in orbit for substantially longer periods than the astronauts, valuable histopathological information could be developed on adaptive and incipient degenerative changes at the cellular level.

Life support system components, subsystems, and the integrated system should undergo a rigorous mode of failure analysis to avoid catastrophic toxic exposures as a result of malfunctioning equipment or the application of stopgap emergency procedures and in-flight modifications or servicing. The effect of proper and feasible corrective actions on the contaminant spectrum should be verified experimentally.

The study of the potential resources for life support systems in the extraterrestrial environment must be pursued. On the material resources side of the extraterrestrial environment rests the only hope for truly interplanetary missions and the exploration of the planets. Our best prediction is that on such missions, toxic manifestations from trace contaminants could become the true limiting factor to mission duration if resupply of oxygen and filtering media is impossible.

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Space-Cabin Contaminants: Sources and Control

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Insofar as human requirements are concerned, the primary objectives in the design of the space capsule are to provide an environmental work area in which the mission can be carried out in comfort, with maximum efficiency, and without significant injury to the occupants.

Safely sustaining man in a closed system for a relatively long period of time is not particularly new or unique. This problem has been handled by the Navy for years, and many successful missions have been performed in which prolonged periods of submergence in nuclear-powered submarines have been required. The experience and data compiled on submarine-contamination problems have direct application to space-cabin function. While the problems in the two systems are similar, the environmental control problems in spacecraft are greatly accentuated by the internal and external environments of the vehicle. There have been no major difficulties with regard to trace concentration of toxic contaminants in missions of up to 14 days. The major problems, then, appear to be associated with missions lasting longer than 2 weeks and those that could not be easily aborted into the friendly atmosphere of Earth or, possibly, from acute failure of systems and equipment. The major needs in regard to trace contamination, then, are as follows:

(1) Prevention, as much as possible, of contamination by trace concentrations of toxic substances. This involves determination of the origin of trace contaminants, identification of the nature of possible contaminants, selection of materials with regard to their offgassing and degradation products, and selection of systems and equipment with regard to toxic products of malfunction or failure.

(2) Rapid detection of trace contaminants in confined spaces.

(3) Adequate removal (or other methods of returning to nontoxic levels) of the contaminants from the closed environment.

(4) Adequate knowledge of man's long-term tolerance to various trace contaminants.

(5) Evaluation of the effects of problems peculiar to the space vehicle on the toxicity of contaminants.

Possibly because of its high leakage rate, no significant trace contamination of the Gemini vehicle has been noted. However, because near-zero leakage is necessary to conserve the atmosphere on extended manned missions, the buildup of contaminants from the equipment and from man himself could become a serious problem. Some contaminants may be irritating but not life threatening, while others, by a cumulative effect, may actually be life threatening. Some contaminants may be directly irritating to the skin, eyes, or upper or lower respiratory tract, while others may produce a systemic toxic effect after being absorbed into the body. Although many of the possible contaminants have no effect on respiration, they are important in relation to respiration because the majority of them are in the gaseous phase and are most commonly taken into the body by that means.

Although much is known about the toxicity of various trace contaminants, the deficiency is that most of the knowledge has been obtained on the basis of industrial exposure. The threshold limit value (TLV) represents the upper limits of toxic concentration to which nearly all workers can be exposed day after day without ill effect and is designed to be used for only 8-hr exposures in a 5-day workweek for a 30-yr or more work span. In addition, much of the information on contaminants has been obtained from animal studies and extrapolated to man.

ORIGIN AND SOURCES

Trace contaminants present a formidable challenge in space vehicles. I have already mentioned a basic approach to resolving the problem. First, the problem must be defined in terms of the contaminant, theoretical or present, in the closed system. Second, after the theoretical or actual contaminants have been delineated, defined, and described, instrumentation must be designed for qualitative monitoring of the substances. Third, methods of removal or control must be practical.

A great deal of knowledge has been accumulated concerning the origin of trace contaminants. In a closed ecologic system, many contaminants will appear in the immediate environment of the astronaut. Under normal conditions, most would be of no concern, but because of the vehicle's closed ecologic system, input is continuous and outflow is limited. Therefore, gradual accumulation occurs over a period of time.

It is generally agreed that there are six possible sources of contaminants: man, materials, machines, equipment and systems failure, extravehicular, and secondary generation.

Man

From man, the principal sources of these substances would be expired air, urine, feces, and perspiration. Saliva and desquamated skin could also contribute. Carbon dioxide is the principal contaminant of expired gas and is a normally present constituent. Its removal is, of course, an absolute necessity in a closed system, but this has been accomplished in many other situations in the past and, therefore, is a problem with which scientists are familiar. It is well known that carbon monoxide is produced endogenously and excreted primarily in expired gas. Over 100 individual electrolytes, nitrogenous substances, lipids, carbohydrates, organic acids, vitamins, and hormones have been identified in the urine. Nitrogenous substances account for the greatest part of these. Feces amount to about 150 g per day and contain many substances. Fecal odor is due primarily to the presence of aromatic substances, chiefly indole and skatole, derived from the deamination and decarboxylation of tryptophane. Flatus will also be introduced. Its principal gases are carbon dioxide, methane, organic sulfides, hydrogen, and mercaptans. This will vary with changes in the diet. Chromatograms of saliva indicate the presence of ammonia, acetone, methanol, ethanol, methyl ethyl ketone, acetonitrile, and volatile amines. Sweat has urea, phenols, ammonia, and electrolytes. Coexisting with man within the space vehicle cabin will be micro-organisms, fungi, and algae. These may also produce noxious gases.

Materials

Until the precise nature of the structure of the space capsule and the materials to be used are described, it is not possible to state with certainty all of the possible contaminants. Hodgson and Pustinger have described a program to establish the offgassing and oxidation products from individual cabin materials. They have tested 150 materials and over 1500 gaseous environments to identify and estimate concentrations of gas-off products. They also found that at 25° C, little increase in gas-off products occurred after the first 30 days if there was no purging and if the chamber was not recharged; but if the chamber was purged and recharged, additional gas-off products accumulated after the first 30 days. Thomas and Beck have noted the problems of "boil-off" induced through operations inside space capsules at low pressures. Release materials will be derived from surfacing materials, adhesives, plastics, plasticizers, oils, solvent fluids, and metals. Based on submarine experience, careful avoidance must be made of such common substances as polishes, paints, lighter fluids, shaving soaps, and hair tonics to avoid air contamination. Carbon monoxide is not only produced endogenously but is also a degradation and offgassing product of many materials.

Machines

Air contamination may result from normal operation of some machines. Study of the gaseous contaminants originating in submarines is not entirely applicable, but it does provide a useful approach to determining possible sources of contaminants. These have resulted from operations of devices controlling CO_2 levels, batteries, and electronic and electrical equipment. The Navy has also been very careful about equipment that might smoke and foam under normal operating conditions, such as tape recorders, duplicating machinery, etc. The volume of submarines, however, will permit more leeway than the smaller space cabin insofar as allowable contaminants are concerned. More than 50 different gases from the several hundred believed to be present in the sealed environment of nuclear-powered submarines have been isolated. This complex mixture of gaseous atmospheric contaminants comes from many sources. Neither the acute nor chronic symptoms of intoxication attributable to exposure to any of these compounds has been reported in submarines; it would appear that such control methods should be sufficient in the sealed environment of the future space vehicle, but the small volume of the spacecraft would permit a quick rise in concentration from a small contamination leak. It has been estimated that only 0.0005 of the amount of contaminant is needed to reach similar concentration in the air of the space capsule as compared to the submerged submarine.

At least 46 contaminants were identified in the internal environment of the Mercury spacecraft as a result of stripping the atmosphere of contaminants by means of activated charcoal for postflight analysis by Saunders. The major constituents, accounting for 99.5 percent of the total, were CO_2 and Freon-114. The pattern of the contaminants was similar in all flights analyzed, and practically all evolved in the outer cabin atmosphere as distinct from the separate atmosphere of the astronaut's pressure suit.

Equipment and Systems Failure

It is possible to have equipment and systems that produce no contamination at all when functioning properly, but that, with malfunctioning or failure, produce toxic trace contaminants. On occasion, selenium rectifiers have given problems in aircraft. In a simulated space cabin, nitrogen dioxide and ammonia were reported as being generated through malfunction of the water recovery system. Carbon monoxide is one of the most common trace contaminants. Its commonest source in small amounts is ordinary smoking. Carbon monoxide and aldehydes are frequent breakdown products of equipment failure. In a systems failure resulting in fire in a confined space, large concentrations of carbon monoxide, possibly lethal, may be produced. Toxic environments result from thermal decomposition of electrical equipment, hydraulic fluid, and oil. In 1966, Saunders reported that the crew of manned environmental systems assessment developed symptoms of appetite decrease, nausea, vomiting, itchiness around the eyes, headaches, sore gums, and painful jaws. This was in the first few days of a 30-day study with five men in a closed system. The mission was aborted on the fourth day. The trace contaminant producing these symptoms was determined as dichloroacetylene that possibly resulted from some systems or equipment malfunction. There are many other possible contaminants that we could mention as being breakdown products in equipment malfunction or failure—this is a very prominent possible source of toxic contamination and one that must be given much consideration.

Extravehicular

This is an unknown quantity because no vehicle has been exposed to long-term space flight or to the simulated conditions of such. Since the condition of $0g$ cannot be simulated, only postulations can be made prior to actual long-term manned flight. Actually, movement of external contaminants into the spacecraft is unlikely because the pressure gradient will be such that escape from the capsule into the external environment is much more likely. Radiation in space may create new decomposition products from cabin materials, however.

Secondary Generation

It has been suggested that electromagnetic radiations may enter the capsule from without or be generated from lighting aboard. These wavelengths may catalyze formation of aerosols similar to the photochemical reaction that occurs in Los Angeles.

Additional Comments

In a study designed to describe the effects on man of a mixture of oxygen and helium at 258 mm Hg total pressure (O_2: 175 mm Hg; He: 74 mm Hg), four human volunteers were exposed to this atmosphere for 56 days. The atmosphere was then analyzed for major and minor constituents by Adams and coworkers. Sixty-eight minor constituents were detected and concentrations were below the level thought to cause physiological effects. Another study with four men in a closed system for 30 days showed the maximum concentrations of carbon monoxide, carbon dioxide, ammonia, sulfur dioxide, hydrogen sulfide, nitrogen dioxide, chlorine, hydrocarbons, aldehydes, cyanide, and phosgene to be well below alert values. But these investigations have not, in general, been specifically designed to study contamination. Conkle and coworkers have conducted a study to define the contaminants associated with human occupancy of a sealed environment in an oxygen-nitrogen atmosphere at 760 mm Hg total pressure with an oxygen partial pressure of 165 mm Hg. The study consisted of an 11-day background (unmanned) and a 14-day manned period. A total of 97 compounds was identified, with 22 noted only during the manned portion of the study. Methane production was within the limits of flatus production. Carbon monoxide was produced at the rate of 0.37 ml/man/hr and was the only compound produced by man at such a rate that it clearly would require removal in long-term sealed atmospheric habitation.

In many other closed environment studies, including submarines, simulated flights in various test chambers at such places as SAM and Langley, and Mercury and Gemini vehicles, numerous trace contaminants have been identified, although the sources of some of these have not been identified.

In summary, then, so far as the origins go, numerous trace contaminants have been identified in the atmospheres of confined spaces. Their origins have been found to be primarily from endogenous production within the body, degradation and offgassing of materials within the closed space, or some breakdown or malfunction of equipment or system. Other possible origins of contaminants have been discussed. Some trace contaminants have been identified and others have been recovered but not identified. It is likely that a great many others will be noted as further studies proceed.

CONTROL

Manned spacecraft are faced with a unique problem in the need to measure confined, continually recycled atmospheres and the contaminants therein for, as I previously mentioned, after the theoretical or actual contaminants and their sources have been delineated, defined, and described, instrumentation must be designed for qualitative and quantitative monitoring of the substances. The detection system must be rapid enough to prevent the occurrence of significant contact with toxic levels of contaminants. These minute samples present a problem, for although initially they may have little significance, they will probably have a cumulative effect on the astronaut. As they are compounded, the problem becomes more perplexing. The cabin materials that give rise to noxious gases and vapors may not be too different from those found in undersea craft. The differences that will be present, however, have been mentioned. There are payload limitations requiring a closed ecological system for supplying a habitable environment during prolonged manned space flight. The cabin will most likely be operated at less than 15-psi pressure, thus enhancing greatly the problems of boiloff from such common substances as paints, varnishes, adhesives, plastics, oil solvents, fluids, and even metals, to mention only a few. Zero-*g* conditions will also give rise to problems with particulate matter such as dust and aerosols, which will have a tendency to clump into larger and larger aggregates and be harmful to both man and filtering systems.

Another, and possibly the most important limitation, is the electric and mechanical power supply. Submarine engineers were able to deal satisfactorily with most of the problems mentioned as a result of the advent of nuclear power, which allowed almost unlimited power for air-conditioning systems, air-filtering beds, air-pollution instrumentation, and contaminant warning systems. Even then, cabin air became contaminated. The requirements for space-cabin design are thus very stringent.

To reiterate, then, the first step in control is an attempt at prevention of contamination with toxic substances by determining the origins, identifying the contaminants, and selecting materials, equipment, and systems with regard to degradation products and products of malfunction and failure. The next step is rapid detection of toxic contamination when it does occur. Most of the studies previously mentioned have been carried out in chambers or environments where the concentration of the contaminant can be rigidly controlled. Identification of many of the contaminants has been made by removing all the noxious gases from the atmosphere by means of activated charcoal—analysis and separation being carried out later. Detection of the contaminant and determination of its concentration have been carried out primarily by gas chromatography and mass spectrometry, but the ability to sense the complete spectrum of the spacecraft contaminants has not yet been achieved. If contamination, even the most remote sign of contamination, cannot be prevented (and it is highly likely that it cannot), then it is obvious that a detection system is an absolute necessity. As already mentioned, the primary objectives in the design of the space capsule are to provide an environmental work area in which the mission can be carried out in comfort, with maximum efficiency, and without significant injury to the occupants. We must be aware, then, of the possible contaminants to which the occupants may be exposed over an indefinite time, singly and in multiple combination, without adverse effects and aware of those to which they cannot be exposed for any length of time. The presence of any in this latter group must be detected early, and they must be removed or preparations must be made for their levels to be continuously monitored and controlled, such as must be done with carbon dioxide.

The next step, then, is adequate removal of contaminants; that is, a method for returning the atmosphere to a nontoxic level in the closed environment. Conventionally, activated carbon has been used to remove aerosols, and a catalyst is used to remove contaminants such as carbon monoxide. Cryogenic trapping systems are being studied. Air from any source can be made acceptable and pleasant if sufficient equipment can be used for the removal of contaminants, freshening, and purification. The basic problem is to provide a safe atmosphere within the limitations imposed by the restrictions in the weight of machinery necessary to accomplish the task. It is important to know about the theoretically possible contaminants and probable acceptable TLV values for continual occupancy. Even though predictions are made of possible contaminants and measures taken to assure control within acceptable TLV's, provision must still be made for the emergency solution to the problem of the sudden accidental appearance of toxic material in high concentrations. These would probably best be countered by using the emergency self-containing air support and dumping the cabin gas.

The problem of toxicity of substances occurring in a closed ecologic system has been the subject of a number of symposia and reports, and lists of possible contaminants have been compiled. A National Academy of Sciences ad hoc committee is now in the process of establishing and making recommendations on air standards for long-term manned space flight. These are all necessary steps before final methods for control can be established. The problems peculiar to the space vehicle and their effects on the toxic actions of air contaminants must also be considered. These include weightlessness, increased oxygen tension, increased radiation levels, electromagnetic energies, increased particulate load, reduced pressures, vibration, noise, and acceleration.

SUMMARY

In summary, then, the theoretically possible sources of contaminants are man, machines, materials, equipment failure, extravehicular, and secondary generation. The major needs are prevention, as much as possible, of contamination; rapid detection of toxic substances; adequate knowledge about TLV's for continual occupancy; and methods to maintain nontoxic levels of contaminants.

As I visualize the situation, the problem areas and gaps in knowledge are:

(1) Adequate identification of the contaminants.

(2) Prevention of the production of contaminants by system failures or release from materials. In selecting materials to be used aboard the spacecraft, it is valuable to have a toxicological checklist to determine the potential problems anticipated from the off-gassing or degradation of the product.

(3) Knowledge of the effects of special space vehicle factors, such as $0g$, on accumulation and toxicity of contaminants.

(4) Development of appropriate instrumentation to sense the complete spectrum of spacecraft contaminants.

(5) Further development of systems to remove a variety of trace contaminants from the closed environment of the space vehicle.

Nutrition and Food Requirements for Space Voyage

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The subject of nutrition and food management for space flight is a very broad one. The problems of short-term and extended flights require separate solutions.

The short-term flights, up to 14 days, actually do not present a serious nutritional problem because man can survive without food for this period. In this period of time, work and performance degradation are not very great and no serious metabolic malfunctions occur. The problem that has occurred in the short-term flights has been dehydration. This is a separate problem and will be discussed individually. The discussion of the possibilities of the longer term flights, up to 1000 days or more, presents an entirely different problem. Man must be supplied with adequate calories and all the other necessary nutrients. This will be the major part of this discussion.

GASTROINTESTINAL TRACT PROBLEMS

In addition to the problems of nutrient and water intake in space, there is the associated problem of the functional integrity of the gastrointestinal tract. It has been pointed out several times that contamination of the cabin atmosphere increases the toxicity of the closed environment. One source of such contamination is flatulence, hence foods that increase the intestinal gases increase contamination of the air. In addition, there are the problems of nausea, vomiting, and diarrhea. Vomiting in 0*g* atmosphere where particles remain suspended can be disastrous. One can visualize how vomiting can contaminate the atmosphere both with the particulate matter and with the aromatics. Diarrhea, which could be the result of bacterial contamination or of allergies to the food, would be an equally great disaster to the astronauts in a closed environment. The management of fecal waste has been minimized by the use of low-residue diets. Bowel movements occur every 3 to 5 days and consist of solid inspissated fecal masses that are comparatively easy to handle. Diarrhea is a problem that could be brought about by improper food handling or by the improper choice of food for the situation or the conditions involved.

EFFECT OF 0*g* ON METABOLISM

Even primitive man knew that when a body was warm the man was alive and when it was cold he was dead. This obviously meant that heat or energy was an integral part of the maintenance of life and that a human being, as long as he is alive, gives off heat. This heat has to be supplied by some form of energy. This energy comes from the food that we consume. Some environments have a greater demand on energy requirements than others. In cold environments where the heat dissipation from the body is great, when adequate protective clothing is not provided, metabolic rates increase to provide this increased heat loss. In warmer climates, if the body temperature does not rise, heat dissipation is lower because of the equilibration between the body heat and the external temperature. The replacement heat demands are lower and metabolic rates drop. The food requirements of man under any and all conditions in which he is going to work should be determined. The orbital environment is unique and to date there have not been any adequate measurements of the food or energy requirements of man under these conditions. This is not because it has not been tried or because the people in charge of the program are not aware of the problems. It is because the difficulties have been so great, and under the constraints of the development of the programs, this type of physiological measurement or medical program has not been completed. At the present time, the energy requirement of the astronaut is not known exactly. The stresses to which he is subjected in the capsule at liftoff, and subsequently, create certain demands or change the demands on these metabolic requirements. The effect of $0g$ on metabolic or work requirements is unknown. There are indications as to what some of these effects will be, but there are no quantitative definitive measurements available to date that can give the data from which the proper calculations could be made. The food requirements for the astronauts in space under the current conditions are a matter of guesswork; however, it is educated guessing, and I am sure that nobody is going to suffer for want of calories in these short-term flights.

What happens to the basal metabolic rate at $0g$? Is the muscle relaxation such that oxygen or caloric requirements decrease appreciably or is relaxation insufficient to be a major factor in oxygen or caloric requirements? This is completely unknown. The Soviets have presented some data that would indicate that in the case of the female astronaut, there was a decrease of about 30 percent in her oxygen requirements after 3 days; in the case of a 5-day astronaut, there was a decrease of about 35 percent in his oxygen requirements that subsequently returned to normal. This is not incompatible with the theoretical anticipation of the changes that could occur with the relaxation associated with $0g$. Some of Dr. Don Wheadon's analysis of the urine from Gemini 7 carried out at the National Institutes of Health give an indication of a nitrogen loss that could be an indication of muscular atrophy. This is compatible with the concept that there may be a decrease in the resting metabolic rates at $0g$. During the periods of mechanical work the problem is entirely different. There has been a fair amount of work carried out on the terrestrial surface in connection with energy expenditures in pressurized suits. Energy expenditures as expressed in kilocalories (kcal) are quite different in a spacesuit than in ordinary clothing. Walking at the rate of 1 mph at sea level in light clothing requires about 100 kcal. This is for the "standard man" of 154 lb, 5 ft 10 in., walking at the rate of 3 mph. If this man puts on an unpressurized spacesuit, which is heavily insulated, then his cost of walking per mile jumps from 100 kcal to approximately 250 kcal. This is really the penalty he pays for wearing clothing that is somewhat binding and certainly prevents adequate heat dissipation. If the spacesuit is pressurized at about 3.5 psi (as are the current models), the astronaut is forced into an abduction position because of the ballooning of the suit. The cost of walking a mile becomes 400 to 500 kcal instead of the original 100 kcal. It is apparent that unless improved pressure suits become available, extravehicular activities are going to cost a lot in terms of food and oxygen.

FOOD FOR LONG-DURATION FLIGHTS

In the long-term flights, the total weight of the food system becomes critical. It becomes essential to know the requirements exactly to couple the engineering constraints of weights and volume with the metabolic requirements of the man and the design of the optimum system for the situation evolved. Up to now, the short flights of both the American and Soviet astronauts have served to solve certain basic problems. Man can chew at $0g$ and there is no problem in deglutition. The peristaltic motion of the gastrointestinal tract proceeds on essentially a normal mechanism, and the food bolus is propelled through. Digestion is normal. Before man had the opportunity of spending time in space, there were many people who said there would be problems in the gastrointestinal tract. The lack of definite interface between the fluid and the gas at $0g$ will create problems in the stomach with the normal gas bubble and in the intestines with peristalsis. Fortunately, these predictions did not prove to be true, and the gastrointestinal functional problems have not been a major part of any of the difficulties concerned with the flights to date.

The concept of Mars or Venus flybys or planetary stations makes it necessary to plan for life support systems capable of keeping a man up in this environment for periods of 3 to 5 or more years. Reliable life support systems must provide oxygen, water, and a complete diet. Not only must this diet be adequate in terms of nutrients, macro and micro, and water, but it must be acceptable to the man. He must consume it and not develop nausea or anorexia. The metabolic requirements must be known exactly so that the diet can be designed to be adequate for the conditions under which the man will work, but not enough is known about the conditions under which he will work to define the basic requirements. The designers are working with several unknowns and attempting to come up with answers that will be close to the truth. For planning purposes, one must proceed but one must be prepared with several contingency plans in case the situations change or information is developed that will allow one to make more exact plans.

For flights extending beyond 60 days, the weight and space requirements are such that the penalty is too great to bring food from the surface of the Earth. Regenerative systems both for food and oxygen will have to be developed. If such a system could do both at the same time, it would be ideal. The questions of the tradeoffs as to the various possibilities will be discussed very briefly as we go along. Such systems that can probably regenerate oxygen from carbon dioxide and reclaim some of the wastes from the urine and the feces are related to the growth of certain unicellular plants such as the various types of algae and bacteria. There are some types of bacteria, as for instance, the hydrogenomonas, where one would require a power source to electrolyze the water to provide hydrogen. The organism can survive on hydrogen plus urea as a source of nitrogen. (Urea is available in the urine.) The use of this type of organism, however, presents many difficulties. Let me just point out some of the problems that would be present if one were to use this type of organism as a total source of calories. These organisms are about 80 percent protein by weight. They contain about 10 percent lipid and trace amounts of carbohydrates. The biological value of the protein of this type of organism compared to egg whites is about 77 percent. It is quite a good protein and would be very adequate for human nutritional requirements. They will supply about 400 cal per 100 g of dried organism. Four cal/g is a very concentrated source of nutrition, and, from this point of view, they look quite ideal. If a human were to consume this hydrogenomonas as the sole source of calories and proteins, then many other problems would arise. To meet the caloric requirements would require about 750 g of the organism.[1] This would mean that the man would be taking in about 500 g of protein a day because you will recall that this organism is approximately 80 percent protein. This could be a tremendous waste of energy. First, there is the energy required to synthesize the protein, and second, the fact that one cannot metabolize proteins completely because urea (the end product) is still a potential source of energy. This imposes a great burden on the total system. What is more important is the burden it poses on the kidneys. 500 g of protein a day increase the obligatory water requirements to a point more than triple that which would be required under a more aver-

[1] I wish to thank Dr. Doris Calloway, of the University of California in Berkeley, for making these data from her COSPAR 1967 paper available to me.

age protein intake. Water is the limiting factor under some conditions in the spacecraft, and certainly the burden on the kidneys of having to wash out this amount of metabolic nitrogenous end product becomes a possible source of serious danger, particularly if any dehydration does develop. The lack of sensation of thirst has been reported in short-term flights. We have no concept as to what happens to the thirst mechanism when a steady state is reached on the long-term flights. Suppose that the low-thirst mechanism exists later as it does earlier. The accumulation of nitrogen in the blood would be sufficient to create a serious problem. The water requirements would increase to over 5 liters a day. In addition, there is another problem that large amounts of these organisms bring about—the nucleic acid content of bacteria.[2] Normally, in our daily diet, we consume about 2 g of nucleic acids a day, and we do know that under certain conditions if as much as 8 g of nucleic acid a day are consumed by an individual, the concentration of blood uric acid will rise as high as it does in people with gout. If people are going to consume the 750 g of bacteria to supply the daily caloric requirements, there would be about 50 g of nucleic acid in this dietary intake. If it does raise the blood uric acid content in normal people to the level that can be anticipated, then deposits of the urates in the tissue and crystals that are painful and disabling can be expected in the urine. Theoretically, this is a good source of protein that at the same time is capable of helping regenerate an oxygen system, but its drawbacks in the area of water requirements and the renal systems are such that it appears impractical for long-term flights. I think we will have to go to other types of regenerative systems, and use these as a supplement rather than as a principal source. One may have to use more than one system because, if the amino gram requirements are not fulfilled by the proteins from the algae, a small amount of protein from the bacterial system would supply the amino acids that would fulfill the amino gram requirements of the algae. We have to work with the engineers and supply them with the biological data to select the method that would result in the optimum system for the weight, volume, and power requirements. The utility of the system must be such that it can be used for the specific mission. I question whether a system can be devised that will work for all missions. I think that each mission will have to have its own system to supply the individual requirements of the individual astronauts because the protein requirements of each individual are somewhat different. It will be necessary to titrate these requirements to fairly minuscule differences on account of these volume, weight, and time limitations. Certainly we will have to design the system to meet the demands of the size of the crew, the duration of the flight, and the individual members of the crew themselves.

Dietary recommendations must be very practical. Some of you may remember the biscuits that came with the K-rations in World War II. They were eventually renamed the "K–9 biscuits." These were ideal for nutrition and had the nutrients that man needed in them, but they were not acceptable to the troops. Let us not design diets for the astronauts that are nutritionally optimum but practically worthless. These secondary problems may arise from too sharp a focus on the nutritional optimum. We cannot expect to optimize each one of the systems. We will have to optimize the total voyage rather than any one individual system or individual component in the mission.

The diet itself should be simple, with emphasis, if possible, on natural foods that will supply the nutritional components. I believe that a liquid diet should be used during those missions where metabolic measurements are being made. We must get the measurement of the true metabolic requirements of these individuals. We know from our standard metabolic work that these liquid dietary mixes are easy to handle. They are uniform in composition, and we, therefore, can measure the dietary intakes simply by the simple tech-

[2] *Ibid.*

nique of measuring the volume of liquid-diet intake. Certainly for the first voyages some type of liquid homogenized diet should be preferred, for this very basic reason of supplying data, but this does not mean that liquid diets would be used entirely and will be used eventually for the long-term voyage. These studies of the metabolic requirements and metabolic degradations are extremely important because to date there have been no satisfactory metabolic measurements. Urine collections have been inadequate, not because the people have not wanted to do it, but because the difficulties of the situation have been such that the urine collections have not been complete and the analytical work on the few urines that have been collected have shown that the problem of collection is a major obstacle. The problems of balance preclude the use of stews and other types of mixed foods at the present time. If a stew is served, one may pick out a piece of meat and leave the vegetables behind. This makes it difficult to calculate the intake, and, for this reason, the homogenized mixture is preferred.

The composition of the diet should be approximately 12 percent protein, 50 to 55 percent carbohydrate, and 30 to 35 percent fat. You will recall the work of Johnson and Sargent at the University of Illinois over the period of many years on optimum food ratios for survival diets. They found under all conditions and over a variety of caloric intakes and expenditures that this particular ratio was the one that served the purpose best. During certain periods of the flight, however, it becomes apparent that the sodium and potassium requirements are going to change because of adrenal response to stress. It may well be that we will have to supply up to 15 g of sodium chloride a day and at the same time we will have to minimize the potassium to about 1 g a day to satisfy this adrenal response to stress. Approximately 2.5 liters of drinking water a day will be required if the protein intake is not allowed to get to the point of increasing obligatory water requirements. Water intake can be based on a very simple measurement: specific gravity of the urine. This must be kept below 1015 to avoid hemoconcentration. The pH of the urine will vary with the composition of diet. This can be determined preflight.

The weight of the food, water, and bottled oxygen or chemical sources of oxygen for each man each day is 14 or 15 lb (6 to 7 kg). In terms of the 1000-day flights, this is about 2500 kg per man per year. Fifty-five hundred lb, or 2.5 tons of food, oxygen, and water, are required at launch for each year that the man is in space. For the three-man flights, this would be 6 to 7 tons for each year. This is a tremendous weight penalty and is the reason regenerative systems must be employed. The biological quality of the protein in algae can be adjusted quite easily to serve the purpose. The chief difficulty with algae as a food source is poor cell-wall breakdown and resulting gastrointestinal disturbance. In London, 2 or 3 weeks ago at the COSPAR meeting, a Soviet speaker stated that the gastrointestinal disturbance brought on by the chlorella (a type of algae) intake was so bad that they do not anticipate using it in their long-term space voyages.

It may be necessary to change the ratio of carbohydrates to fats under certain conditions. The measurement of man's metabolic activities usually includes his respiratory quotient (RQ); that is, the ratio of oxygen to carbon dioxide in his exhaled air. This is an indication of the type of food that is being metabolized. An RQ of 1, meaning CO_2 and O_2 are equal, indicates that only carbohydrate is being oxidized. Burning fats result in an RQ of 0.7. The RQ from proteins is somewhere in between, at about 0.85, because the carbon matrix of the various amino acids is mixed. The unicellular regenerative systems have an assimilation quotient corresponding to the RQ. Most of the algae under study have an assimilation quotient of 0.89. It becomes obvious that if the respiratory quotient of the man deviates very greatly from 0.89, the regenerating system will fail in the course of time because the O_2 regeneration will not be compatible with CO_2 production.

The metabolic mixture for the man should be designed so that his respiratory quotient at least approximates the assimilation quotients of the regenerative system and, thereby, avoid major changes that can lead to bad results. I have not mentioned the calcium problem. One can say from the reports that in some of the early short-term flights, there was apparently X-ray evidence of extensive bone demineralization. During the long-term flights, where procedures and exercise were carried out, the demineralization problem apparently was not as severe as it was during short periods. Preventive or corrective measures are certainly available and can be developed.

SESSION III

Life Support and Mission Modeling

***Chairman:* F. J. Maher**

Water Management for Extended-Duration Manned Space Missions*

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This paper describes the first two water-management techniques that the Douglas Aircraft Co. is evaluating in manned chamber tests for application to extended-duration space missions. The two techniques are the open-cycle air-evaporation system in which humidity control and water recovery from urine are accomplished in a single, combined system; and the multifiltration technique for wash-water purification and filtering of humidity condensate and urine distillate. The tradeoff considerations that influenced the selection of these techniques are discussed. The paper also discusses the chemical pretreatment of urine and the control of odors, trace contaminants, and microbes. Data on water quality are included.

INTRODUCTION

This paper discusses open-cycle air evaporation and multifiltration, the first two spacecraft water-management systems that Douglas is evaluating in manned-chamber tests. The two systems have the following goals:

(1) Recovery of drinking water from approximately 1 liter/man-day of humidity condensate (ref. 1)

(2) Recovery of drinking water from approximately 1½ liters/man-day of urine (ref. 1)

(3) Cleanup of 2 liters/man-day of wash water used to maintain personal cleanliness

The relative purity of urine, wash water, and humidity condensate, before and after processing, is indicated in table I by four quantitative measures: pH, specific conductivity, chemical oxygen demand (COD), and total residue. These four are probably the most significant of the many standard measurements (ref. 2) that can be made. (pH is a measure of H^+ and OH^- ions. Usually, in the case of urine distillate, low pH is caused by volatile organic acids and high pH is caused by ammonia.)

Specific Conductivity

Specific conductivity is a function of the ionic species present in water. If the amount and identity of each ionic solute is known, then the specific conductivity of a solution can be calculated, as there is a definite relationship between ion concentration and specific conductivity for individual species. The specific conductivities per unit concentration for several salts and ions at infinite dilution and at 77° F are as follows:

Salt or ion:	*μmho-cm⁻¹ / mg/liter*
H^+	349.7
OH^-	11.6
NH_4^+	4.08
$NH_4^+OH^-$	7.74
NH_4Cl	2.80
$(NH_4)_2CO_3$	2.92
NH_4HCO_3	1.49

*The work reported in this paper was conducted by the Douglas Missile & Space Systems Division, Advance Biotechnology and Power Department, under independent research and development (IRAD) funds, IRAD nos. 81641–002, 81241–003, and 80641–002.

TABLE I.—*Typical Contamination Levels of Several Types of Spacecraft Water*

Item	Human urine (no treatment)	Used wash water (no treatment)	Humidity condensate with air charcoal in purge stream (no post-treatment)	Urine distillate from air evaporation with chemical pretreatment (no air charcoal; no post-treatment)	Urine distillate from air evaporation with chemical pretreatment (with air charcoal; no post-treatment)	Urine distillate from air evaporation with chemical pretreatment (with air charcoal; with post-treatment)	Wash-water distillate from air evaporation with chemical pretreatment (no air charcoal; no post-treatment)
pH	4.6 to 8.0	4.5 to 5.5	5.9 to 8.0	4.5 to 8.8	4.5 to 8.8	6.5 to 7.5	6.0 to 7.0
Specific conductivity, μmho-cm^{-1}	16 000 to 20 000	500 to 700	150 to 300	9 to 90	9 to 90	<5	4 to 10
Chemical oxygen demand, mg/liter	12 000 to 15 000	200 to 1200	200 to 1300	20 to 350	20 to 80	<4	10 to 20
Total residue, mg/liter	38 000 to 47 000	1300 to 2500	2 to 35	2 to 12	2 to 12	<2	2 to 10

$(NH_4)_2SO_4$	2.32
NaCl	2.17
KCl	2.01
$CaCl_2$	2.44
$CaCO_3$	2.54
$Ca(HCO_3)_2$	1.26

In figure 1, the relationship between pH and specific conductivity is shown assuming that only H^+ and OH^- ions are present.

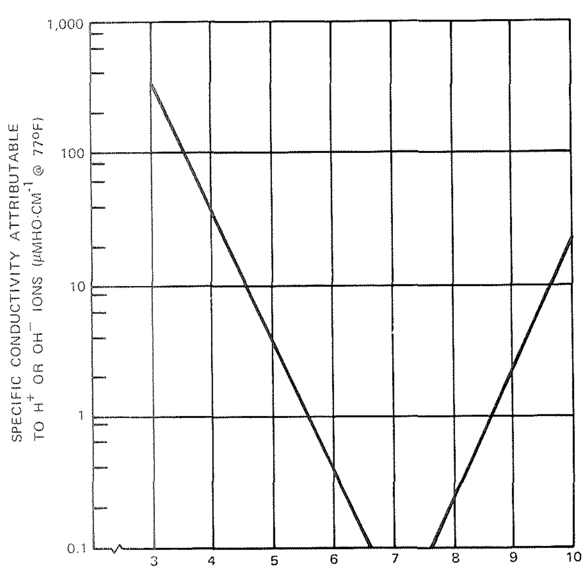

FIGURE 1.—Effect of H^+ and OH^- ions on specific conductivity.

The oxidation of most organic compounds by dichromate is 95 to 100 percent of the theoretical value. Ammonia, benzene, toluene, and pyridine are not oxidized (ref. 2).

Total Residue

Total residue, when determined as outlined in reference 2, is the total concentration of relatively low vapor-pressure solutes, because in the determination, the water sample is dried in a steam bath followed by oven baking at 103° to 105° C. Thus, high vapor-pressure solutes like NH_3, CO_2, HCl, formic acid, and phenols are driven off. The remaining residue is composed primarily of the low vapor-pressure solutes. Such solutes get into the distillate, not by phase change or gaseous diffusion, but by physical entrainment and mechanical transport to the condenser (carryover) or by dissolution of materials in contact with the condensed phase.

The difficulty in processing contaminated water for reuse is related to the total weight of the contaminants, the number of different contaminants, and the nature of each contaminant. In decreasing order of difficulty, the spacecraft waters rank as follows: human urine, used wash water, humidity condensate, urine distillate, and wash-water distillate.

SYSTEM SELECTION

Efforts to develop reliable water-processing systems with low launch and resupply weights have been in progress since the mid-1950's. Every known purification technique and variation thereof has been examined, including phase change, filtration, adsorption, chemical alteration, electrolysis, pyrolysis, electrodialysis, and reverse osmosis. There have been many different processes, systems, and components proposed, based on one or more of these techniques, that incorporate various novel features to achieve adequate performance in the unfamiliar, 0*g* spacecraft environment. A considerable effort has been expended comparing rival systems (refs. 3 to 10), and most investigators agree that the more promising systems are vacuum distillation, vapor pyrolysis, electrodialysis, vapor compression, air evaporation, and multifiltration. This paper discusses only air evaporation and multifiltration, the first two water-recovery systems that Douglas plans to evaluate in manned-chamber tests.

The decision to evaluate air evaporation and multifiltration first was based on the simplicity and advanced state of development of the concepts and on tradeoff studies that considered operation in null gravity, degree of reliability, fixed weight, expendable weight, power requirements, percentage of water recovered, availability of waste heat, and system volume. In addition to these considerations, the following important points, discussed in reference 11, favor air evaporation:

(1) The system has high reliability that derives from a minimum number of dynamic components and controls.

(2) There are no solid heat-transfer surfaces in contact with urine, hence there are no scaling problems.

(3) Because of the use of wicks, no artificial gravity in the form of spinning parts is required in the evaporation step.

(4) Air evaporation is a nonboiling process; therefore, carryover, promoted by foaming and boiling, is not a problem.

(5) Essentially 100 percent of the water in urine is recovered because each wick evaporator is taken to a dryness of approximately 40° F dewpoint.

(6) Separation and venting of urine gases occur naturally in the wick evaporator.

(7) Urine temperature remains low in air evaporation (equal to the airstream adiabatic saturation temperature), therefore, there is less contamination of the distillate with high vapor-pressure urine solutes.

(8) The air-evaporation technique does not require vacuum. Therefore, housing weights are less, leakage is not critical, and special auxiliaries such as vacuum pumps, traps, dynamic seals, and high-head water pumps are not required.

(9) Because of the simplicity of air evaporation and the relatively small number of components, the predicted time and cost to develop flight-qualified hardware is less than for other systems.

Published tradeoff studies (refs. 1 and 4) confirm Douglas conclusions that the air-evaporation technique is competitive for purification of urine and wash water, and that the multifiltration technique is competitive for wash water, humidity condensate, urine distillate, and wash-water distillate. The only overlap in application for these two techniques is in respect to wash water; in this case, the choice is influenced to a large extent by mission length: shorter missions favor multifiltration and longer missions favor air evaporation. Because there is little doubt that an open-cycle air-evaporation system that can successfully process urine can also process wash water, it was felt that the maximum information would be obtained in a manned chamber run by choosing multifiltration to process the wash water.

The open-cycle version of air evaporation was selected for evaluation over the closed-cycle configuration because proof of feasibility of the former also establishes feasibility of the latter, while the reverse situation is not true. Also, open-cycle air evaporation is superior to the closed cycle in all tradeoff aspects. In the open-cycle air-evaporation system, urine processing is integrated with cabin air-conditioning and humidity control, so that the only components required in addition to those already needed for humidity control are a urine evaporator, a full-flow charcoal filter, and an air heater.

Figure 2 is a flow diagram of the open-cycle air-evaporation system that will be evaluated in a proposed 60-day manned space-cabin simulator test. It shows typical values for temperature, relative humidity, airflow, pressure drop, evaporation and condensation rates, and water-purity levels. A fan circulates filtered cabin air through a heater, wick evaporator, activated charcoal filter, condenser, and water separator, and discharges dehumidified air back to the cabin. The condensed water is pumped through a multifiltration unit consisting of a bacteria filter, an ultraviolet light, and activated charcoal and ion-exchange beds, and is stored at pasteurization temperature to be used for drinking and food preparation. A more detailed description of each component and of the urine feed-control system is included in reference 11.

Figure 3 is a flow diagram of the wash-water multifiltration system that will also be evaluated in the proposed 60-day space-cabin simulator test. The system purifies used wash water sufficiently for reuse as wash water.

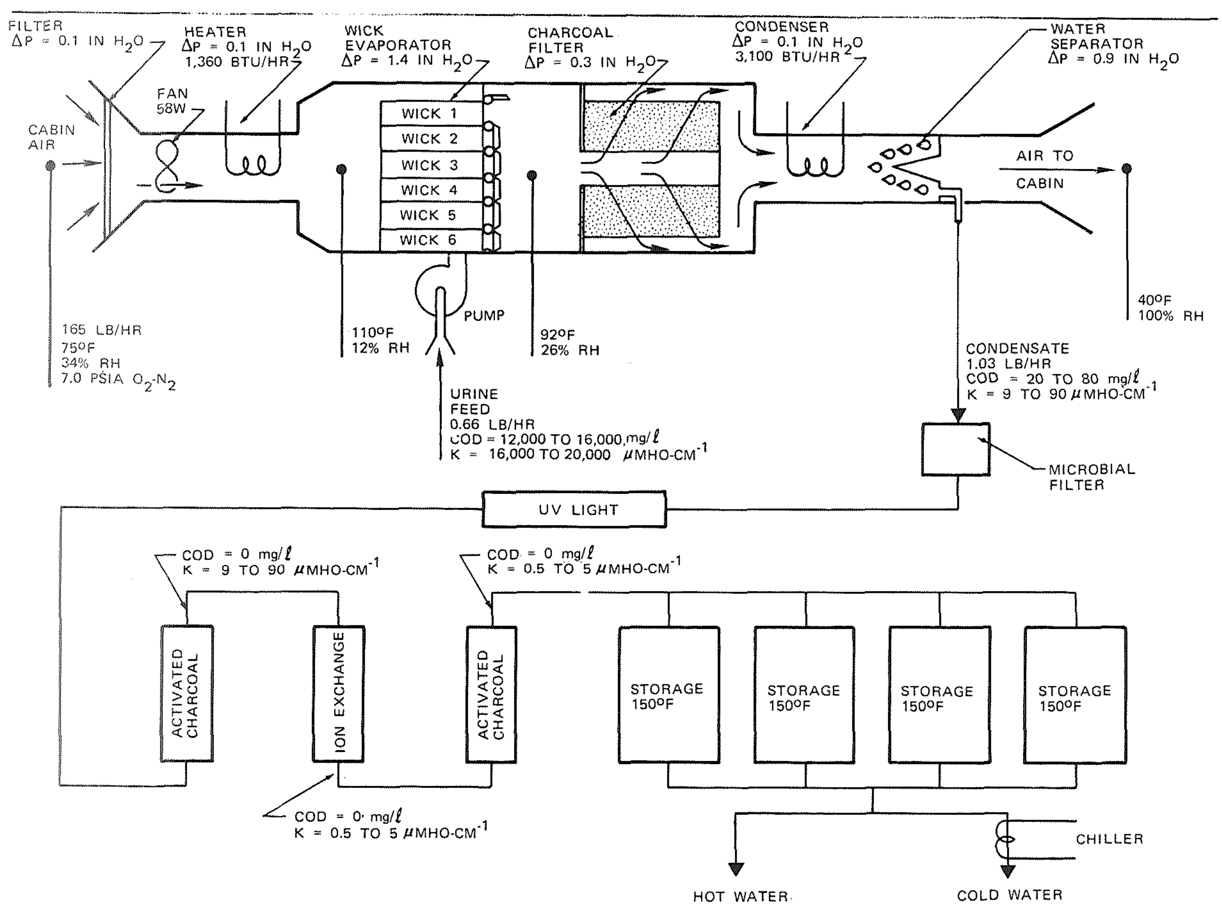

FIGURE 2.—Open-cycle air-evaporation system for urine distillation.

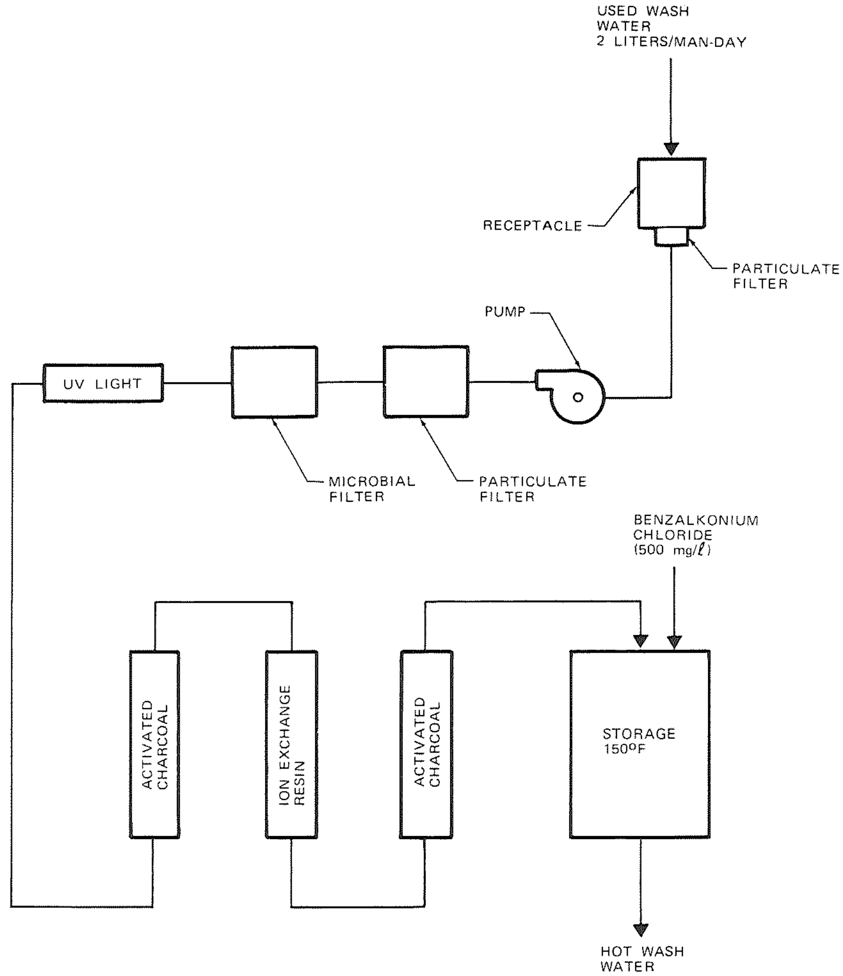

FIGURE 3.—Multifiltration system for wash-water purification.

Potability Considerations

In urine distillation systems, the primary source of possibly toxic contaminants is the urine itself. Human urine contains more than 140 different substances (ref. 12) that are broadly categorized as electrolytes, nitrogenous substances, vitamins, metabolites, and hormones. Its composition differs considerably from individual to individual and with variation in diet.

On the average, a liter of urine contains about 967 g of water and 41 g of solutes. About 70 percent of the species present in urine are nonelectrolytes and nearly all are in true solution.

Normal human urine from healthy individuals is considered nontoxic to animals and man (refs. 13 and 14), provided the urea has not been decomposed by bacteria or heat. Decomposition of the urea content raises the ammonia concentration in urine from a nominal 550 mg/liter to 14 000 mg/liter, rendering it toxic. The consumption of freshly voided urine in survival situations, such as mine cave-ins and war prison camps, is reported to have saved many lives. However, raw urine can be recycled only for short periods because the solutes quickly build up to intolerable levels.

Nearly all of the processes that have been proposed for separating the solutes and water of urine require some form of urine pretreatment. In reference 15, eight rules for the successful production of potable water from human urine by distillation are defined. Three of these rules are concerned with chemical pretreatments: (1) Insure urine sterility by chemical addition or other means, thereby precluding bacterial decomposition of urea; (2) fix the free ammonia in urine by adding a chemical that forms a stable ammonium salt; and (3) oxidize the odoriferous volatiles in urine with a chemical oxidizer.

Urine distillation differs from the more commonly understood distillation of sea water in many respects, the most important being that urine has a high organic fraction as compared to sea water and nearly 100 percent of the water in urine must be recovered, whereas only 50 to 75 percent of the water in sea water is normally recovered in sea-water conversion plants. Because much of the water in urine is evaporated from a highly concentrated brine that contains high vapor-pressure organic solutes, urine distillate has a considerably higher fraction of dissolved species than does sea-water distillate.

In the Douglas open-cycle air-evaporation system, the raw urine is treated chemically to stabilize it in respect to microbes, free ammonia, and certain volatile organics. This processing serves to maximize the retention of urine solutes as residue in the wick evaporator and thereby relieve the burden on downstream activated-charcoal and ion-exchange beds.

The current choice of chemicals for pretreating urine is an aqueous solution (density = 1.42 g/ml) of 39.8 percent sulfuric acid, 9.8 percent chromium trioxide, and 3.1 percent copper sulfate. Each liter of urine is treated with 4 ml of this solution, which results in the following amounts:

Item:	*Amount used, gm/liter*
H_2SO_4	2.26
CrO_3	.56
$CuSO_4$	.18
Total	3.00

The resulting pH of the treated urine is from 1.9 to 2.8.

The chromium trioxide serves as a germicide and an oxidant. As a germicide, it prevents the growth of most micro-organisms and thereby precludes the bacterial production of the enzyme urease, which, if present in sufficient quantity, would catalyze the decomposition of urea to ammonia and carbon dioxide:

$$H_2NCONH_2 + H_2O \xrightarrow{\text{Urease}} 2NH_3 + CO_2$$

The ammonia that would be produced in this fashion is about 14 000 mg/liter, most of which would outgas in the evaporator and be absorbed in the distillate, rendering it nonpotable. Because urease-producing bacteria are prevented from growing by the germicidal action of CrO_3 and because the natural decomposition of urea is slow at the evaporation temperature being used, most of the urea in urine remains intact in the wick evaporator.

As an oxidant, CrO_3 converts many of the odoriferous volatile organics to less volatile or nonodoriferous forms, thereby considerably reducing the odor level of the distillate and the loading on the downstream adsorption beds. Also, CrO_3 is capable of destroying organic poisons.

Copper sulfate is a recent addition to the pretreatment solution and was added to effect a better and longer control of mold. In recent long-term bench tests, *Penicillium* sp. was found growing in urine treated with a solution similar to the one above, but containing only H_2SO_4 and CrO_3. In 3 to 4 yr of preceding bench testing with this pretreatment, no similar occurrence was observed, and frequent microbiological assays of treated urine were always negative. This instance is a good example and underscores one fundamental aspect of the microbiological problem: the amazing ability of microbes to adapt to almost any situation.

Sulfuric acid is used to fix approximately the 550 mg/liter of ammonia, which would otherwise be evolved from the decomposition of ammonium carbonate and ammonium bicarbonate as the distillation proceeds. When H_2SO_4 is added to urine, the sulfate radical replaces the carbonate and bicarbonate radicals that normally buffer the ammonium ions:

$$(NH_4)_2CO_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4 + H_2O + CO_2$$

$$2NH_4HCO_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4 + 2H_2O + 2CO_2$$

The most important question in an open-cycle air-evaporation urine-processing system has been whether urine odors and trace contaminants introduced into the airstream during the evaporation process can be adequately removed by filtering before the airstream is returned to the cabin. In theory, filtration of the airstream through activated charcoal filters, subsequent to evaporation and prior to return of the air to the cabin, should accomplish the desired cleansing action.

In a manned test (ref. 16), it was demonstrated that for a period of 5 days such filtration was effective. No odor breakthrough was observed during the test period, and the reactions, behavior, and medical condition of the four-man crew were in no way different from those observed in space-cabin tests that omitted the open-cycle air-evaporation method of urine processing (ref. 17). In recent bench tests at Douglas, a total of 387 liters of urine was processed, which is 27 liters more that the total urine expected from four men in the proposed 60-day run, with no odor breakthrough. On the basis of these tests, there is no reason to believe that filtration of the airstream will not continue to be effective for substantially longer periods.

Because human urine is nontoxic (refs. 13 and 14), except as previously qualified, it would intuitively seem that urine distillate, which contains only one-thousandth as many solutes as urine, would also be nontoxic. Of course, there is a possibility that toxic materials added to urine as stabilizing pretreatments might get into the distillate or cause chemical changes that might find their way into the distillate. This fear appears unwarranted in light of toxicity experiments, which include long-term consumption tests with rats (refs. 18 and 19), 56-day and 36-day consumption tests with primates (ref. 20), two 2-man space chamber tests lasting 17 days and 30 days (ref. 21), and a test at Douglas in which a subject consumed 55 liters of water reclaimed from urine by use of an air-evaporation system. A typical analysis of the water consumed in the Douglas test is shown in table II. This sample did not benefit from filtration and is representative of the lowest grade half of the 55 liters consumed in the toxicity test. Both USPHS standards (ref. 22) and the recently recommended AMRL standards for aerospace (ref. 23) are listed for comparison.

To preclude the introduction of toxic components into nontoxic urine distillate, caution must be exercised in the design, construction, and the selection of materials for distillate handling and storage systems. Special attention must be given to possible contamination by dissolution of construction materials and seepage from external sources. To obtain water with the high purity of the filtered water shown in table I, activated charcoal and ion-exchange beds must be thoroughly washed prior to use to remove residual ionic and organic materials, which are normally present in the as-received condition. For example, distilled water from most charcoals has an initial specific conductivity between 100 and 1000 μmho-cm^{-1}, and the initial effluent from most ion-exchange resins has a chemical oxygen demand up to 100 mg/liter.

Microbial contamination of urine distillates and humidity condensates, especially in an open-cycle air-evaporation system, is of some concern. The ultimate microbe population will depend, to a large extent, on the initial cleanliness of the system and space cabin, provided airborne bacteria are maintained at low levels.

The highest microbe level that can be permitted anywhere in spacecraft water-management systems has not yet been re-

TABLE II.—*Typical Analysis of Unfiltered Urine Distillate From Air-Evaporation System*

Item	Unfiltered urine distillate	USPHS recommended maximums (ref. 22)	AMRL recommended maximums (ref. 23)
pH at 70° F	8.1	10.5	5.0 to 10.0
Specific conductivity at 70° F, μmho-cm^{-1}	78.6		1700
Color, mg/liter	1.0	15	15
Turbidity, mg/liter	<5	5	25
Odor	0	3	3
Wet-chemical analysis, mg/liter:			
Total residue	4.0	500	1000
Volatile residue	3.0		
Fixed residue	1.0		
Nitrogen, ammonia	9.8		
Nitrogen, albuminoid	1.3		
Nitrogen, total	11.3		
Nitrogen, organic	1.5		
Nitrogen, nonprotein	10.0		
Nitrite	.007		
Nitrate	.01	45	100
Chlorides	.8	250	450
Alkalinity	39.0		
Total hardness	16.5		
Free CO_2	3.5		
Iron	0	.3	1.0
Manganese	0		.1
Chemical oxygen demand	28.2		100
Sulfate	0	250	250
Copper	0	1.0	3.0
Chromium, hexavalent	.015	.05	.05
Fluoride		1.7	2.0
Phenols		.001	.05
Metal analysis, μg/litter:			
Ag	([a])	50	500
Al	45		
As	([a])	50	500
B	15		
Ba	([a])	1000	2000
Bi	([a])		
Be	([a])		
Ca	25		
Cd	([a])	10	50
Co	([a])		
Cr	11		
Cr^{6+}		50	50
Sn	([a])		
Ti	([a])		
Zr	([a])	5000	15 000
Zn	([a])		
Cu	4	1000	3000
Fe	16	300	1000
Hg	([a])		
In	([a])		
K	([a])		
Si	27		
Mn	.3	50	100

TABLE II.—*Typical Analysis of Unfiltered Urine Distillate From Air-Evaporation System*—Concluded

Item	Unfiltered urine distillate	USPHS recommended maximums (ref. 22)	AMRL recommended maximums (ref. 23)
Metal analysis, μg/liter—Continued			
Na	11		
Ni	[a]		
Pb	[a]		
Sb	[a]		
Li	[a]		
V	[a]		
W	[a]		
Mg	9		
Sr	[a]		
Se	[a]	10	50

[a] Not detected.

solved. Although there appears to be no evidence that the presence of moderate bacteria counts in drinking water prior to its pasteurization is grounds for rejection, the prudent course is to maintain microbe levels as low as practical.

The Douglas goal is to keep microbe counts throughout all water-processing systems close to zero. This is achieved by thorough initial cleaning and decontamination of all components, by use of microbe filters and ultraviolet light in the multifiltration systems, and by storage of the processed water at pasteurization temperature. The effectiveness of ultraviolet light in killing bacteria and viruses is reported in reference 24. These results have been confirmed by independent work at Douglas (ref. 25) using spores of *Bacillus subtilis*, var. niger in distilled water to simulate highly resistant bacteria, and *Escherichia coli* B/T2 bacteriophage to simulate human viruses in size and susceptibility to ultraviolet exposure.

On the basis of 67 days of closed-chamber tests, Douglas has found that microbes in a four-man space-cabin simulator can be controlled to acceptable levels by attention to the following points:

(1) Reduction of nutrient materials in the cabin to minimal levels

(2) Thorough initial cleaning and decontamination of the cabin interior, including machinery and systems

(3) Prevention of accumulation of debris by having adequate debris collection and storage techniques

(4) Maintenance of airborne bacteria at low levels by continuous sterilization of a bleed airstream

In a 5-day, four-man space-cabin simulator test, which included processing urine by open-cycle air evaporation (ref. 16), airborne bacteria levels, as determined by the Anderson sampling method, compared favorably to clean, well-ventilated buildings in which the bacteria levels are usually from 1 to 2 organisms/ft^3 of air. For comparison, levels as high as 700 bacteria/ft^3 have been recorded in dusty, poorly ventilated schoolrooms. Microbe surface populations obtained within the cabin by the Rodac plate method were within normally observed limits. Airborne microbes were continuously removed by action of the catalytic burner, which oxidizes many trace contaminants to harmless gases. Airborne microbes and trace contaminants were also removed by deposition in the open-cycle air-evaporation system and by adsorption in charcoal, molecular sieves, and silica gel beds.

The proposed 60-day, four-man space-cabin simulator test is expected to establish the adequacy of the air-evaporation and multifiltration water-management systems as well as other life support systems. Before starting the 60-day chamber run, more water recycling experiments will be conducted in which four men will consume urine distillate and humidity condensate processed by the open-cycle air-evaporation system for a period of 5 days. These tests will serve as baselines for the 60-day test and are expected to confirm previous chemical, microbial, and toxicity findings that indicate that the open-cycle air-evaporation system does indeed produce high-grade drinking water from urine and humidity condensate.

SUMMARY

The open-cycle air-evaporation and multifiltration systems described herein have been extensively investigated in bench tests that have resulted in improvements in urine pretreatments, evaporator design, urine-feed control, charcoal-bed design, posttreatment filtration, and microbial-control techniques. The next step is to evaluate the systems in manned chamber tests. If these are successful, then a 0*g* test should be undertaken.

Wick Life

With viscose rayon felt wicks, the amount of wick material required in 1*g* tests is between 1½ and 2 lb of wick per 100 lb of urine processed. An improvement in this figure is expected, because in 0*g*, urine residues should effect a more equal distribution and not clog the bottom portion of the wick first, as happens at 1*g*. Several interesting ways of prolonging and improving wick life have been proposed:

(1) Wick regeneration

(2) Impregnation of wick material with an agent to counter the natural decrease in surface tension that occurs in urine concentrates

(3) Reduction in the amount of urine solutes by chemical or electrochemical pretreatment techniques

(4) Use of improved wick materials

(5) Use of a wick material, such as carbon felt, in which many of the urine solutes could be heat degraded and driven off as gases without decomposing the wick

(6) Removal of urine residues from the wick as a concentrated brine

(7) Use of nondegrading, permeable membranes instead of wicks

Activated Charcoal Life

The ultimate life of the airstream activated charcoal bed has not yet been determined, but bench-test data show that the required amount of charcoal is less than ½ lb of charcoal per 100 lb of urine processed. Charcoal life can be improved by improving bed design, using better charcoals, and regenerating charcoal.

Optimum Configuration

The overall weight and power penalties of the open-cycle air-evaporation system can be improved by optimum integration of the system with humidity and thermal-control loops and by optimization of the wick-evaporator geometry, including consideration of wick length, width, and height; wick spacing; wick spacers; and overall size and number of evaporator units (for example, the use of one large evaporator as opposed to a number of smaller units).

Water Separation

There are many 0*g* water separators under development. The hydrophobic-hydrophilic separator shown in figure 2 will be tested during the 60-day chamber test. Other separator options include the elbow, the motor-driven centrifugal, the turbine-driven centrifugal, the integral-wick, and the porous-plate condenser types.

Fan Power

The overall fan and motor efficiency of the fan shown in figure 2 is 44 percent, which leaves some margin for improvement.

Urine Feed and Feed Control

The improved urine-feed and feed-control system, described in reference 11, is not optimized nor is it necessarily the best approach to the feed problem. There is room for considerable improvement in this area.

Urine Collection and Transfer

Many improvements can be made in the systems that have been built to collect, pretreat, transfer, and feed urine.

Urine Pretreatment

Although the chemical urine pretreatment described in this document appears to be close to the stoichiometric minimum weight for the general pretreatment approach of fixing free ammonia, oxidation of volatile organics, and microbial control, there is quite possibly a more attractive combination of chemicals than the one mentioned here and in reference 15. Also, there are other valid approaches to the pretreatment requirement; for example, electrochemical oxidation of urine eliminates many urine solutes by converting them to useful cabin gases (ref. 1). Such approaches appear to be attractive from an expendable weight point of view and warrant further investigation.

Volatile Organics

Positive identification of the urine odors and volatile organics in humidity condensate and urine distillate, as represented by COD, would enable accelerated tests on charcoal beds.

Microbial Control

The problem of long-term microbial control in space vehicles should receive continuing attention. Complete sterilization of spacecraft and crew is probably unreasonable, even if it could be achieved and maintained. The spacecraft and its systems must be designed to cope with microbes. No situations should exist that would result in rampant microbial growth should inadvertent contamination occur. Propositions are needed for practical approaches, methods, and techniques.

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Man, His Environment, and Microbiological Problems of Long-Term Space Flight

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Man's decision to travel in outer space has challenged the ingenuity and resources of the scientific community. The field of microbiology has responded to this challenge in three broad areas: (1) Spacecraft sterilization—sterile unmanned flights to Mars; (2) exobiology—search for extraterrestrial life; and (3) manned flights—man in closed environments.

Many investigators in universities, industry, and the Government are developing techniques and operational procedures to meet the NASA regulation that unmanned flights to Mars be sterile (ref. 1). It is recognized that terrestrial contamination would make investigations in exobiology or the search for extraterrestrial life difficult, if not impossible.

The Space Science Board has repeatedly and publicly pointed out the importance of the search for extraterrestrial life and in 1964 stated: "Its importance and the consequences for biology justify the highest priority among all objectives in space science—indeed in the space program as a whole" (ref. 1). Because the requirements for sterility and the search for extraterrestrial life involve primarily microscopic forms of life, it is only natural that microbiologists are deeply involved in these programs.

In manned space flight, microbiologists are concerned with a wide spectrum of possible problems associated with placing man in a closed environment for long periods of time. Progress is being made in many areas toward the goal of long-duration manned space flight. A considerable portion of this effort is focused on the total space-cabin environment, including research and development on life-support subsystems (ref. 2). Microbiological investigations in support of this entire program are now underway at NASA and other institutions. This paper summarizes the current status of this research and identifies some potential problem areas; the last section outlines the research needed to fill the gaps in our knowledge.

LIFE SUPPORT REQUIREMENTS

Before man is able to explore the solar system, provisions must be made to serve his life needs and to insure his safe return to Earth. It will be necessary to provide food, water, "climate control," protective clothing, and waste removal. It is apparent that for long-duration missions, stored supplies, if used, would require enormous weights. Near-Earth missions can rely on resupply, but planetary missions cannot, and for such missions recycle systems are necessary. Another way of looking at the same problem is to consider man's basic intake and output requirements (data reprinted from ref. 3):

	lb/day
Intake:	
Oxygen	2.0
Water	6.6
Food	2.0
Total	10.6
Output:	
Carbon dioxide	2.5
Water:	
Perspiration and respiration	3.3
Urine	4.0
Feces	.4
Solids (fecal)	.4
Total	10.6

Man consumes the equivalent of his weight in about 15 days. In only 6 months, he takes in about a ton of oxygen, food, and water. Therefore, it will be necessary to use some of man's output for developing an input. Urine appears to be one of the first wastes that will be reclaimed because it can readily be made drinkable (urine is 93 percent water). Another area that can result in conserving weight and space is to produce oxygen on board. One way to supply a portion of oxygen is to recover it from water and/or carbon dioxide. Recovery of oxygen from water can be accomplished by electrolysis (ref. 3).

Currently under investigation at the Langley Research Center in Hampton, Va., is a research test facility to study and test critical life support subsystems for long-duration space missions. The integrated life support system (ILSS) is a cylindrical chamber with domed ends as shown in figure 1. The chamber has a diameter of 18 ft 2 in. and a height of 18 ft. The interior volume (4150 ft^3) is divided into two levels to accommodate the various functional requirements of the crew. An airlock chamber is attached to the external shell of the test bed at the lower level to permit access to the test bed when the chamber is at pressures less than atmospheric. Figure 2 is an exterior view of the ILSS test facility.

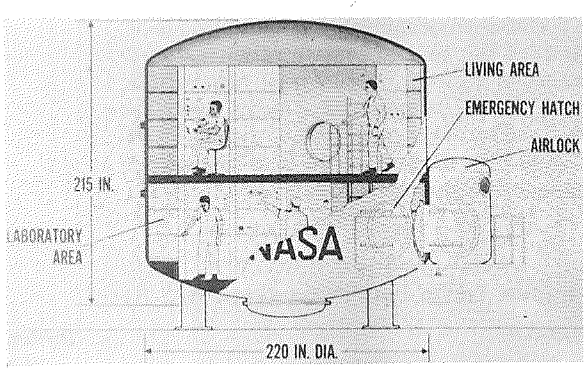

FIGURE 1.—Cross-section view of the ILSS test bed.

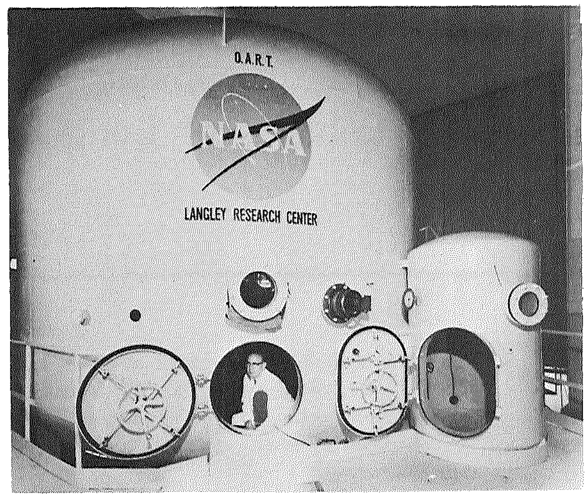

FIGURE 2.—Exterior view of the ILSS test bed.

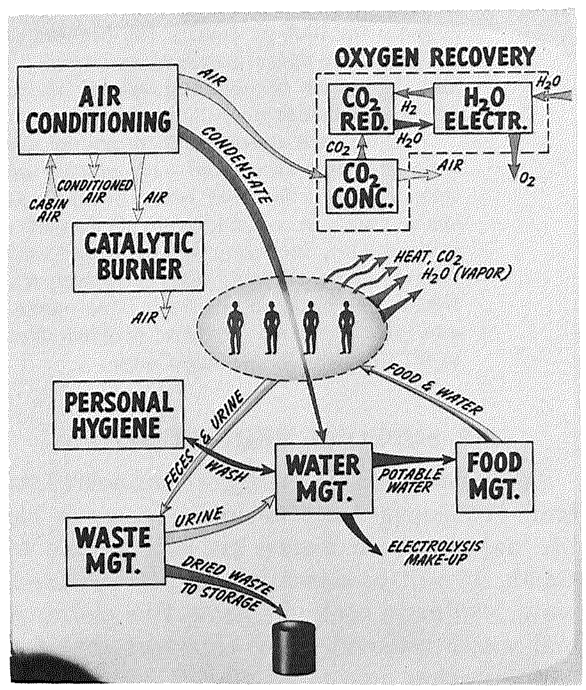

FIGURE 3.—Flow diagram of the ILSS regenerative processes.

The ILSS regenerative processes are shown in figure 3. In this system, water is recovered from urine, humidity condensate, and wash water using a wick-evaporator concept. Oxygen is recovered through electrolysis with the hydrogen reacting with the oxygen to generate more water. The carbon from carbon dioxide is collected as a solid. In this system solid wastes are stored.

MICROBIOLOGICAL INVESTIGATIONS

During the past 5 yr, a number of microbiological studies have been conducted on the effect of space-flight conditions on man and experimental animals. This section summarizes these efforts and also refers to studies made in Antarctica and on nuclear submarines for a comparison with different types of closed environmental systems.

Space-Environment Test Chambers

A limited number of microbiological studies has been conducted in manned space-environment test chambers and some of the characteristics of these chambers are summarized in table I (refs. 4 to 11). The important point in this table is the wide range of test conditions and objectives. Atmospheric conditions ranged from a normal gas mixture to 100 percent O_2 and pressures from 14.7 to 3.5 psi; the number of test subjects varied from two to six and the longest manned test was 56 days. Further, the depth and sophistication of the microbiological studies varied from test to test. Nevertheless, a number of interesting microbiological results emerge from these studies. In three of the five tests there was clear evidence of a transfer of micro-organisms between subjects (refs. 4 and 7 to 10). In one test, not only did a transfer take place, but it resulted in a replacement of the normal mixed flora of the nose with a pure culture of the transferred bacteria (ref. 4). These results are in marked contrast to studies conducted in Antarctica on small groups of men cut off from physical contact with other communities for long periods of time. Here it was shown that persistent carriers of *Staphylococcus aureus* kept their own strains, as determined by phage typing, despite living in very close contact with each other (refs. 12 to 14). On the surface, it would appear that space-cabin conditions more nearly resemble the

TABLE I.—*Characteristics of Space-Environment Test Chambers*

Location of chamber	Dimensions	Atmosphere	Number test crew	Number tests	Length of test, days
USAF School of Aerospace Medicine	12 ft long 8 ft high 5 ft wide	Ambient to essentially 100 percent oxygen, sea level to 33 500 ft	2	11	14–30
	19 ft long 8 ft wide Double wall 3 compartments	Oxygen-helium 258 mm Hg total: 175 mm Hg P_{O_2} 74 mm Hg P_{He} 1.9 mm Hg P_{N_2}	4	1	56
Republic Aviation Corp	30 ft long 13-ft diameter 2 compartments	100 percent oxygen, total pressures of: 3.8 psi, 5.0 psi, 7.4 psi, 14.7 psi.	6	4	14
Aerospace Medical Research Laboratories, Air Force Systems Command	1100 ft^3 controlled activity facility (CAF) (20 ft–20 ft)	Atmospheric 14.7 psi: 20 percent O_2 80 percent N_2	4	5	11–15 (CAF) 28–35 (chamber)
The Boeing Co	2400 ft^3 20 ft long 10 ft wide 8 ft high	Atmospheric 14.7 psi: 20 percent O_2 80 percent N_2	5	1	30

present problem in hospitals regarding the ease with which staff and patients pick up strains of staphylococci. Alterations in skin microflora occurred and space-type dies produced changes in the number and types of fecal bacteria (refs. 5, 9, 11, 15, and 16). In one chamber test involving five men for 30 days, there was such a marked reduction in the number of airborne micro-organisms that the subjects were breathing microbiologically clean air (ref. 4). Although data were not available for examination, Soviet investigators found in a 120-day chamber test that the number of microbes per unit volume of air rose considerably (ref. 17). These differences highlight the difficulties associated with attempting to compare results between chamber tests.

Nuclear Submarines

The Naval Biological Laboratory has conducted a number of studies on respiratory infections and airborne microbiological contamination during the course of eight nuclear (Polaris) submarine cruises. The epidemiological features were unique and consisted of about 110 men living in a closed environmental system for periods up to 7 weeks. As a rule, herd infection, herd immunity took place with infection occurring the first week and group immunity by the fourth week. One patrol, no. 5, followed the usual herd-infection, herd-immunity pattern, but at the sixth week they took on three new crewmembers and upper respiratory infections rose almost immediately. Air counts were relatively low, less than 10 bacteria/ft^3 of air and counts were related to station activity. It was the general impression that upper respiratory infections were not caused by airborne bacteria but by close contact (ref. 18).

On one patrol an outbreak of *Mycoplasma pneumoniae* occurred that had a long latent period of 26 days. It was assumed that the disease was contracted from the civilian population of West Scotland before the patrol commenced (ref. 19).

Space-Flight Studies

Only a limited number of microbiological studies have been reported on space flights in the United States and the Soviet Union. In a recent U.S. study, Gemini crewmembers and flight hardware were sampled before and after flight. The data indicated a simplification of the indigenous microflora of the crews with a decrease in the type and increase in total numbers. There was evidence that a transfer of micro-organisms between crewmembers took place. Samples from the flight hardware indicated a buildup of micro-organisms, but a simplification as to types was observed (ref. 20).

Studies conducted by Russian investigators before and after certain Vostok flights showed interesting immunological changes and alterations in the auto or indigenous microflora. For example, with some crewmembers there was an increase in lysozyme activity, a natural antibacterial substance, in the cosmonaut's saliva during the prelaunch period. It was concluded, however, that the bactericidal properties of the body as measured on the skin and neutrophil activity were generally within normal limits. Increased neutrophil activity was noted after the flights with certain of the cosmonauts. The autoflora of the four cosmonauts remained more or less within normal limits during preflight training. On postflight examination, two of the astronauts had an increase in the number of throat micro-organisms; that is, approximately 10 times higher than the physiological norm. In one case, there was an increase in the number of bacteria recovered from the deeper layers of the forearm skin (ref. 21).

Experimental Studies

Several experimental studies have been conducted on the effect of space-flight conditions on infectious agents and disease. This effort has produced a new term in microbiology, "parabarosis," or altered barometric pressure and atmospheric composition on susceptibility to infection. In general, these studies have shown that altitude stress lowers resistance to infection with *Klebsiella pneumoniae, Pasteurella tularensis,* and *salmonella* (refs. 22 to 24) and produced larger skin lesions with *Staphylococcus aureus,* which healed at a slower rate than those in mice maintained at ground level before challenge (ref. 25). On the other hand, resistance of mice to mengovirus was related to changes in experimental conditions. In other words, altitude stress alone did not influence resistance to infection, but changes from space-cabin conditions to ground level, and vice versa, did result in increased susceptibility to the virus (ref. 26).

Giron and Schmidt (ref. 27) found that acclimatization of rabbits to normal P_{O_2} at 18 000 ft for 7 days was without demonstrable effect on production of antibody against vaccinia virus. Huang (ref. 28) was able to show that parabaric conditions markedly inhibited interferon production. Mice maintained either at a simulated depth of 213 ft in sea water (95 psig), or at a simulated altitude of 37 000 ft (3.1 psig) for 2 weeks, showed approximately eightfold depression in the level of serum interferon compared to the control mice kept in a similar chamber but maintained at 1 atm with air from a tank.

Soviet investigators have found that dogs exposed to space-flight factors exhibited a wavelike fluctuation of the phagocytic index. During the first week after flight, the phagocytic index was low. Moderate immunological changes persisted in all dogs for months and sometimes years. It was concluded that the appearance of *Escherichia coli* in the oral cavity in the immediate postflight period reflected a drop in the immunological activity (refs. 29 and 30).

SPACE-FLIGHT FACTORS AND MICROBIOLOGICAL PROBLEMS

Before considering some of the microbiological problems that might occur in space cabins, it is worthwhile at this time to briefly review some of the factors involved in the classical epidemiology of infectious diseases. A comparison of these factors with the space-cabin environment might cast some light on the types of microbial diseases to expect in space flight.

Exogenous Versus Endogenous Disease

The usual modes of transmission of infectious agents are food, water, air, and contact (including both direct and indirect through fomites and vectors). The ingestion of water contaminated with the typhoid bacillus, inhalation of air containing tuberculosis, or the bite of a mosquito harboring yellow fever are classical examples of the exogenous type of microbial disease. On the other hand, an examination of the factors peculiar to space flight—sterile water, "clean" air and food, constant temperature and humidity, altered gas atmosphere, confinement, cosmic radiation, altered biorhythm, and weightlessness—shows that several of the factors usually involved in exogenous microbial diseases will be missing, or at least downgraded in effectiveness. For example, even though the astronaut will drink water recovered from urine, humidity condensate, and wash water, the water will be sterile. Therefore, one can eliminate water as a source of concern in the transmission of microbes inside the space cabin. In all probability, the space-type diet will be treated in such a manner as to prevent spoilage on long missions. Such food may not be sterile, but it will probably have a low bacteria count and certainly be free of the classical foodborne pathogens such as staphylococci, shigella, and salmonella. A highly efficient circulating and filtration system including catalytic burners will tend to reduce the number of airborne micro-organisms. In addition, three other factors will have a tendency to downgrade air as a mode of transmission inside the space cabin. First, it can be assumed that during preflight isolation the astronauts will exchange upper respiratory tract micro-organisms and, in general, equilibrate in regard to a common immunity. Second, as outside individuals will not be introduced into the space cabin, there will be little chance for a new source of upper respiratory pathogens. Finally, in the absence of gravity one may anticipate that the particles normally deposited in the respiratory tract by sedimentation, principally those particles of 1–8μ in diameter, will be exhaled again with no deposition (ref. 31).

Some factors that could alter host resistance to infection are nutrition, hormones, normal flora, weather, disease state, and stress. The precise means by which these abnormal states influence the host-parasite conflict are, in most instances, understood poorly, or not at all. Two factors—indigenous or normal flora and weather—are worth considering in some detail because of their possible implications in space-cabin environments.

Indigenous Flora

Strictly speaking, the normal flora cannot be classified as a host resistance mechanism because the microbes are outsiders living with but not part of the host. It is felt, however, that the flora does interfere with colonization by outside parasites because they only support a finite number of microorganisms. There is also the possibility that the normal flora affects general host physiology by a continuous stimulation of the immune system. It is known, for instance, that alteration or elimination of the host flora can produce drastic results as seen in patients on long-duration antibiotic therapy (refs. 32 and 33).

Evidence is already available from ground-based simulator studies, experimental animals, and space flight that alterations occur in the indigenous flora. Subjects on long-term space-type diets have shown changes in the numbers and types of intestinal flora (refs. 11 and 16). It is thus becoming apparent that alterations in the indigenous or normal flora will be important on long-duration missions. This subject is discussed again in the section on "Research Needs."

Weather

It is known that many infectious diseases display a regular pattern of seasonal incidence. For example, *Streptococcal pharyngitis* is most frequent in early winter, and diarrhea resulting from coliform and other organisms prevails in the summer. These seasonal patterns are usually explained by a variety of factors, such as prevalence of insect vectors, temperature, and humidity, and crowding of the host. Seasonal fluctuations may also be caused at least in part by the effects of the weather on host physiology and resistance mechanisms. However, for many infectious diseases, seasonal patterns are completely unexplained (ref. 33). As the space cabin will be maintained under constant temperature and humidity, one can rule out the influence of weather or seasonal variation as a factor in the epidemiology or spread of exogenous microbial diseases on long-duration missions. In addition, the obvious lack of any insect vectors inside the space cabin plus the above-mentioned factors all tend to downgrade the role of exogenous diseases on long space missions.

Endogenous Microbial Diseases

Therefore, if one accepts the concept that the truly infectious type of microbial disease with an exogenous origin will be downgraded in the space-cabin environment, it would appear that the microbial diseases of endogenous origin will become important. The expression "endogenous microbial diseases" refers to any pathological condition caused by micro-organisms acquired at some prior time that have persisted in the body as part of its indigenous microbiota. Microbial diseases caused by these types of microorganisms include the coliform and other Gram-negative bacilli, staphylococci, nonhemolytic streptococci, various kinds of yeasts and fungi, and probably many viruses still unidentified (ref. 32).

It is known that endogenous microbial infections can become activated by many different kinds of changes either in the host or in the environment. For example, persons who carry the virus of herpes simplex commonly have a high level of neutralization antibodies for this virus in their serum; however, they can experience transient episodes of virus multiplication under the influence of nonspecific stimuli—as varied as certain types of fever, fatigue, exposure to the Sun, or section of the trigeminal nerve. The result is then the production of herpes blisters even in the presence of humoral antibody to the virus (ref. 32).

Many other similar examples could be cited, but the important point is that endogenous microbial diseases are, to a large extent, indirectly the expressions of environmental forces. Although nonspecific stresses increase the vulnerability of the host to endogenous micro-organisms, it can be cited there is little, if any, understanding of the mechanisms through which these effects are exerted.

It thus becomes clear that if one accepts the hypothesis of the role of endogenous microbial diseases in space-cabin environments, it becomes equally important to understand the factors that precipitate such diseases.

In addition to the major problem area of endogenous microbial diseases that could develop on long-duration missions, space-flight conditions could also be felt at different biological levels within the space cabin. These have been divided into micro-organisms and host effects. The final outcome of these effects could very well be expressed in the general problem of endogenous microbial disease.

Micro-Organisms

It is well known that viruses, bacteria, and other micro-organisms can undergo mutations affecting most of their characteristics including virulence and immunologic specificity. One well-known mutagenic agent is radiation and one can assume that long-term exposure, albeit at low levels, to cosmic radiation will produce changes in both micro-organism and host population of a space cabin. What specific changes, if any, will result from such an exposure are impossible to predict at this time. One can visualize, however, a combined effect in which radiation depresses host response through the phagocytic system and at the same time selects a mutant with increased virulence. The end result could be the selection of an organism from the indigenous flora with the capability to divide in a host with a weakened defense mechanism. Although specific cause-and-effect relationships will be difficult to establish for such situations, it is this type of problem that one could very well encounter under long-term space flight.

Host Effects

Reference has already been made to the possible deleterious effects of cosmic radiation on host response to infectious agents. Another factor peculiar to space flight that could affect the astronaut's ability to cope with exogenous or endogenous infections is the overall stress imposed by long-term space missions. There is one experimental study that might cast some light on this potential problem area. In this experiment, the stress induced by taking mice from ground-level conditions to high altitudes, and vice versa, was sufficient to lower the animal's resistance to the mengovirus. Although more data will be needed before definitive conclusions can be reached, it is possible that space-flight stress could be mediated at the cellar level. If this is the case, then the role of viruses in the precipitation of endogenous infections could be extremely important on long-duration missions. Again, cause-and-effect relationships will be difficult to establish, but research should be directed toward a more complete understanding of space-flight stress factors on this problem.

RESEARCH NEEDS

In a science as young as space, it is not surprising that a lack of data exists on the microbiological aspects of manned flight. As a matter of fact, until man decided to explore outer space and the ocean depths, there was very little motivation or reason to study the effect of these environments on man and the associated microbiological problems. Now, as man prepares for long-duration missions, it becomes important to know that man with his micro-organisms can survive in these types of environments. Therefore, it becomes important not only to identify problem areas but also the gaps that exist in our knowledge and the research needed to fill these gaps. It should also be pointed out such programs are not only important to our space program but such information could very well be applied to a better understanding of the health and welfare of man on Earth.

The remainder of this paper discusses some of the research needed in support of long-term manned space flight. It should be pointed out that these programs are based on speculations developed in the previous section and represent limited thinking; this list is far from exhaustive—other areas will also require examination and as data develop, shifts in program emphasis will take place. Finally, it should be pointed out that the research needs identified are those that can be conducted in ground-based facilities. The study of other factors, i.e., cosmic radiation, weightlessness, and altered biorhythms, affecting microbiological problems of man in closed environments, will have to be conducted in Earth-orbiting space laboratories before interplanetary missions are attempted.

Space-Cabin Environment Studies

To date, only a limited number of studies have been conducted in ground-based space-cabin simulators. It is evident that more work is needed in this area before man attempts interplanetary travel. First, these studies should be of long duration and duplicate in time the length of anticipated space missions. Such studies may be a year or longer in duration. It is anticipated that many of the microbiological problems discussed in this paper will not appear, or at least will not be major problem areas, under the conditions of short-term missions. Second, there is a need to conduct these studies under the conditions of an integrated life support system. This means that the subjects will drink water recovered from urine or humidity condensate, consume space-type food, and breathe the space-cabin atmosphere. Last, the microbiological studies must be inclusive enough to cover not only man and his total environment, but it must include all major groups of micro-organisms including viruses.

Indigenous Flora Studies

The indigenous flora or microbiota of man has been extensively studied by numerous investigators and these results have been summarized in books and reviews by Rosebury (ref. 34), Marples (ref. 35), Dubos (ref. 36), and Gall (ref. 37). Yet the exact role of the microbiota in man's health and welfare is not known. Further, it is felt that a large percentage of indigenous micro-organisms cannot be identified, let alone enumerated, for lack of adequate cultural techniques. These facts plus the observations that changes occur in the indigenous flora under space-cabin conditions highlight the need for extensive studies in this area. Of paramount importance to such a program will be a clear understanding of the numbers and types of micro-organisms indigenous to man under "normal" or non-space-cabin conditions. Special attention should be paid to the intestinal flora because of the close relationship between host nutrition, physiology, and intestinal micro-organisms. During this program new isolation techniques will have to be developed to insure recovery of the host microbiota.

Immune Response Studies

The possible influence of the space-cabin environment upon the astronaut's immune mechanisms should be investigated. Significant alterations of the immune mechanisms may produce prejudicial effects upon normal physiological processes and, in particular, may result in increased susceptibility to infection. The following immunological studies should be conducted on astronauts before, during, and after exposure to space-cabin environments: determination of total serum proteins, serum electrophoresis, serum immunoelectrophoresis, serum ultracentrifugation, and single radial immunodiffusion for quantitating of serum immunoglobulins.

Endogenous and Exogenous Microbial Diseases and Chemotherapy

If bacterial infections do occur under simulator test conditions, it will be important to determine if the causal agent is one transmitted by classical means or if the disease is endogenous in origin. It is equally important to determine if the infection will respond to accepted antibacterial therapy or if severe reactions will be generated in a subject who has an altered flora as a result of the space-cabin environment. Again, determining the role of the indigenous microbial flora in the ecology of space-cabin environments becomes important.

Airborne Micro-Organisms

As a part of the total microbiological picture of man in a space-cabin environment, it will be important to determine the numbers and types of micro-organisms in the circulating air. This is particularly important in regard to alterations in the indigenous flora, the transfer of micro-organisms between subjects and the immune response. An important part of such a study will be a careful characterization of viral isolates.

Experimental "Parabaric" Studies

Although a start has been made on examining parabarosis under laboratory conditions, much more work is needed in this area. In contrast to space-cabin simulator studies, which are expensive to conduct and limited in number, much meaningful data can be obtained in the laboratory using small animals and scaled-down test chambers. Studies similar to those proposed for man should be conducted plus further examination of the effect of space-flight conditions on resistance to exogenous infections.

Theoretical Studies

It is also recommended that the microbiological problems of closed systems be examined through the use of appropriate mathematical models. Although this technique has not been widely employed in biology, its usefulness in dealing with other complex multifactorial problems suggests it has a role in bioastronautics. Through this approach, a number of factors closely interrelated yet constantly changing in a somewhat predictable manner are identified. If appropriate mathematical models can be found, or developed, their fluctuations can be reduced to mathematical formulation and can thus be subjected to simultaneous study. With computer aid, the change produced by one variable present in the system or introduced at will can be compared with the change resulting from another variable. The fact that many large variables such as temperature, humidity, and diet are under control in a space cabin suggests such models may be a practical way to approach this problem. If progress could be made in this area, it would encourage the use of such models in examining the multivariable situations found in nature (refs. 32 and 38).

Life Support Subsystem Development

Water Management

One of the most critical subsystems in any integrated life-support system is water management or the recovery of potable water from urine, humidity condensate, or wash water. A number of physical-chemical approaches for water recovery are being actively pursued and the status of this effort was recently reviewed by Popma and Collins (ref. 39). Although considerable progress has been made on the engineering side of the program, there are still many unsolved microbiological problems. For example, only recently were bacteriologic standards set for water-recovery systems. Although still tentative, these standards state that the bacterial counts must not exceed 10 micro-organisms/ml in any part of the system. When one considers the source of the recovered water and the constraints of closed ecological systems for long-duration missions, it soon becomes apparent that public health standards would not be acceptable. The introduction of these new standards places before the microbiologist a broad set of questions that require answers. For example, what is the best method for online sterilization of the system? What are the online monitoring requirements to insure that the standards of no more than 10 micro-organisms/ml are being met? Also, what are the long-term effects on the person who consumes water with these standards? It is anticipated that numerous other problems will develop as work progresses in this area.

Waste Management

It is anticipated that on short-duration missions, solid wastes will be stored on board the spacecraft. For long-duration missions, for example, interplanetary travel, it will be necessary to treat and dispose of the waste in a microbiologically safe manner. A number of prototype systems for both short- and long-duration missions have been developed; to date none of them meet all the requirements for an esthetically acceptable and microbiologically safe system that will operate under $0g$ conditions. It is obvious that the microbiologist will have to work very closely with the engineer in all phases of design, development, and testing of any waste-management system.

Personal Hygiene

For a number of reasons, including psychological, it will be necessary to provide the astronaut on long-duration missions with acceptable and microbiologically safe personal hygiene measures. It may be necessary to provide full-body shower facilities, and certainly day-to-day face and hands cleansing must be acceptable and safe. Again, close working relations must be established between the engineer and microbiologist to insure that all design requirements are being met.

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Life Support Systems Integration

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Achieving an optimized design of regenerative environmental control and life support (EC/LS) systems requires integration at three levels: subsystem, system, and total spacecraft.

Two types of subsystem level integration are desirable. One type is process integration that interfaces mass transfer, reaction-rate control, and phase-separation techniques. A second type is operational mode integration that interfaces selected techniques and design schemes for producing system operational flexibility.

System-level integration is paced by thermal-balance considerations. These considerations involve the techniques of supplying heat to the endothermic processes and coolant to the system hardware and cabin environment.

At the total spacecraft level, integration occurs most intimately between the EC/LS system, the power system, and the thermal-control system. The common denominator for these three systems is energy in the form of heat.

Tests have been conducted on a full-scale research model integrated system. The tests have indicated that the regenerative processes are feasible but that extensive development of subsystem hardware is necessary before regenerative systems can be applied to flight vehicles.

INTRODUCTION

During the past 10 yr, Government research laboratories and private industry have been cooperating in research efforts directed toward finding techniques and processes that can regenerate useful products from the waste products available in manned spacecraft. Most of these research efforts have consisted of a study of a promising physicochemical technique, followed by the development of a laboratory model that was used to demonstrate feasibility of the technique. The majority of the laboratory models were individual units designed for specific inlet conditions of mass flow, purity of flow, pressure, and temperature. These inlet conditions were accurately controlled and, therefore, the process efficiencies were not subject to frequent change caused by variations in inlet conditions. This type of research is necessary to uncover and evaluate new approaches to regenerative life-support processes; however, the true feasibility of the technique and embodying component cannot be established until it has been integrated into a total system where its inlet conditions are established by the output of a previous component. To demonstrate feasibility as a part of an integrated EC/LS system, the component must be integrated into such a system for functional checkout. Integration within regenerative EC/LS systems and between EC/LS systems and other systems aboard a spacecraft has been studied and discussed many times during the past 5 yr. Several excellent reports and papers (refs. 1 to 4) treat the subject in technical depth; however, actual integration of hardware into working models has been accomplished on a very limited scope. One such accomplishment was the cooperative program between NASA and General Dynamics/Convair that led to the research model integrated life support system (ILSS) now being researched at the Langley Research Center in Hampton, Va. This research tool is a valuable aid in an ongoing research program to isolate, define, and solve the technical and practical problems associated with integration of regenerative EC/LS systems at the subsystem, system, and total spacecraft level. Observations made during the conceptual design, detailed design, and fabrication phases and experiences gained during experimental phases of the ILSS program have provided the baseline for this discussion of life support systems integration.

DEFINITION OF INTEGRATION

Webster's Dictionary gives several definitions of the word "integrate." The first three definitions given can be taken as a combined definition of the word when applied to regenerative EC/LS systems. The definitions are (1) to form into a whole, (2) to unite with something else, and (3) to incorporate into a larger unit.

Each of the definitions describes a separate level of the total integration procedure. The first definition, to form into a whole, describes integration at the subsystem level. At this level, components and units are integrated into subsystems that have specific functions, such as the recovery of oxygen from carbon dioxide and recovery of potable water from waste water. The second definition, to unite with something else, describes integration at the system level. At this level, subsystems, such as those for water recovery, oxygen recovery, and waste management, are integrated into a complete EC/LS system that has the broad function of sustaining life. The third definition, to incorporate into a larger unit, describes integration at the total spacecraft level. At this level, the EC/LS system and other systems, such as the electrical power and thermal control systems, are integrated into the overall optimized spacecraft concept. Each of these levels of integration must occur if the resulting EC/LS system is to be truly integrated.

THE LANGLEY INTEGRATED LIFE SUPPORT SYSTEM

An artist's concept of the ILSS is shown in figure 1. Figure 2 is a composite photograph of the regenerative EC/LS system within the carbon-steel test bed. The system was designed to support a four-man crew in a $0g$ environment for a period of 1 yr. Resupply at 60- to 90-day intervals was assumed. This design point mission model was chosen as typical of the missions likely to evolve in the NASA manned space program. Studies also revealed that the regenerative EC/LS system required to support the mission model would embody techniques applicable to a wide range of extended missions.

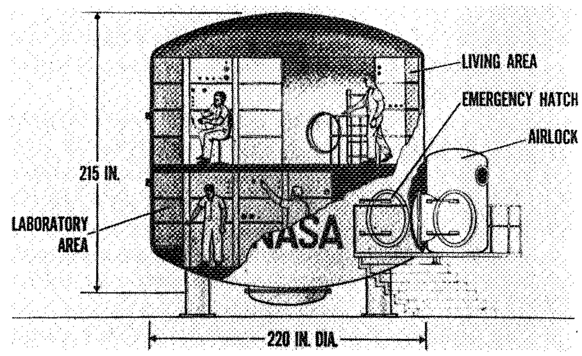

FIGURE 1.—Artist's concept of the ILSS—interior of the test bed.

Because the ILSS technology has a broad application and because its development and testing represent a unique step in the evolution of integrated EC/LS system technology, it will be used as a focal point for the following discussion.

INTEGRATION AT SUBSYSTEM LEVEL

Atmosphere Control Subsystem

The atmosphere control subsystem is one of the major integrated subsystems in the ILSS. It is within this subsystem that

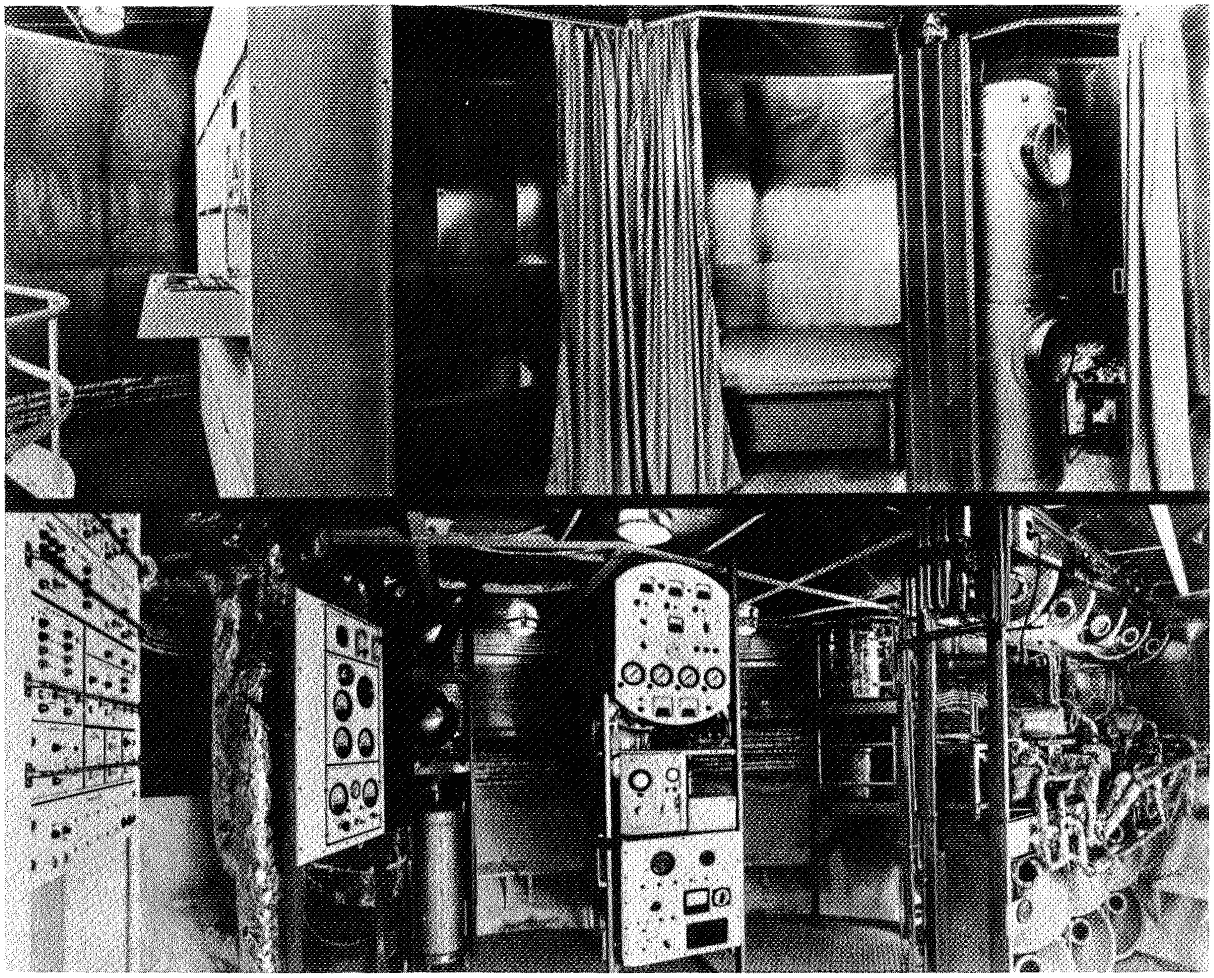

FIGURE 2.—Composite photograph of the EC/LS system.

oxygen is recovered from carbon dioxide, makeup gases are added, and the atmosphere is purified to maintain a habitable environment. The oxygen recovery portion of this subsystem is a good example of process integration at the subsystem level.

Figure 3 is a schematic of the oxygen regeneration process in the Bosch mode of operation. A general, but summarizing, analysis of the integration problem can be made by observation of the materials balance depicted on the figure. According to the theoretical materials balance, it is possible to recover 7.48 lb/day of oxygen (four-man requirement at an average of 150 percent basal metabolism rate) from 9.28 lb/day of carbon dioxide and 0.82 lb/day of makeup water. The theoretical balance is based on

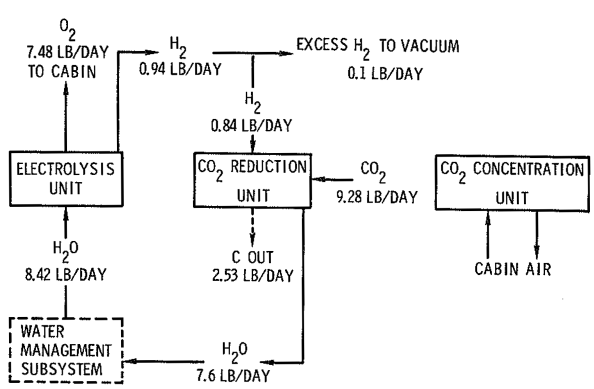

FIGURE 3.—Oxygen regeneration—Bosch mode.

the stoichiometry of the two basic chemical reactions involved, carbon dioxide reduction:

$$CO_2 + 2H_2 \rightarrow 2H_2O + C$$

and electrolysis of water:

$$2H_2O \rightarrow 2H_2 + O_2$$

The integration problem is one of controlling the chemical reactions and hardware operational sequences to achieve the theoretical yield of oxygen. Some of the details of the general integration problem can be pointed out by a discussion of the units that make up the oxygen recovery loop.

Carbon Dioxide Concentration Unit

The first unit in the loop is the regenerable carbon dioxide concentrator shown in figure 4. The concentrator receives a continuous flow of approximately 30 ft^3/min of air direct from the cabin air-conditioning unit. The flow to the concentrator exits the air-conditioning unit immediately downstream of the heat exchanger and air-water separator. At that location, the air is at its lowest temperature and dewpoint. These are favorable conditions for the following adsorption phenomenon. Adsorption occurs in silica-gel and artificial zeolite beds. The silica-gel beds remove remaining traces of moisture to a low dewpoint of approximately −70° F, and the zeolite beds selectively adsorb 40 to 60 percent of the carbon dioxide in the airstream. During operation, one silica gel and one zeolite bed are adsorbing, while a second pair of beds is being desorbed. The silica-gel bed is being desorbed back into the cabin airstream to prevent loss of water. The desorbed carbon dioxide is stored in an accumulator tank from which it is available for reduction in the carbon dioxide reduction unit. The energy for desorbing the molecular sieve beds is being supplied as heat by a waste heat process circuit originating from a simulated radioisotope Brayton-cycle power system. The hot fluid enters the desorbing zeolite bed at approximately 375° F. The concentration unit also contains a cooling fluid circuit for maintaining proper thermal conditions in the adsorbing beds and associated heat exchangers.

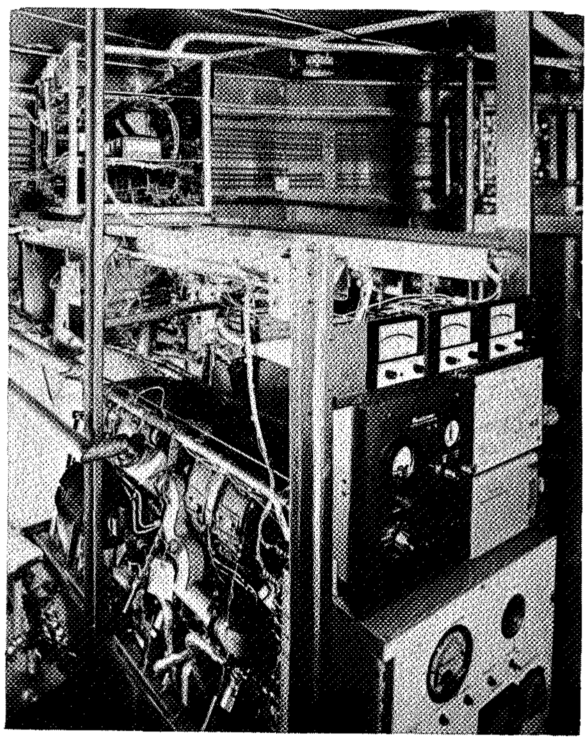

FIGURE 4.—Carbon dioxide concentrator.

There are two primary integration interfaces between the concentrator and other units within the oxygen recovery loop. The air exiting the air-conditioning unit and entering the concentrator must not contain moisture in excess of that present in saturated air at 55° F. If excess moisture is present, the silica-gel beds will become oversaturated and they will pass moisture into the zeolite beds. If this occurs, it will destroy the capacity of the zeolite bed to adsorb carbon dioxide. Therefore, the temperature-moisture relationship of the air exiting the air-conditioning unit must be closely controlled when an air-conditioning unit is integrated with a zeolite-type carbon dioxide concentrator. Another integration interface involves the purity of the carbon dioxide desorbed from the concentrator and available for chemical reduction. The most common impurity in the carbon dioxide accumulation tank is nitrogen, which is present in the air trapped in the free air spaces of the canisters containing the zeolite. There is also some unconfirmed evidence that the zeolite material may be adsorbing nitrogen; however, the majority of it can be attributed to residual air. If the carbon dioxide purity in the accumulator falls below approximately 98 percent, sufficient nitrogen can be introduced into the carbon dioxide reduction unit to require remedial action. The purity in the accumulator tank is affected by both adsorption and desorption cycles but perhaps most directly by the initial portion of the desorption cycle. The residual nitrogen (air) in the free air spaces of the desorbing canister is driven off first and if desorbed to the accumulator, a low carbon dioxide purity would result. It is, therefore, necessary to desorb the canister back to the unit intake during early minutes of the desorption cycle. As the desorbing gas becomes essentially pure carbon dioxide, it is desorbed to the accumulator tank from which it is made available to the reduction unit.

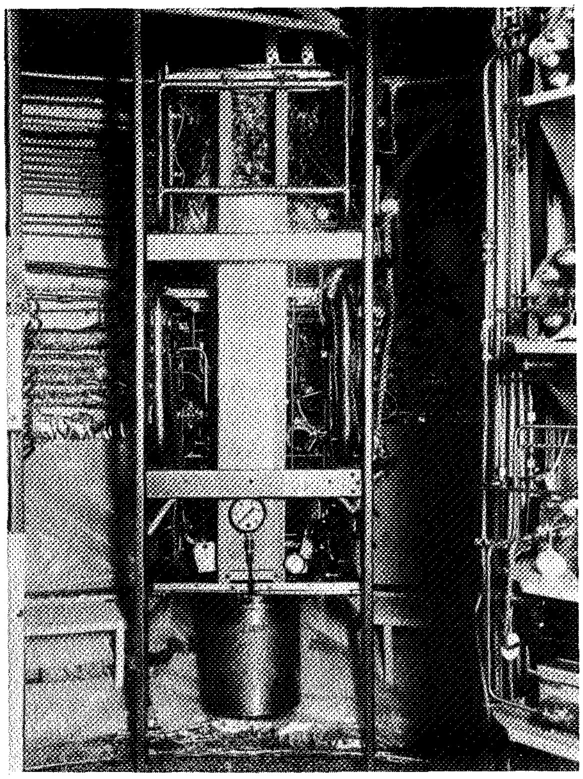

FIGURE 5.—Carbon dioxide reduction unit.

Carbon Dioxide Reduction Unit

The second unit in the oxygen recovery loop is the carbon dioxide reduction unit shown in figure 5. Carbon dioxide is delivered to the unit from the accumulator tank through a solenoid valve that is actuated based on measurement of carbon dioxide concentration in the reactant gas stream as sensed by an infrared analyzer. It is mixed with hydrogen from the water electrolysis unit and passed into a reactor where it is reduced over iron catalyst plates at a temperature of approximately 1100° F. The reaction is the Bosch process represented by the chemical equation

$$CO_2 + 2H_2 \rightarrow 2H_2O + C$$

The carbon that results from the reaction is a waste product and is collected in a filter that must be periodically replaced. The product gases are then cooled, and the steam produced by the reaction is condensed and separated from the gas stream by means of a passive capillary-action-type separator. The gas stream contains unreacted carbon dioxide and hydrogen, uncondensed water vapor, and carbon monoxide and methane from secondary reactions. After being enriched with additional carbon dioxide and hydrogen when necessary, the gas stream is recycled to the reduction unit. The recycle flow is an advantage of the Bosch process because unreacted gases and uncondensed water vapor are not lost. Consequently, the completeness of the reduction and water condensation processes during any short interval of time is not critical.

Integration interfaces between the reduction unit and other units in the oxygen recovery loop and the overall atmosphere control subsystem are numerous. One previously mentioned is the purity of carbon dioxide from the carbon dioxide concentration unit. The common impurity, nitrogen, will decrease the process rate when introduced into the reactor by lowering the partial pressures of the reactants. To remove the nitrogen, a flow of approximately 2 cc/min is bled from the recycle loop back into the cabin. Because the bleed flow will also contain carbon monoxide and methane from secondary reactions, it must be bled through a high-temperature catalytic oxidizer. It was also expected that additional carbon monoxide and methane would be introduced direct into the cabin air through leaks in the plumbing and seals of the reduction unit. Test experience has confirmed the expected leakage. The leakage, however, has been much greater in magnitude than expected. Leakage rates as high as 130 to 170 cc/min have been experienced. Because of the leakage, it has been necessary to periodically operate two catalytic burners simultaneously. This situation is undesirable because of the increased demand for oxygen in the oxidation process and the increase in requirements for electrical power.

Another integration interface involving reactant gas feed is present between the reduction unit and the water electrolysis unit. It involves the movement of hydrogen between the two units. According to the theoretical materials balance shown in figure 3, maintenance of a stoichiometric Bosch process at the four-man oxygen regeneration level will produce excess hydrogen, the excess being supplied in the makeup water that is required for oxygen generation. The excess has not been confirmed by actual tests to date because units of the oxygen recovery loop have not mechanically functioned for long enough periods of time to permit an attempt at a materials balance. The anticipated problem of controlling the hydrogen feed to the reduction unit in stoichiometric ratio with the carbon dioxide feed does not appear to be a severe integration problem as expected. Tests of the reduction unit reported by Clark and Holmes (ref. 5) indicate that the rate of water formation is relatively insensitive to recycle gas hydrogen/carbon dioxide volume ratios ranging from 3.0 to 9.0. This observation has led to the development and testing of an automatic feed gas approach that uses simple control techniques. Carbon dioxide from the accumulator is delivered at 3.5 psig to a solenoid valve that opens and closes on signal from a low and a high setting on an infrared carbon dioxide analyzer. The analyzer is detecting the amount of carbon dioxide in the recycle loop and, thus, a specific amount (ratio of carbon dioxide to total gas) of carbon dioxide is maintained in the recycle gas. Hydrogen is delivered from the electrolysis unit to a pressure regulator set at 3.0 psig. When the recycle gas loop pressure falls below 3.0 psig, indicating the need for additional reactants, the valve opens and admits hydrogen until the pressure again reaches 3.0 psig. This technique assures sufficient quantities of gases for the reaction that will take place stoichiometrically over a long period of time, although for any given short period of time, an exact stoichiometric feed is not necessary.

The inclusion of an alternate reduction unit in the oxygen recovery loop is an integration feature of the ILSS. If trouble occurs in the Bosch reactor, the reactant gases can be directed to a low-temperature Sabatier reactor that shares some common plumbing with the Bosch reactor. Figure 6 is a schematic of the oxygen regeneration process in the Sabatier mode. In the Sabatier reactor, the carbon dioxide is reduced by hydrogen over a nickel catalyst at a temperature of approximately 500° F. The reaction is represented by the chemical equation

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

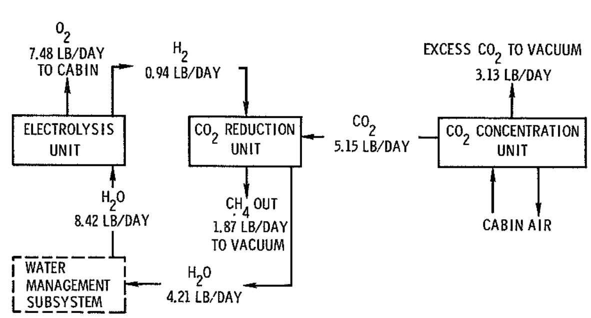

FIGURE 6.—Oxygen regeneration—Sabatier mode.

There is a basic difference between the Bosch and Sabatier process materials balance. The Bosch permits reduction of all the available carbon dioxide, but, because of the increased use of hydrogen in the Sabatier, only a portion of the carbon dioxide can be reduced. From an integration standpoint there are some additional differences. Although accurate control of the hydrogen-to-carbon-dioxide-feed ratio was not a problem with the Bosch method, it is a problem with the Sabatier method. The Sabatier reactor does not have a recycle loop because of the need to continually vent the methane. Thus, reactant gases that are not converted on a single pass and uncondensed water vapor are lost overboard along with the methane. Loss of carbon dioxide less than the 3.13 lb/day excess shown in figure 6 does not create a severe penalty but loss of the hydrogen and water vapor does penalize the Sabatier process. Compounding this problem is the experimental evidence that better water yields are obtained with feed ratios that are hydrogen rich. If the process is hydrogen rich, the unreacted hydrogen will also be lost overboard.

The integration problem of generation and control of carbon monoxide has not been experienced with the Sabatier. The generation problem is inherently less with the Sabatier process and the leakage problem is alleviated because of the lack of a recycle gas loop and rotating catalyst drive mechanisms.

Water Electrolysis Unit

The third unit in the integrated oxygen recovery loop is the water electrolysis unit shown in figure 7. The unit includes three modules, each of which contains 16 cells. The cells contain a 25-percent solution of sulfuric acid electrolyte and water between two ion-exchange membranes. The electrodes are made by coating the outer surfaces of the membranes with a platinum black catalyst powder in contact with a current-distributing screen. The oxygen produced at the positive electrodes is released into the cabin for crew consumption. The hydrogen evolved at the negative electrodes is used in the reduction unit. The integration interface of hydrogen flow between the water electrolysis unit and the reduction unit has been described previously. Another integration interface between these two units involves the purity of the water as generated by the reduction versus the purity requirement as dictated by the electrolysis unit. The water management subsystem also interfaces into the purity problem because of the makeup water that it adds to the total required for electrolysis. This water purity integration interface has not been defined. To date, all feed water to the electrolysis unit has been distilled water.

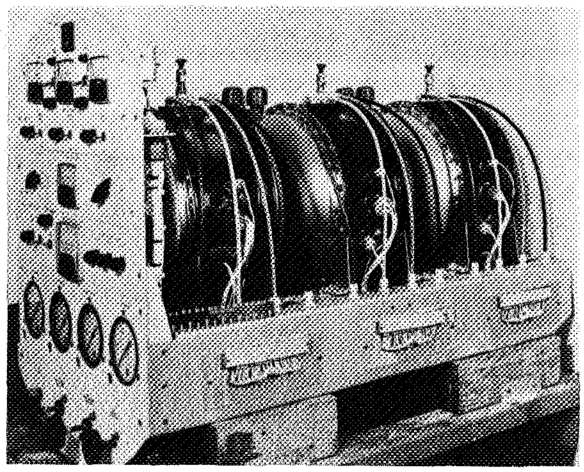

FIGURE 7.—Water electrolysis unit.

Water Management Subsystem

The ILSS water management subsystem is a good example of integration of operational modes at the subsystem level. It is within this subsystem that usable water is recovered from urine, wash water, and humidity condensate. This subsystem also serves as a collection, holding, and dispensing function for water throughout the entire system. The complete subsystem is shown in figure 8.

Wick-Type Evaporation Units

The water recovery process occurs in the wick-type evaporation units, one of which is

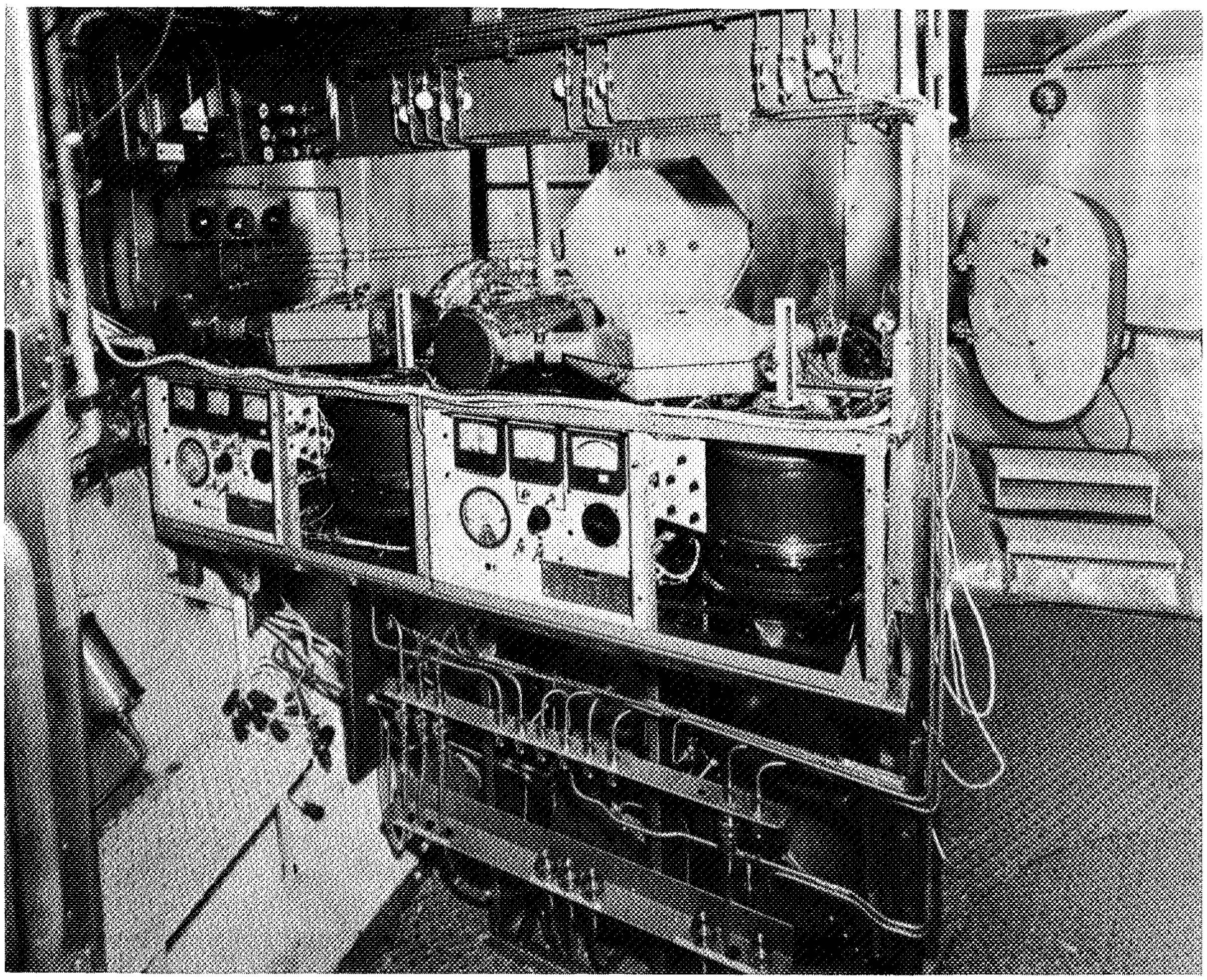

FIGURE 8.—Water management subsystem.

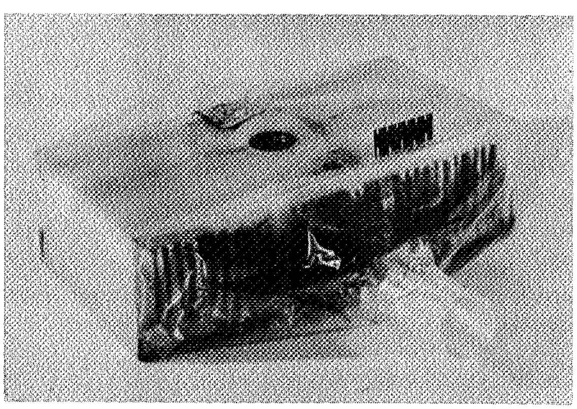

FIGURE 9.—Wick-type evaporation unit.

shown in figure 9. A flow of air heated to temperatures between 120° to 180° F is passed over a wick saturated with waste liquids. The water in the liquids is vaporized, condensed, and separated from the airstream. The separation is accomplished by a turbine-driven centrifugal separator. The water is then pumped to the holding tanks for purity analysis. The waste solids remain in the wick. The airstream is reheated and passed into the wick for another cycle. Chromic and sulfuric acid pretreatment chemicals are added to the waste water prior to processing to lower pH, to fix ammonia, and to prevent the growth of micro-organisms.

Multifiltration Unit

A multifiltration unit is included in the system as a standby for emergency mode operation. This unit uses activated charcoal filters and ion-exchange resin beds to process humidity condensate to potable water. The unit is sized for a 17-day capacity.

Operational Mode

The two types of recovery units discussed are capable of three modes of operation. In the normal processing mode, the total system water balance is as follows:

	Quantity, lb/day/ 4 men
Water required:	
Drinking and food preparation	30.0
Wash water	13.2
Electrolysis makeup	.8
Total	44.0
Water recovered:	
Urine water	13.2
Wash water	13.2
Humidity condensate	19.6
Total	46.0

A schematic of the normal processing mode is shown in figure 10. One evaporation unit is processing urine to wash water, while the other is processing wash water and humidity condensate to potable water. Thus, to process urine to potable water, two process cycles are required.

A secondary mode, the minimum continuous mode, shown in figure 11, is provided by slightly oversizing the evaporation units so that each unit can process all three types of waste waters. In this mode of operation, one

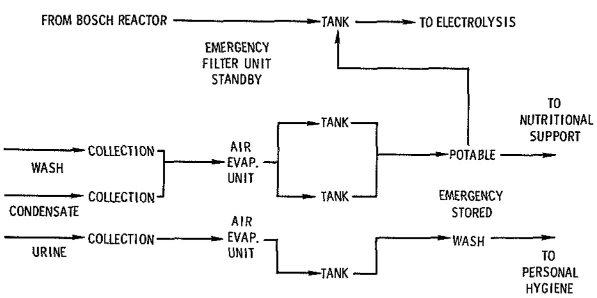

FIGURE 10.—Normal processing mode.

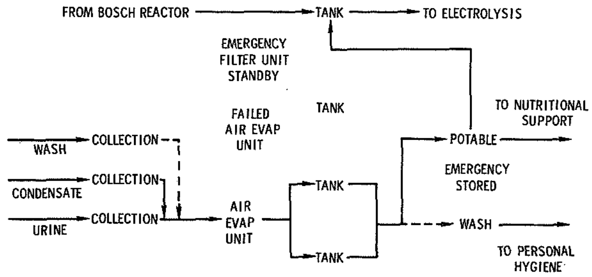

FIGURE 11.—Minimum continuous mode.

evaporation unit has failed and the other unit is processing urine, humidity condensate, and a portion of the wash water. There is only one process cycle from urine to potable water, and the amount of water for personal hygiene is reduced.

The third mode of operation, the emergency mode, is represented in figure 12. In this mode, only the humidity condensate is processed by the emergency multifiltration unit and makeup water is added from the stored supply. Water for washing is no longer available. This design concept and arrangement of the water management subsystem is an example of integration of operational modes to provide redundancy, step degradation, and emergency capability.

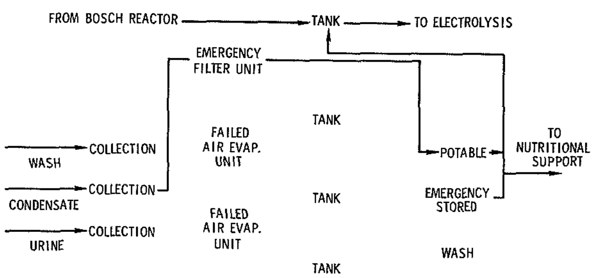

FIGURE 12.—Emergency mode.

Other ILSS Subsystems

The remaining subsystems are not good examples of integration within themselves but are a necessary part of a discussion on integration at the system level. Therefore, in preparation for the later discussion, they are described briefly.

Nutritional Support Subsystem

Nutritional support is provided by freeze-dried, stable-conventional, and frozen foods. The foods are stored, prepared, and dispensed with the aid of the console (fig. 13) and a supplementary freezer not currently a part of the system. Preparation of the food required warm water at 180° F and cool water at 40° F for reconstitution of the dried foods. The reconstitution takes place in small plastic packages that are used as dispensing aids.

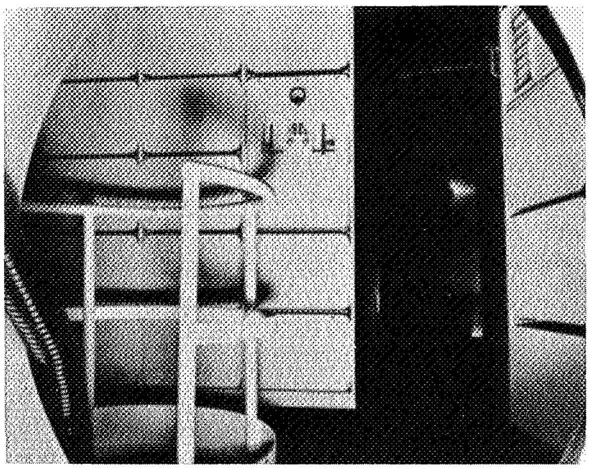

FIGURE 13.—Nutritional support console.

Waste Management Subsystem

The waste management subsystem provides for the collection of all wastes, the processing of solid body wastes, and the storage of waste solids for the entire system. The current configuration of the waste collection and processing unit is shown in figure 14. Urine is collected in a relief tube with the aid of a small flow of cabin air. After being separated from the airstream by a motor-driven centrifugal separator, the urine is pumped to the water management subsystem for processing. The airstream is returned to the cabin. Fecal material is collected in a conical paper filter backed by a permeable hydrophobic polymer fabric. During the collection process a small flow of cabin air is pulled into and through the collection cones. The flow transports noxious odors to activated charcoal filters where the airflow is cleaned prior to returning it to the main cabin airstream. The collection cones containing the fecal material and cleaning tissue are manually transferred to a processing canister in which the fecal material is vacuum dried by a simulated space vacuum aided by waste heat from the process heat circuit. The dried material is then placed in a nonpermeable bag and stored in one of the large storage containers placed adjacent to the collection unit. The vacuum-drying canisters and the storage containers are also used to process solid waste materials from the nutritional support and personal hygiene subsystems.

The functions provided and the quantity of wastes handled by the waste management subsystem are given in table I.

TABLE I.—*Waste Management System*

Waste	System function	Quantity handled, lb/day/ 4 men
Feces	Collection, processing, and storage.	1.3
Urine	Collection and transfer	13.2
Refuse:		
Food and packaging.	Processing and storage	1.6
Personal hygiene.	Processing and storage	.5
Carbon	Storage	2.5

Personal Hygiene Subsystem

The personal hygiene subsystem provides sponge bathing and conventional dental and shaving facilities. Warm water treated with benzalkonium chloride at a dilution of 1:2000 is furnished for body cleansing and rinsing of personal hygiene aids. A cylindrical chamber with a thumb-operated removable piston provides a container for wetting, drying, and cleansing the sponges. Dental cleansing is provided by a conventional toothbrush and ingestible dentifrice. Shaving is accomplished

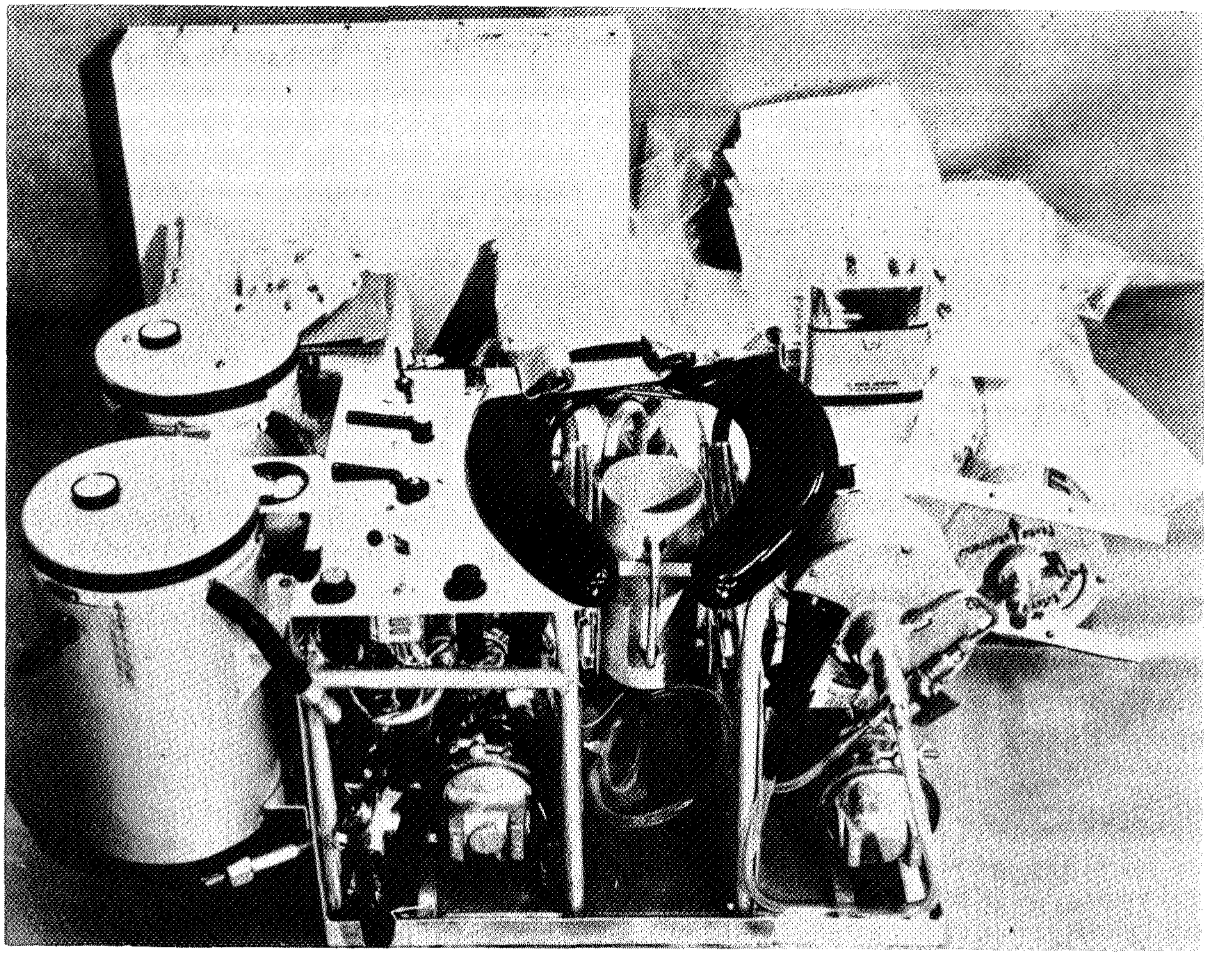

FIGURE 14.—Waste management unit.

with an electric razor. In a flight system, the razor would be modified to include a small induction blower and whisker collection bag.

Thermal-Control Subsystem

The thermal-control subsystem includes three integrated fluid circuits. They are the process heat circuit, the primary coolant circuit, and the cabin air circuit. They are discussed in more detail in the next section of the paper.

INTEGRATION AT SYSTEM LEVEL

A complete treatment of integration of the ILSS at the system level would involve a discussion of every component in every subsystem. Each contributes to some extent to the overall integration procedure. There is one subsystem, however, that is the key to system-level integration. That subsystem is the thermal-control subsystem. It includes three integrated fluid circuits: the process heat circuit, the primary coolant circuit, and the cabin air circuit. A highly simplified schematic of the integration of these three circuits is shown in figure 15.

Process Heat Circuit

One of the candidate power systems for use on extended mission spacecraft is the dynamic Brayton-cycle radioisotope system. The ILSS was designed around a typical extended mission spacecraft concept that included this type of power system. During

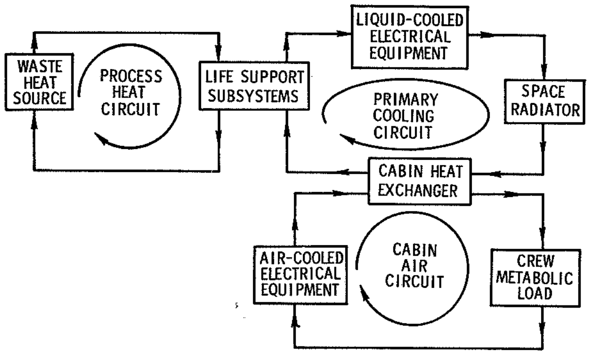

FIGURE 15.—Integration of the thermal-control circuits.

operation of the power system, large quantities of waste heat must be rejected. By using the waste heat to supply energy for the regenerative physicochemical processes, the requirement for energy supplied directly by electrical power from the spacecraft power system can be reduced. In the ILSS, a commercial heating cart delivers a simulated waste heat load to the EC/LS system by means of a silicone fluid at a temperature of 375° F at the inlet to the system. Approximately 15 800 Btu/hr (4.6 kW) of waste heat energy are delivered to the EC/LS system by the process heat circuit shown schematically in figure 16. In the circuit, the EC/LS system components are arranged for the most effective utilization of the waste heat by placing components requiring the highest fluid temperatures upstream of the others and by placing components with cyclic heating requirements, such as the carbon dioxide concentrator, on separate branch circuits. Although cryogenic stores heat exchangers were not installed in the ILSS, provisions were made for them in the system design. These heat exchangers were located on a separate branch of the process heat circuit to permit the total heat transport fluid to be diverted to them if needed for emergency repressurization.

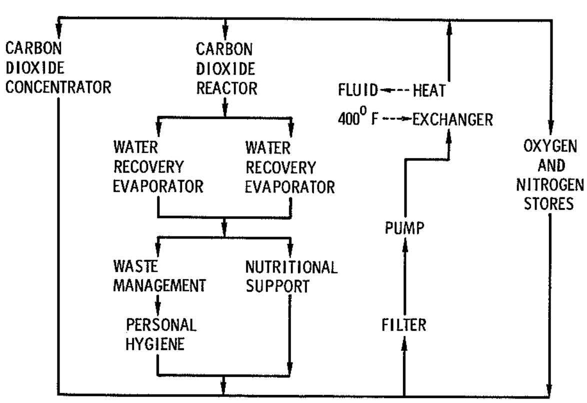

FIGURE 16.—Process heat circuit.

The utilization of the waste heat is an example of optimization by integration; however, it also creates integration problems that have not been completely solved. Absolute containment of the hot fluid is a difficult task. Containment is further complicated by the need to repeatedly break and remake fittings when components are removed for maintenance. Another problem with the integrated process heat circuit is the one of controlling the flow through the EC/LS system. Balancing valves, orifices, and bypass lines must be provided to insure proper fluid distribution through all units when single or multiple units are turned off or adjusted. Control in the ILSS is accomplished manually and requires considerable attention. If waste heat process circuits are to be used in flight systems, a technique for automatic control must be developed.

Primary Coolant Circuit

A primary coolant circuit utilizing a mixture of propylene glycol and water further integrates the EC/LS system. A schematic of the circuit is shown in figure 17. An excerpt from NASA CR–614 (ref. 6) describes the integration:

> The water chiller, cabin air heat exchanger A, and CO_2 reduction unit all require low-temperature coolant for condensing or chilling operations and were located in parallel circuits immediately downstream of the fluid cooling and pumping unit. Heat exchanger B was installed in the fluid circuit immediately downstream of heat exchanger A so that heat exchanger B receives full coolant flow at a maximum temperature of 46° F.
>
> The electrolysis unit was located in a bypass circuit downstream of heat exchanger B. This location permits the unit to receive a constant coolant flow

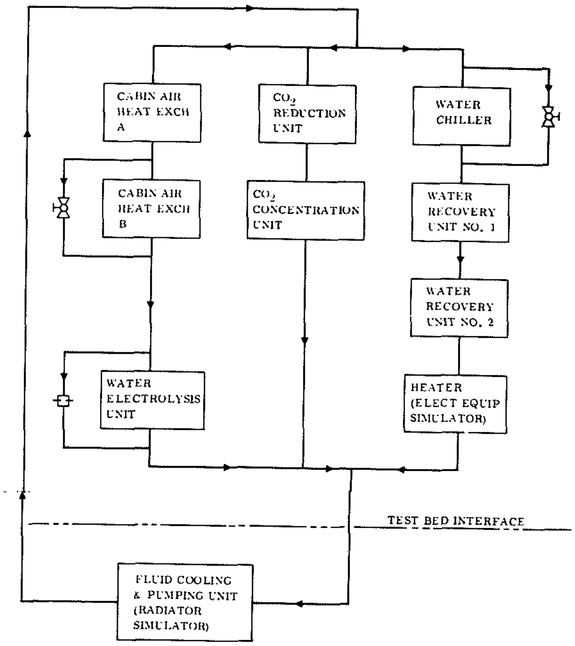

FIGURE 17.—Primary coolant circuit.

at a temperature of approximately 65° F. A fixed orifice was installed in the main circuit parallel to the electrolysis unit to divert the required coolant flow to the unit.

The water recovery units and the coolant-fluid heater (electronic equipment simulator) were installed in series downstream of the water chiller to take advantage of the low-temperature coolant leaving the chiller.

The CO_2 concentration unit, which has large cyclic cooling requirements, was located downstream of the CO_2 reduction unit to minimize its effect upon the remainder of the circuit.

This distribution circuit permits each component to receive coolant at the lowest available temperature without producing excessively high circuit-pressure drop or increasing the total fluid-flow rate above that required to satisfy the cooling requirements of the low-temperature units.

Balancing valves are installed in all parallel branch circuits to allow flow rate adjustment. Enough calibrated flow-measurement orifices have been installed to permit direct or indirect (sum-and-difference) determination of the coolant flow rate to each key component in the circuit.

Integration problems experienced with this circuit are similar to those experienced with the process heat circuit. Originally the primary coolant circuit used a fluorocarbon liquid that was difficult to contain. Upon leaking, it would quickly evaporate. Thus, the point of leakage was difficult to locate. After changing to glycol and water, the leakage problem was reduced. Experience has indicated that the entire problem of maintaining an automatic balanced flow of heating and cooling fluids throughout an integrated system with cyclic thermal conditions will be a difficult one for which to find an optimum solution.

Cabin Air Circuit

The cabin air circuit, shown schematically in figure 18, provides a transfer function for

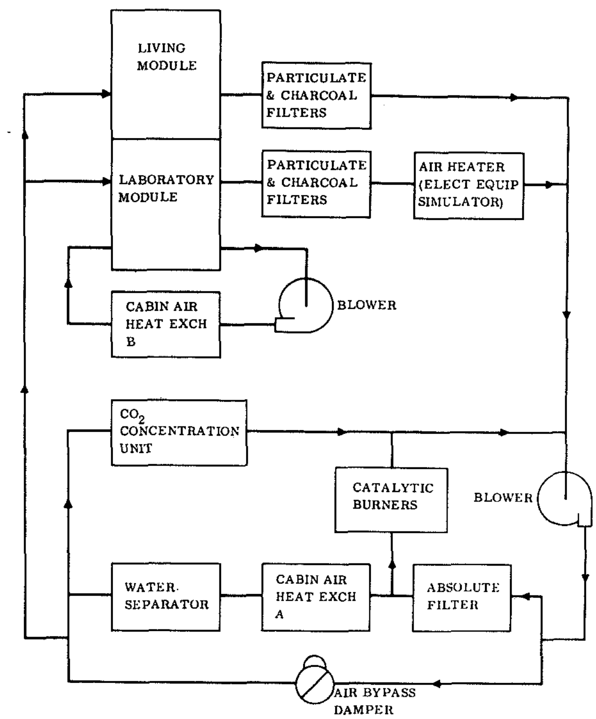

FIGURE 18.—Cabin air circuit.

many of the materials associated with the process loops; however, as part of the thermal control subsystem, its primary function is to transfer sensible and latent heat loads from the cabin atmosphere to the cabin air-heat exchanger. The cabin environment is maintained at a selected temperature in the range from 68° to 80° F and at a relative humidity between 40 and 60 percent. Condensation and removal of excess humidity is accomplished in the cabin air circuit with the heat exchanger and a passive type of air-water separator that utilizes capillary action across porous plates as the phase-separation technique.

INTEGRATION AT TOTAL SPACECRAFT LEVEL

The integration of a regenerative EC/LS system with the total spacecraft is an action that does not occur independently or at any specific time during the spacecraft design. It occurs simultaneously with the development of the total spacecraft concept. Many of the design requirements that are imposed on the EC/LS system are established by the mission model, gross features of the spacecraft model, and crew model that are initially fixed by the mission to be flown and the capability of propulsion systems. The elements of the models include interfaces between the EC/LS system and other spacecraft disciplines, such as configuration and structure, guidance and control system, and mission profile; however, the best example of integration at the total spacecraft level is the interface between the EC/LS system, the power generation system, and the thermal control system. This interface can be observed by an examination of figure 19, which is a summary of the ILSS heat load. Note that the regenerative EC/LS system demands considerable energy, 37 292 Btu/hr,[1] to drive the processes. In a nonintegrated spacecraft, the energy would be delivered to the regenerative processes as heat from resistance heaters. In an integrated spacecraft with a dynamic radioisotope power system, a large portion of the energy can be supplied by heat that is waste from the power system. Thus, the endothermic EC/LS system can act as a heat sink for the power system. As a result, the overall weight and size of the spacecraft can be reduced by reducing the weight and size of the power system, or the savings in power can be used for other purposes, such as conducting onboard scientific experiments.

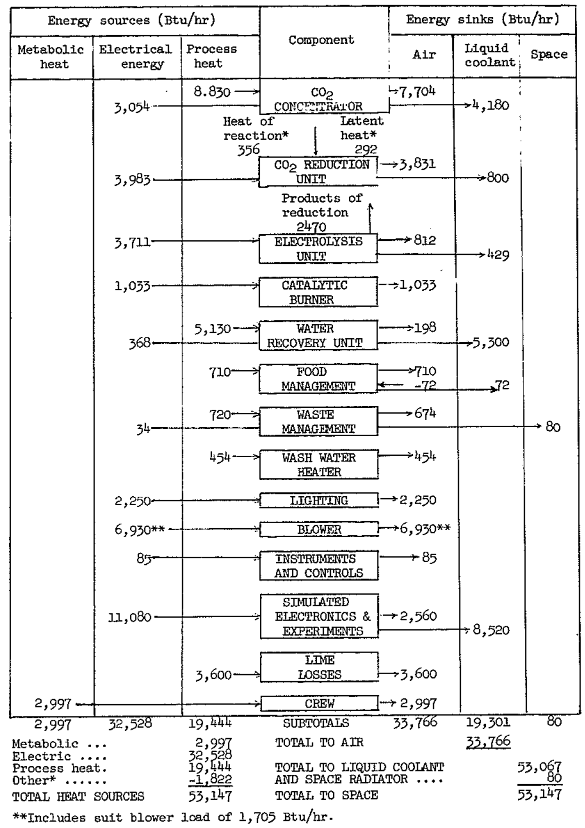

FIGURE 19.—Heat load summary, maximum.

All integration interfaces between the EC/LS system and the total spacecraft cannot be as clearly defined or so quickly reduced to a numerical tradeoff as can the EC/LS system-power system-thermal control system interface. The reliability requirements for extended-mission spacecraft make in-flight maintenance necessary. EC/LS systems must, therefore, be designed and arranged for access. One approach to this problem that is currently receiving study is the one of modularizing the EC/LS system. In addition to easing maintenance problems, modularizing may provide reliability through redundancy. The final arrangement of a single or modular EC/LS system will undoubtedly affect configuration of the total spacecraft.

[1] 32 528 Btu/hr—11 080 Btu/hr (electronics heat load) +19 444 Btu/hr—3600 Btu/hr (lime losses) =37 292. Only electronic and process heat are charged to process heat. (See fig. 19.)

TEST RESULTS

The ILSS used as a focal point for the discussion of life support system integration has been used to isolate and define some of the technological and practical problems that must be solved before regenerative systems can be applied to flight vehicles. It is not within the scope of this paper to present and discuss all of the test results obtained to date; however, it is appropriate to present a few of the most significant results. The cumulative engineering test hours on the ILSS units are as follows:

Unit:	*Total hours*
CO_2 concentration	1441
CO_2 reduction:	
Bosch	869
Sabatier	436
H_2O electrolysis	1300
Catalytic burners	2178
Evaporation (water)	760

The cumulative times include periods of independent operation and periods of operation as part of the integrated system. Four integrated system tests have been conducted:

(1) 24-hr functional evaluation—unmanned, doors open

(2) 7-day integrated system—intermittently manned, doors closed

(3) 3-day integrated system—manned (3 crews, four men in each crew), doors closed

(4) 4-day integrated system—manned (3 crews, four men in each crew), doors closed

Some of the most significant results are discussed briefly in the following pages.

Carbon Dioxide Concentration Unit

This unit has functioned well. It has continued to maintain the cabin carbon dioxide percentage near the 0.5-percent design point. During periods when the unit is functioning properly, the purity of carbon dioxide delivered to the accumulator tank has reached 99 percent. The majority of the difficulties experienced with the unit have been mechanical failures of valves and valve actuators. When valve failures occur, they have an immediate and significant effect on the performance of the unit. Only one bed poisoning has occurred. Early in the subsystem checkout program, coolant flow to the cabin-air heat exchanger was erroneously bypassed around the heat exchanger. This permitted excessive moisture to enter the silica gel beds, allowing them to become oversaturated. Attempts to dry the beds failed, and the silica gel had to be replaced.

Bosch Carbon Dioxide Reduction Unit

The performance of the Bosch reduction process and the resulting water yield has been encouraging. In addition, the anticipated integration problem of controlling feed-gas ratios has not proved to be a difficult problem. A satisfactory solution to this problem was developed and has been discussed in an earlier section of this paper.

The successes, however, have been overshadowed by two problem areas.

(1) *Carbon transport and removal.*—The problem of removal of elementary carbon from the recycle gas stream was anticipated and was taken into account in the unit design; however, the problem is not limited to removal of carbon from the recycle gas. Repeated difficulty has been experienced in getting the carbon off the catalyst plates, out of the reactor, and to the lower end of the heat exchanger when carbon removal by a filter bag is to take place. Figures 20, 21, and 22 illustrate the carbon transport and removal problem. Figure 20 shows a clean catalyst plate assembly. Figure 21 shows a catalyst plate assembly after the plate scraping mechanism failed. This permitted carbon buildup causing failure of the assembly drive mechanism. Figure 22 shows carbon buildup in the neck of the heat exchanger. Details of the carbon transport and removal problem and development efforts to find solutions to the problem are reported by Clark and Holmes (ref. 5).

(2) *Carbon monoxide generation and leakage.*—During the design of the Bosch reactor, it was anticipated that when the unit was heated to the 1100° to 1300° F op-

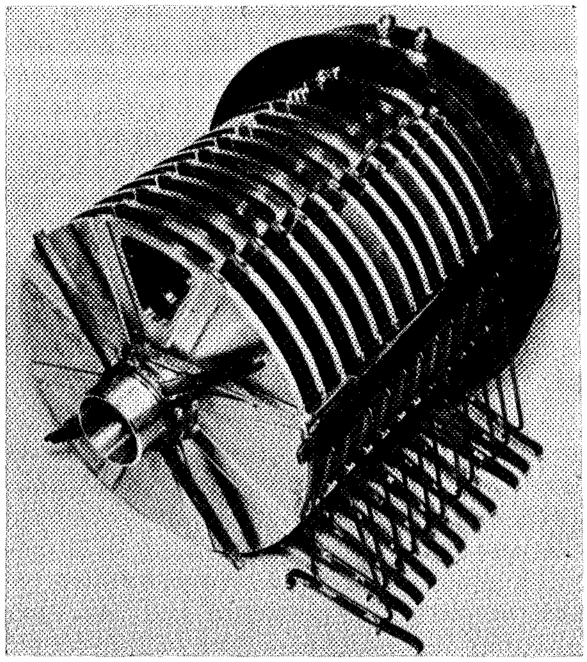

FIGURE 20.—Catalyst plate assembly.

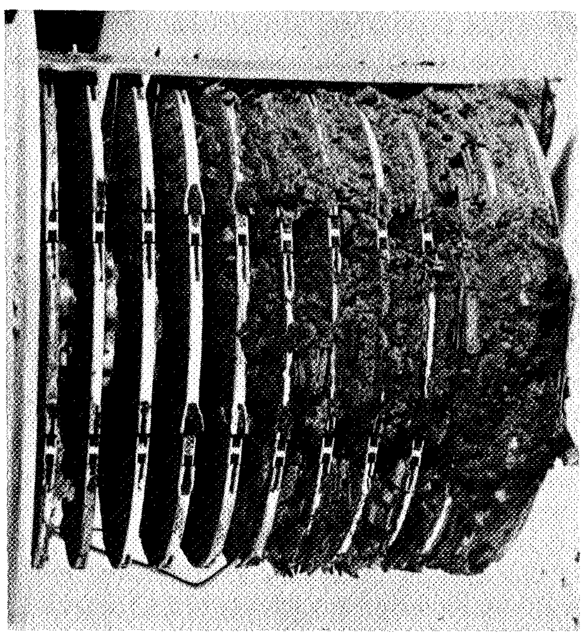

FIGURE 21.—Carbon buildup on plates.

erating temperature, a small amount of the recycle gas would leak into the cabin. The original estimate was a leakage of 2 cc/min

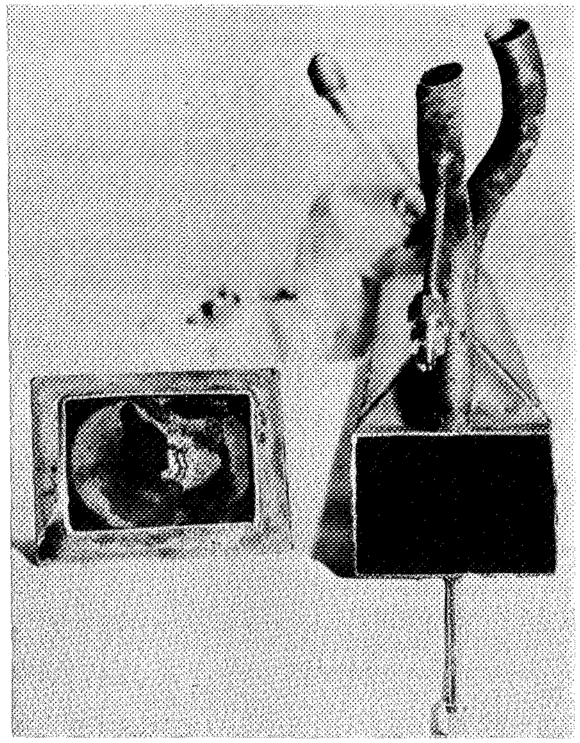

FIGURE 22.—Carbon buildup in heat exchanger.

of recycle gas with a carbon monoxide concentration of 20 percent. The catalytic oxidizer was sized accordingly and was designed to maintain a cabin carbon monoxide concentration of 10 ppm with the oxidizer in the normal flow mode; however, during a 3-day, closed-door test of the ILSS, evidence was gained that the leakage rate of recycle gas into the cabin air approached 150 cc/min. This leak rate overloaded the single catalytic oxidizer and caused the cabin total hydrocarbon and carbon monoxide concentrations to rise. A second catalytic oxidizer had to be placed into operation and both units frequently had to be operated in the boost mode of flow. At one point in the test, the carbon monoxide concentration exceeded the red-line value of 50 ppm. This occurred when the Bosch reactor was shut down and opened for maintenance because of carbon blockage of the recycle gas flow through the heat exchanger.

Water Electrolysis Unit

Prior to the most recent integrated system test, a 4-day test completed in July 1967, operation of the electrolysis unit had been plagued with difficulty. The most severe problem encountered was the popping out of portions of the Hypalon rubber spacers between cells in a stack. One of the Hypalon spacers with embedded coolant tubes is shown in figure 23. Very little force is required to pop out a flexible spacer. This was evidenced many times during stack assembly when normal compression required to seal the stack would pop or squeeze the spacers out in a direction perpendicular to the compression force. When spacers pop out of the stack, liquid containing the electrolyte can leak into the cell stack housing, thus requiring shutdown of the assembly. A satisfactory fix may have been found to this problem as evidenced by the successful operation of the water electrolysis unit during the 4-day test in July. Fiber-glass strips were placed across the cell stacks to support the spacers. Unsupported spans were limited to a distance of 1 in. A previous fix that utilized fiber-glass strip reinforcers placed along the edges of individual cells helped prevent spacer popout but may have contributed to another problem. The metal tubes carrying coolant to and from the cells corroded through at the interface with the fiber glass. As a result, nitrogen from the module housing leaked into the coolant tubes and entered the entire system coolant circuit. In the current configuration, the coolant tubes are enclosed in a polyethylene shrink tubing and they do not contact the fiber-glass reinforcing strips. Additional testing is necessary to determine the long-term result of the fix.

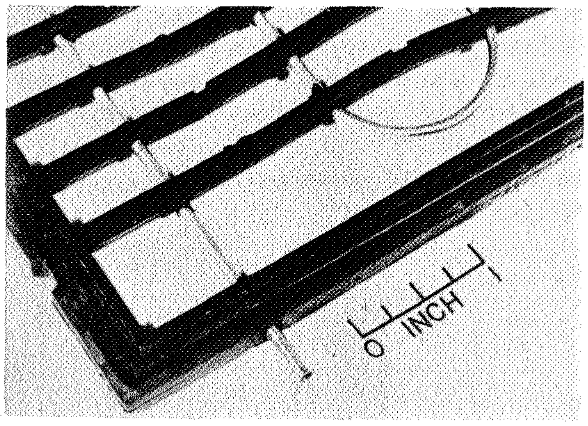

FIGURE 23.—Electrolysis cell spacer.

Problems more specifically related to the electrochemical phase separation processes have also been encountered. Liquid carryover through the liquid-gas separation membranes has occurred to the extent that additional separators have been added to each of the product gas outlets. The problem has been more severe in the hydrogen side of the cells than in the oxygen side. The problem has not been completely defined to date; however, preliminary tests, using color-marked electrolyte and visual observation of the carryover, have indicated that the carryover is due to electrochemical phenomena rather than to capillary movement. Tests have also indicated that the carryover rate may be a function of cell temperature and electrolyte concentration, a higher carryover occurring with increasing temperature and decreasing electrolyte concentration.

An encouraging but unexplained event was the recent 4-day test during which the water electrolysis unit performed without difficulty. Spacers did not pop, liquid carryover did not occur, and cell voltages stabilized at approximately 2.0 V. Additional analysis of the test data may uncover the reason for the success.

Water Management Subsystem

To date, there have not been a sufficient number of controlled tests nor have they been of sufficient duration to produce conclusive results on the quality of the recovered water. Preliminary analysis of water samples from the 7-day test of February 1967 does indicate trends that will be investigated in more detail. Water recovered from humidity condensate and wash water appears to be of good quality based on chemical analysis. Electrical conductivity has been low ranging, between 13 and 19 μmhos/cm. No odor or color has been detected. Water recovered from urine, however, has not been of equal quality. Electrical conductivity has ranged between 127 to 300 μmhos/cm and has a detectable odor and color (turbidity). Traces of urea have been detected and total alkalinity has been relatively high, ranging between 58 to 118 mg/liter reported as calcium carbonate. The system is very difficult to decontaminate biologically. After decontamination, it is also difficult to maintain in a clean condition. Biological analyses of the recovered water verify the presence of a biological contamination problem.

The technique of feeding waste water to the wicks has presented a problem. A single thermistor is placed vertically into the wick. The thermistor senses wick operating temperature, which is a function of the combined temperature of the process airstream and cooling effect of evaporation. As the wick dries, the temperature increases until it reaches a set point at which time a new batch of waste water is fed to the wick. Because the batch feed is based on temperature sensed by the thermistor, the accuracy of the signal from the thermistor is critical. Difficulty has been experienced in getting an accurate signal from the thermistor because small changes in its location with respect to

TABLE II.—*ILSS Atmospheric Analyses, Summary of Averaged Values with Highs and Lows*

Method of analysis	Averaged values								7 day	
	Jan. 31	Feb. 1	Feb. 2	Feb. 3	Feb. 4	Feb. 5	Feb. 6	Feb. 7	Low	High
Process GC, percent:										
O_2	22	22	21	21	21	21	21	21	21	23
N_2	78	76	74	74	74	75	76	77	74	80
CO_2	.79	.80	.78	.73	.75	.75	.74	.78	.60	1.00
CO	0	0	0	0	0	0	0	0	0	0
H_2	0	0	0	0	0	0	0	0	0	0
CH_4	0	0	0	0	0	0	0	0	0	0
H_2O	1.7	2.0	2.0	1.9	1.9	1.7	1.8	1.9	1.4	2.5
Pressure, torr	766	764	759	766	761	757	758	753	750	769
Wet chemistry, ppm:										
NH_3	0	0	0	0	0	0	0	0	0	0
SO_2	0	<1	0	0	0	0	.3	0	0	<1
H_2S	0	0	0	0	0	0	0	0	0	0
NO	0	0	0	0	0	0	0	.1	0	.1
NO_2	0	0	0	0	.1	0	0	0	0	.1
Mercaptan [a]	0	0	0	0	0	0	0	0	0	0
Trace GC, ppm:										
Acetone	0	0	0	0	<.1	<.1	0	0	0	<.1
Alcohol [b]	0	4	5	<.5	<1	<1	3.5	<1	0	10
Benzene	0	0	0	0	0	0	0	0	0	0
Trichloroethylene	0	0	0	0	0	0	0	0	0	0
CO	1	1.5	1.5	.3	<.5	<.5	1.2	<.5	0	2
CH_4	0	1.5	1	1	1	1.5	4	1	0	12
H_2	7	100	58	52	52	48	59	50	7	160
Total hydrocarbons,[c] ppm	3	4	6	5	5	6	6	6	2.5	15
CO analyzer, ppm	4	2	1	1.5	1.5	1.5	1.8	2	0	6

[a] As methyl mercaptan equivalent.
[b] As methyl alcohol equivalent.
[c] As methane equivalent.

wick and wick spacer materials produce large differences in sensed temperatures. If the thermistor senses a temperature higher than the overall representative wick temperature, batching is too frequent and flooding results. If the thermistor senses a temperature lower than the overall representative wick temperature, batching is not frequent enough and the wick dries out and causes changes in the chemical makeup of the product water.

Trace Contamination

Some results of contamination studies as related to operation of the Bosch reactor have been discussed in a previous section of the paper. As was stated, high carbon monoxide and significant total hydrocarbon level concentrations were detected. However, studies made during the 7-day test of February 1967 as reported by Pearson and Johnson (ref. 1) indicate a clean atmosphere when operating with the Sabatier reactor. Table II (ref. 7) is a table of contaminants looked for and found by online monitoring equipment. Note the low, 0 to 6 ppm, carbon monoxide and low, 2.5 to 15 ppm, total hydrocarbon concentrations.

Other trace contaminant identification work using multistaged cold traps for sampling and gas chromatography and mass spectrometry for analysis is being conducted but results are still preliminary. A typical preliminary analysis of samples from the 3-day test of June 1967 has identified 34 trace compounds making up a combined total of 18 mg of sample.

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Space Mission Modeling and Simulation Techniques

C. B. MOORE
General Dynamics

A rapid growth is occurring in the use of computerized simulation techniques and modeling in the planning and development of advanced space missions and systems. The analysis, planning, and integration of total man-system missions offers a great challenge to the space-systems analyst, the program planner, and the operations researcher. This paper contains a description of a methodology and mathematical model developed and used in meeting such a challenge. Specific problems of mission planners are addressed, and study results that are illustrative of the utility of such simulation and modeling techniques are presented.

A mathematical model of a simulated space station mission is described and emphasis is placed on the handling of crew-related factors in the model logic and library. The model is especially suitable for use in parametric analyses or in the evaluation of alternatives (tradeoff studies). Thus, in the early stage of mission planning, when data are inadequate or accuracy is suspect, use of the model is particularly advantageous. Because of the flexibility of the model, a determination can be made of the sensitivity of mission effectiveness to a number of crew-related factors: e.g., crew task times, crewman proficiency, overtime allowables, work-shift lengths, work policies, crew rotation profiles, work-rest-sleep cycles, life support requirements, and crew illness. There is a discussion of a computerized methodology for use in comparing and balancing capabilities of astronauts versus the requirements and the demands of the total space mission. The methodology is illustrated as a planning tool in establishing requirements and capabilities of long-duration space stations.

The utilization and role of simulation models as management-decision aids in resolving key issues in the planning of space programs are set forth, and future needs and challenges are delineated.

INTRODUCTION

During the course of this conference, discussions have been directed at detailing the many elements and problems of long-duration space flight, the role of man in space flight, and the various new and advanced technologies that have been or will be brought to bear on these space undertakings. Harnessing these dynamic technologies, fitting the many elements together into a meaningful and successful space program, and completing a successful set of space missions present a formidable challenge to the management capabilities of the United States.

It seems fitting that there should be a few comments offered on the technologies, methods, and procedures that are being marshaled to meet this management challenge. The systems analysis approach will be outlined and a sample of a space mission simulation model that can be used to analyze the total elements of a space mission will be given. The models, the analysis procedure, and the simulations to be discussed at this time are directed toward the total space mission; this comprehensive perspective will differ from views presented from the standpoint of one or more elements of a space mission.

SYSTEMS ANALYSIS APPROACH

Fundamental to the understanding (and, certainly, to the application) of space mission modeling and simulation techniques is an understanding of the systems analysis approach. There are many varied definitions of systems analysis and there are many practitioners of the systems analysis procedure; needless to say, systems analysis has not become an established and completely recognized science despite the many successful applications of this vital technical process.

The Meaning of Systems Analysis

For purposes of this discussion, systems analysis will mean: "The process of quantifying the elements of a space mission, with particular emphasis on measuring the interrelationship of the elements and their impact on the total space mission."

The intent of any worthwhile systems analysis is at least twofold: to approximate the real world and to focus the attention of management on the major problems and, thus, to aid in the management-decision process.

A schematic of the systems analysis approach is presented in figure 1. It will be recognized that the basic steps are the fundamental ones normally described in the basic scientific method.

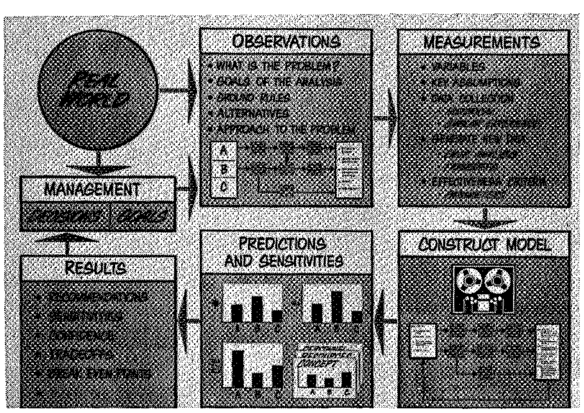

FIGURE 1.—The systems analysis approach.

There are essentially four basic steps: first, the observations by which the basic problem is defined, the goals of the analysis established, the ground rules delineated, the feasible alternatives offered, and an approach to problem solution outlined. With these basic questions and ground rules established, the second step may be begun. It involves the taking of measurements wherein the key variables, the key assumptions, and the basic data required for the analysis are collected from historical and similar experiences. These new data are generated during engineering analysis and tradeoffs among the key parameters. This measuring process results in the establishment of the effectiveness criteria and the measures of goodness. The third step in the systems analysis approach is the construction of a model, usually a model that can be programed on a high-speed computer. Through the model and its assemblage of mathematical relations, a variety of simulations can be made; these simulations must be as "real world" as possible with emphasis on the key elements. The next step, often thought of as the final step in the basic scientific method, is the making of predictions and sensitivities that relate the major variables and, hopefully, isolate the major problems and issues of the situation being analyzed. In the real world, however, for a systems analysis to be useful to the manager, a fifth step is necessary: that of putting the results into a form that is useful to the management; this formating exercise consists of making various recommendations and comparisons of the alternatives initially established. The basic sensitivities, the confidence that relates to the basic input and output data, a delineation of the key tradeoffs, and, in particular, the breakeven points or the points of indifference—all of these are important to the manager so that he may make clear and rapid decisions relating to a complex space mission or to a particular space program.

Need for Systems Analysis

At least three basic items have contributed to the need for systems analysis in the space mission and space program field: (1) an explosive technology; (2) the many alternatives available to meet a space objective; and (3) the resource constraints in the form of dollars, men, key material, and the various other forces that compete for the dollar.

As has been described in the upper part of figure 2, the technology explosion that began around 1950 is evidenced in almost all fields of human endeavor. Speed regimes have been hurdled by transportation systems; range is increasing; the trend for effective weight is downward; altitude has been increasing; the reliability levels that are achievable have been improving at a rapid rate; and the cost has been spiraling upward. These trends in technology have been carried over into the space field, and space efforts have, in many cases, further accelerated the trends. Along with the steady advances in technology, many alternatives for meeting space objectives are presently available or are rapidly becoming a reality. For example, it might be economical, desirable, and, in fact, necessary to invest in probes prior to a manned mission or to undertake an unmanned or even a manned flyby prior to a long-duration mission.

In this dynamic environment, there is a marked increase in the number of resource constraints to be considered and in the competition for these resources. The available money, skilled men, key materials, competition for the dollar, etc., must be factored into any space program planning exercise. In this environment, systems analysis offers a means of bringing all of the essential elements of the problem together in a timely, integrated manner, so that systematic, effective decisions may be made.

Systems analysis applied in space program planning brings into proper perspective all of the key elements, such as systems performance, cost, environmental factors, human factors, mission elements, reliability, operations, schedules, logistics requirements, and personnel; analysis focuses these elements. As has been illustrated in the top of figure 3, these elements may be thought of as a master jigsaw puzzle wherein the objective of systems analysis (and, in turn, the job of the manager) is to put the pieces together as adroitly and economically as possible.

Initially, many alternatives may be identified in the problem statement. These alternatives are then reduced through the application of stated policies, assumptions, and constraints to those alternatives that are reasonably feasible. Through more sophisticated systems analysis techniques, frequently employing simulation models, alternatives for the operational phase may be selected. It should be noted that the systems analysis approach is dynamic with time. Time is an

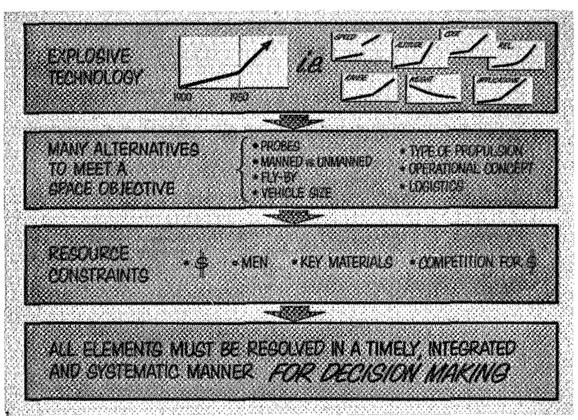

FIGURE 2.—The need for systems analysis.

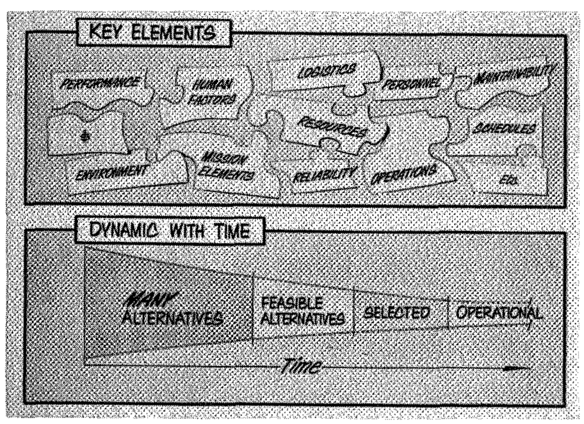

FIGURE 3.—Key elements and dynamics.

important factor; any alternatives are available in the initial planning stages, and these may be systematically reduced to feasible alternatives and then further refined into a selected alternative for use in the operational phase. It should be noted, also, that systems analysis and the use of modeling and simulation techniques is not constrained to the planning stage entirely but can be a useful tool throughout the design phase; these techniques often can be carried into the operational phase of a long-duration space vehicle.

THE ADVANTAGES OF SIMULATION

Simulation is sometimes referred to as a generator of synthetic experience; present knowledge can be blended with intuition in simulation to gain new knowledge without experiencing the actual conditions. Obviously, the benefits derived from this attribute of simulation are many. An economical means is provided for rapid synthesis of situations encountered when comparing alternatives. Problems may be petitioned for systematic analysis with the technological experts brought to bear and responsible for the inputs in key areas; these can then be recombined to obtain total program understanding. Many pitfalls, such as suboptimization, bottlenecks, or improper alinement between key areas, may be recognized before expensive and time-consuming operations are put into effect. The basic advantages of simulation are summarized in figure 4. These advantages can be categorized as follows: (1) rapid assessment of alternatives, (2) problem petitioning for systematic analysis wherein major problem areas are isolated and basic technology can be focused for the solution of the problem, and (3) reduction or elimination of opportunities for suboptimization or overemphasis of a particular segment or part of the problem. By means of these three factors, total program understanding is promoted. In addition, the benefits accrue to the entire space program family: manager, project engineers, analyst, and the entire technical community.

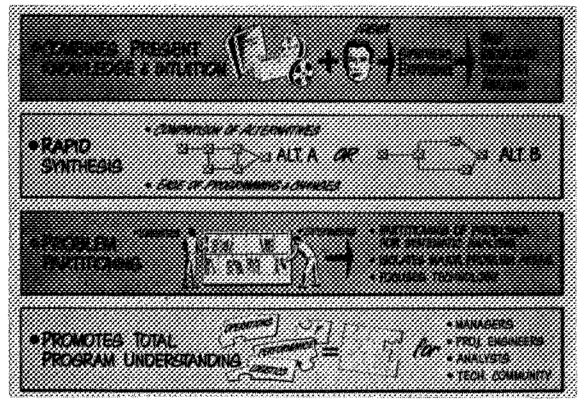

FIGURE 4.—Advantages of simulation.

A dynamic experience of growth is being realized by the family of users of simulation; an enthusiastic and growing number of managers, project engineers, analysts, and, indeed, most segments of the technical community are exploring the advantages offered by simulation. In some of the more familiar fields (particularly in the design of military vehicles), simulation has often been thought of as a luxury because it is possible, without resort to simulation, to design a vehicle, fly it, and then work out the bugs; in the space program world, however, this luxury has become a necessity—because the first attempt must be a success.

LEVELS OF MODELING

Modeling activity encompasses all levels of the space program; representatives are depicted in figure 5. At the total space program level, models are directed toward problems involving the return from the total space effort and toward the effective allocation of resources to the total space program. At the next level, program planning may be performed in one of the major areas of a proposed space program activity such as lunar, planetary, Earth orbital, or deep space. At this level, it is of primary interest to find the most appropriate mission sequences to accommodate a stated objective. At an individual mission or program level, mission effectiveness and simulation models are used

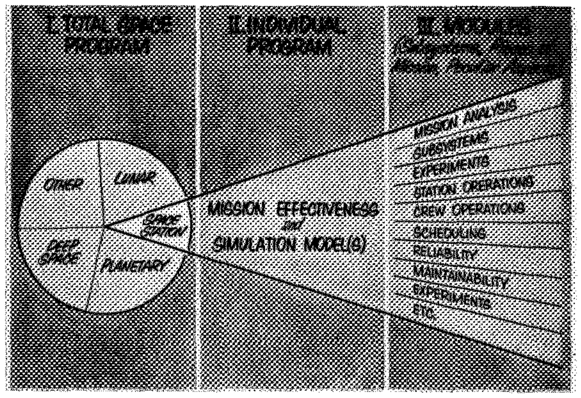

FIGURE 5.—Levels of modeling.

in an attempt to gain further insight into operational conditions, thereby problems or inefficiencies may be anticipated. Models are also available at the module level and sometimes may be combined into total mission models; some models, however, may not be physically combinable, but outputs are compatible for manipulation by analysts at the higher levels.

SPACE STATION MISSION SIMULATION MATHEMATICAL MODEL

The space station mission simulation mathematical model was developed for NASA's Langley Research Center by the Operations Research section of General Dynamics, Fort Worth, under contract NAS1–5874. The model was put in operation at Langley Research Center in April 1967. Additional research is currently underway to expand the capabilities and capacities of the basic model.

In the discussion that follows, the basic highlights of the model will be summarized under four headings: objectives, model concept, typical model applications, and three major submodels. These selected examples are included to provide a clearer understanding of the benefits to be derived from the use of the model. Particular emphasis will be placed on how the model can be used. It should be emphasized that the examples to be demonstrated are typical of model usage and are offered for ease of understanding of the model. Certainly, the answers will vary with changes in input parameters, such as extent and type of experiment program, mission duration, and mission objectives.

Objectives

A Manned Orbital Research Laboratory (MORL) system concept, capable of fulfilling basic space-related research and development objectives, was derived through previous studies. In an earlier paper in this conference, Dr. Wolbers of Douglas Aircraft Co. discussed the basic details and the design features of the MORL concept.[1] A need was thus generated for a detailed mathematical model that would, by effective utilization of previously developed space station data and data to be generated in the future, serve as an implementation of a MORL program or another future long-range space program.

The key considerations and provisions that were factored into the model are depicted in figure 6. The model is structured for easy updating and flexible operation to accommodate the new data and the new concepts that will be generated as the space station program evolves. In addition, the particular needs of the model user have been considered. Numerous options, both program and input, have been provided to reduce peripheral output and unnecessary operation. Care has also been taken to insure that

[1] See p. 21.

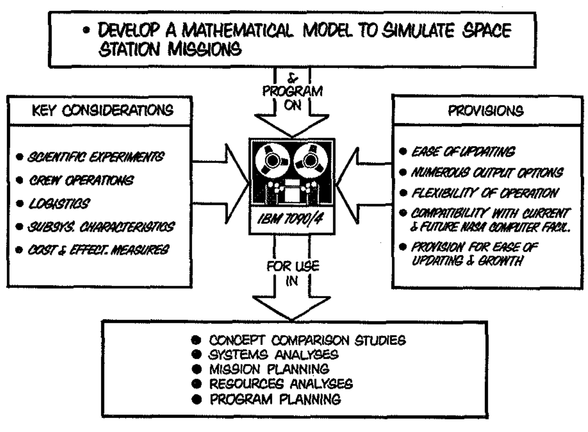

FIGURE 6.—Program objectives.

the presence of these options does not complicate model usage.

The model is suited to the solution of problems that involve mission concepts, systems analysis, resource analysis, and mission planning. Comparative studies are generally performed by controlling problem input; for example, an alternative experiment program can be compared and evaluated by reading in the applicable data in lieu of the baseline experiments library. Special library is used only when required for a particular problem; however, a complete baseline library was provided in the model.

The model was developed in seven basic steps: (1) analysis of the model application and utilization requirements that were accomplished through detailed and intense discussions with the NASA personnel who were going to use the model; (2) delineation of the desired output and, in turn, the input requirements; (3) an intensive data collection, collation, and analysis effort; (4) detailed analysis and development of functional relationships for various categories, such as experiments, missions, systems, crew operations, logistics, scheduling, reliability, cost, and effectiveness parameters; (5) development of the basic model structure, including programing concepts, and the development of model routines and required data libraries; (6) basic data preparation and checkout of the model; and (7) model implementation and training of NASA personnel in model usage. The basic model study plan is depicted in figure 7.

Perhaps the most important feature in the above steps was the provision that the model application and utilization requirements be thoroughly defined early in the model development program so that a model more responsive to the needs of the user could be provided. An equally important feature was the provision for extensive data library storage that can be changed, modified, and extended with minimal ease, thus avoiding time-consuming and expensive model changes as new information becomes available.

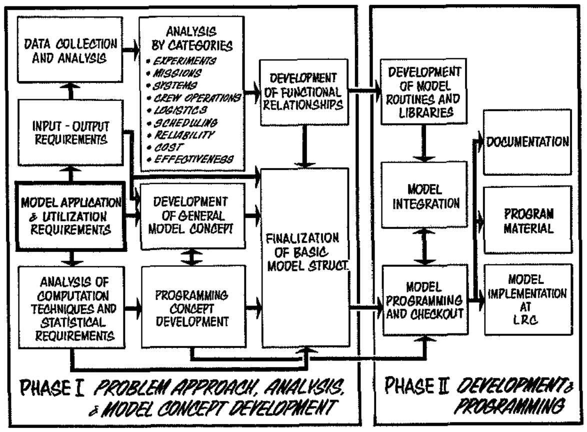

FIGURE 7.—Model study plan.

Model Concept

The space station mission simulation mathematical model consists of three computer programs or submodels, each applicable to a different phase of the operation. The basic model concept is illustrated in figure 8. Preliminary analyses are performed with the preliminary requirements model (PRM); mission plans are developed by the space station model in the planning mode; and mission simulation is accomplished by the space station model in the simulation mode. The PRM generates output data and prepares libraries for use by the planning mode; the planning mode provides a data tape for use in the simulation mode and also produces its own printed output.

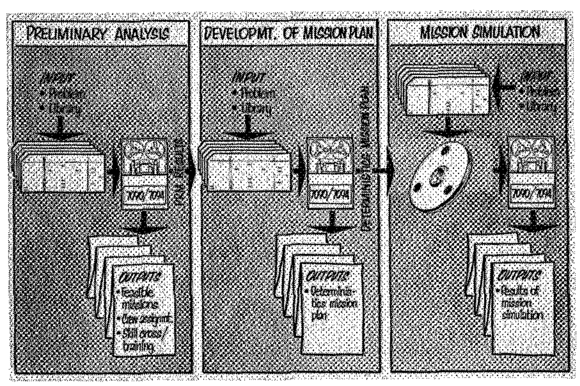

FIGURE 8.—Space station mission simulation mathematical model concept.

The simulation mode, in addition to receiving output from the planning mode, prepares a data tape for input to other simulation mode runs.

By dividing the model into three programs, run time and user time are conserved because the model user may select various levels of refinement through choices of models or model modes to be used. For example, in the early stages of mission plan evaluation, the PRM can be used to make a gross evaluation of the mission parameters and to delineate the relationships that exist between these parameters. The requirements for many studies in which little detail is not needed can be satisfied within this one phase. Such data can be used in assessing the feasibility of various mission concepts and in making an initial determination of mission requirements, such as preliminary cost, crew safety provisions, operational requirements, logistics vehicle, mission duration, facilities required, principal resources, experiment requirements, maintenance demands, and crew man-hours.

The planning mode can be used to obtain a refined estimate of the mission parameters and to provide detailed data for assessing the effectiveness of the various station activities. The data provided in this phase will satisfy many additional studies; thus the model user may select a more refined level of detail to suit his problem needs. Additionally, computer run time and operation are minimized in these first two phases by the fact that the PRM and planning modes are highly efficient deterministic models.

Finally, the simulation mode provides a means for determining the effects of contingencies on the mission plan; this allows a highly sophisticated evaluation of the mission parameters to be made. The extent of deviation by the simulated mission from the mission plan may be assessed. Data obtained from this mode of operation can be used to determine contingency procedures and requirements and to estimate the degree of confidence that can be achieved in realizing mission goals.

It should be noted that, particularly in man-related capabilities, this simulation mode could be used to define the needs for certain specific training programs, especially those related to the training of astronauts and scientific personnel aboard the spacecraft. The basic schematic of the model utilization sequence is illustrated in figure 9.

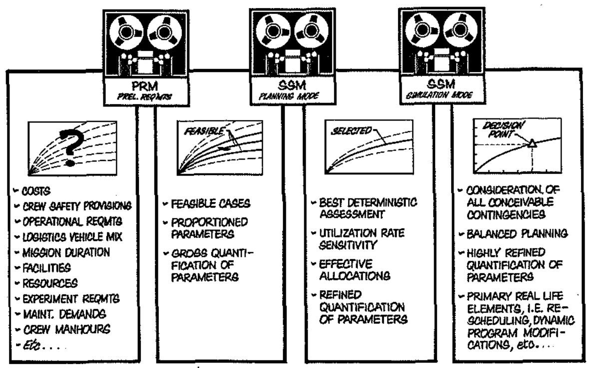

FIGURE 9.—Model utilization sequence.

Typical Model Applications

The need for decisions will exist in all phases of the space station program: from design to operations. Access to the space station model will allow management to establish the consequences of the alternative courses of action prior to making the decision. This will allow selection of the best course of action consistent with available information.

As has been depicted in figure 10, the

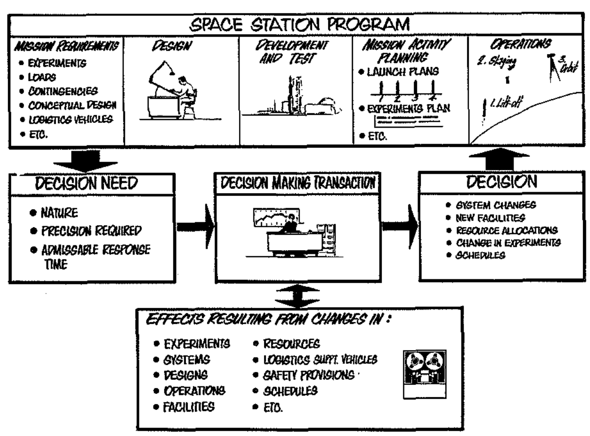

FIGURE 10.—Model applications and utilization.

nature of the decision to be made, precision and accuracy requirements, and the admissible response time for the decision are necessary characterizations to the formulation of management's response. Once the factors used to describe the decision needed are specified, the decisionmaker can evaluate the available alternatives and proceed to a decision. The model is called into use to determine the consequences of various alternatives, although management retains the responsibility for the final decisions. The element that is changed through use of the model is the degree of uncertainty within which management functions.

Many of the space station problem areas are interacting and must be evaluated as an entity; a number of these areas of consideration are depicted in figure 11. A primary application of the model is to determine the relationships between various experimental groups and station resources, crew skill mixes, logistics cost, etc. By using the model to process the possible programs, an effective balance of experimental return and available resources may be established.

A typical problem might be to develop a logistics schedule that would provide the necessary crew skills, station supplies, and experimental equipment to complete a planned experimental program with a minimum number of launches. To accomplish this, effective use of available experimental man-hours must be made by proper experiment scheduling. At the same time, one must

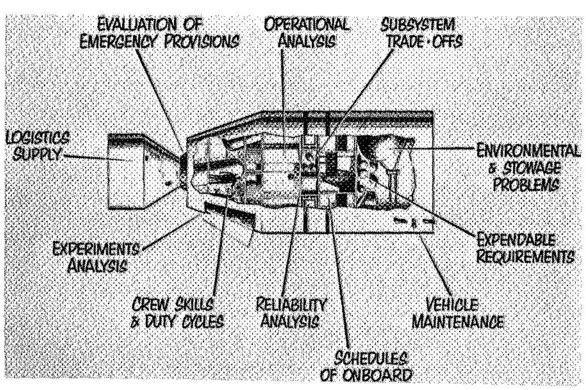

FIGURE 11.—Typical model applications.

be concerned with constraints, such as crew skill and station resource availability.

Another example, requiring a greater level of detail, would be the study of spare-parts inventories. Although onboard maintenance is considered necessary, it is contingent upon having the proper spares available. Obviously, there is a limit to the number of spares that can be stored aboard the space station or supplied by the logistics vehicle. The effects of various mixes of onboard spare parts on mission effectiveness could be measured by the simulation mode if the spare-parts inventory was systematically varied.

In general terms, the model can be used to study problems in which consideration is given to the effectiveness aspects of a medium-sized space station. Many of the problems can be resolved by using libraries supplied with the model—a feature that greatly simplifies the input burden. These libraries have been prepared from MORL or MORL-related study reports. If the problem requires the use of other libraries, these may be substituted for those supplied with the model by following the instructions contained in the model instruction manuals.

Experiment-related studies may be viewed either from the standpoint of changes in experimental accomplishment that result from differences in experiment programs, or from the standpoint of changes in experimental accomplishment caused by differences in levels of resources necessary to the experiment program.

In the first instance, the initial model was designed to accommodate up to 150 experiments, but has recently been modified to consider 400 experiments. The composition requirement for an experiment package that will utilize the capability of the planning mode or simulation mode is described in reference 1. When the PRM is used independently, only the total experiment hours, skill requirements, and total duration need be known.

An alternate set of experiments for study purposes may be derived through variations in an initial set of experiments, such as those provided with the model, or through the definition of a new set. Variations in an experiment set may occur through rearrangement of experiments (priority, investigational areas, etc.), deletions, additions, or revision of experiment requirements (descriptions).

The majority of the model structure was developed for resource management and accounting, and the most prominent resource consists of man-hours categorized by skill classification. The PRM can be used to evaluate the effects of varying the degree of crew specialization, or it can be used to appraise other factors that relate to crew versatility, or performance; these include crew rotation plans, overtime allowables, proficiencies, allowable shift lengths, and variations in crew size (up to nine men).

The crew skill and initial assignment philosophy factored into the preliminary analysis continues into the mission planning and simulation phases. In the mission planning phase, performed by the planning mode, additional crew-related factors are introduced; these are primarily related to an increase in scheduling detail in which checks are made to ascertain that the appropriate crew types and man-hours are available for the timely execution of an experiment. In the simulation mode, additional crew-related factors are considered, including crew illness effects, contingency task assignments, task interruptions, and a more detailed consideration of overtime policy. Although the model is structured to select and efficiently utilize the crew, resource checks are made on power, communications, equipment, system outputs, and 10 classifications of expendables. In the planning and simulation modes, additional checks are made of resources utilized.

In its assessment of experimental accomplishment, the PRM considers an additional resource: the logistics payload capability (weight and volume) provided by planned logistic launches. The logistics routine is common to the PRM, planning mode, and the simulation mode. However, the consideration of unscheduled events, such as vehicle failures or launch delays, occurs only in the simulation mode.

Relationships between experimental accomplishment and resource utilization may be constructed in all phases of model operation. The inherent flexibility in changing resource levels, policies, etc., enables the formulation of many problems of a parametric nature.

Further details of the basic description of the model may be found in references 1 to 5.

The remaining pages in this section will be devoted to presenting in more detail some of the basic characteristics of the three basic submodels and to providing some typical examples that are particularly pertinent to the subject of this conference.

Major Submodels

Preliminary Requirements Model

The PRM is a computer program designed to perform the scheduling, subject to the constraints imposed by crew training, available crew time, and logistics capabilities, of activities involved in a space station mission. This program receives input data describing the resource requirements of the experiments to be performed and the station operations policies to be followed. Then, in accordance with these policies, the model assigns tasks from the experiment program to the members of the crew and prints out the results of the mission.

The fundamental purpose of the model is to provide a means for obtaining a rapid evaluation of the results of proposed missions. The large number of program options available in the PRM makes it a useful device for studying Earth-orbital missions. Although the PRM is similar in function to the planning mode (both models essentially are deterministic scheduling devices), the modeling techniques used in the PRM are less detailed and, therefore, less time consuming. Its simpler input requirements and shorter running time make the PRM particularly useful in cases where mission results are required on a gross basis only or during the early stages of mission planning when input data are relatively inexact.

The operational sequence of the PRM is depicted in figure 12. In general, the PRM operates on a logistics cycle that conforms (subject to some modifications resulting from launch constraints) to the crew rotation cycle plan. The logistics routine is used to determine the width of the launch interval and the payload capacity available for experimental equipment. Based upon the skill mixes possessed by candidate crewmen, a crew is selected and assignments are scheduled for each crewman. The program continues until the next launch interval, or until the mission is completed. At the end of the mission, a summary is made of the above parameters and of other effectiveness measures.

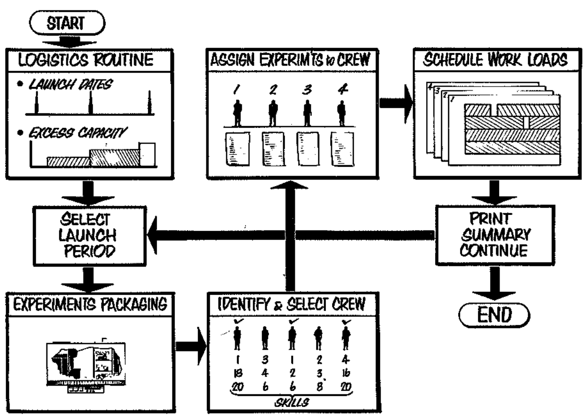

FIGURE 12.—PRM operational sequence.

The two key features of the PRM are its ability to select crewmen based on skill cross-training considerations and to make initial crew assignments. This information is subsequently used by the planning mode.

Examples of some of the types of studies in which the PRM could be applied are shown in figure 13 and some typical results obtained by using the model are given. The upper graph illustrates the sensitivity of the rate of completion of a given experiment package to various degrees of crew cross-training. The lower graph shows the portion of an experiment package completed by crews of various sizes during a 540-day mission. Three crewmen were rotated and subjected to skill optimization at the end of each 90-day interval. Both crewmen were "skill optimized" in the case of the two-man crew.

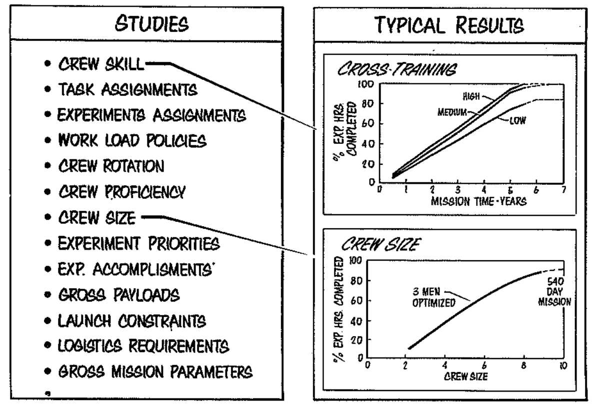

FIGURE 13.—Preliminary requirements model studies.

PRM example 1: crew cross-training.—A typical example might be the task of determining to what extent astronauts should be cross-trained for performing scientific experiments (fig. 14). Previous studies have indicated that many of the experiments planned for a scientific research space station will require high crew-skill levels for the members to make the necessary judgments concerning the experiments. If these skills are provided by astronauts with a high degree of specialization in singular fields, then work schedules for a program consist-

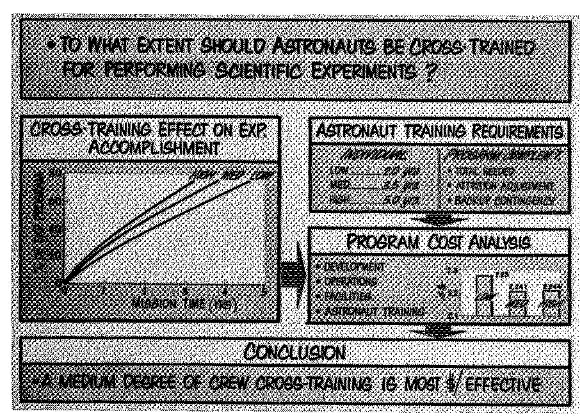

FIGURE 14.—Crew cross-training.

ing of experiments from several fields may be low in efficiency. This results in longer missions, and thus, higher mission costs. On the other hand, the necessary training to acquire and have astronauts with a high degree of cross-training in readiness throughout a long-duration mission is also expensive. The problem then is to find the level of cross-training that results in the lowest mission cost. For the particular experiment program that was considered, a medium cross-trained crew was determined to be the most cost effective. A medium cross-trained crewman possesses the ability to perform with a high proficiency in his basic field and those fields that are closely allied. A highly cross-trained crewman is one who can perform with a high proficiency in any field included in the experiments program. A low cross-trained crewman is one who has high proficiency in only one major field.

PRM example 2: experiment program stratification.—Another typical question that managers might desire to answer would be the issue of total crew requirements change as activity patterns for major areas of scientific research are varied. Occasionally it is desirable to sequence these experiments according to utility ranking and other considerations, such as availability of special equipment. If planners of experiments mix groups in satisfaction of these considerations, a penalty in overall program may result. An investigation was performed using the PRM to determine if this was an issue of major concern. Three plans of experiment program stratification were analyzed and are depicted in figure 15. It was determined that the amount of accomplishment was relatively insensitive to the experiment program stratification plan chosen.

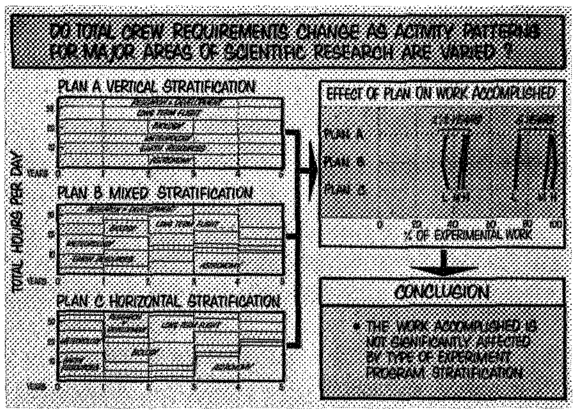

FIGURE 15.—Experiment program stratification.

PRM example 3: crew rotation.—Another typical question that might be asked by program manager is this one: how sensitive is mission accomplishment to crew-rotation plans? Long-duration space missions will require periodic resupply and crew rotation. Excluding those situations in which man is a part of the experiment (i.e., biomedical experiments), benefits are gained from this opportunity to select crewmen more appropriately trained for the highly skilled tasks in the next supply interval. The PRM has been used to test numerous rotation plans. Three plans shown in figure 16 are indicative of the results which have been obtained. It may be noted that rotating six men each 90 days reduces total mission duration by 17 percent over a rotation scheme of one astronaut each 90 days.

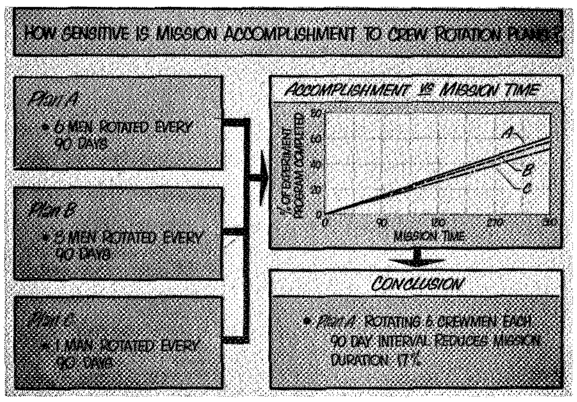

FIGURE 16.—Crew rotation.

It should be recognized, however, that a final decision is not warranted at this point. Rotation of six men will require the development of an entirely new crew carrier, the cost of which may more than overcome the economic advantages gained. The role of the model in this, as in most cases, has been to provide the analyst with the parametric relationships whereby he can proceed with his evaluation to a suitable conclusion.

Planning Mode

The planning mode of the space station simulation model has been designed to develop a mission plan that approximates the plan for an actual program. The planning mode is deterministic and uses expected values for system parameters. In the planning mode, as in the PRM, the entire mission is viewed as a single problem. Although its operational sequence is relatively simple, as shown in figure 17, the planning mode offers considerable sophistication over the PRM. Initially, the station expendable requirements are determined for 10 categories; this is accomplished by use of the station operation routine. Next, the logistics schedule is established by the use of the logistics routine. The scheduling routine is then employed to schedule the station-keeping and personal requirements. Experiments are then scheduled until the remaining resources or experiments are exhausted. The evaluation routine provides a summary of the mission requirements, cost, and effectiveness; in addition, the routine includes a capability to indicate confidence versus number of launch vehicles or program cost required. Such an estimate is based upon the reliability of the logistics launches and provides an indication of the results to be obtained in the simulation mode.

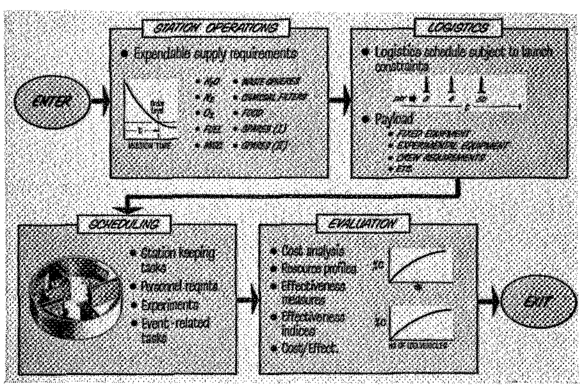

FIGURE 17.—Planning mode.

Data used by the planning mode are obtained from three sources: problem data, PRM-prepared libraries, and libraries within the planning mode; these sources are depicted in figure 18. This model is relatively simple to input because much of the information is input in the form of prepared libraries. The problem data define mission calendar start date, duration of mission, libraries to be used, orbital parameters, and experiment priorities (if this option is used). The experiment priority option allows the model user to express a preference in the order in which experiments are considered for scheduling.

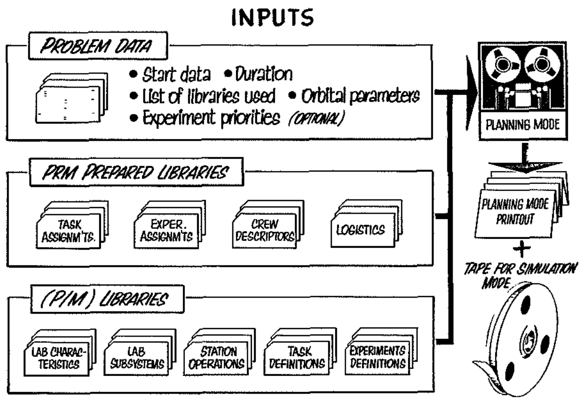

FIGURE 18.—Operating the planning mode.

The PRM libraries include crew task assignments, experiment assignments, crew description (such as number of crewmen, skill type, and rotation), and a logistics library.

The planning mode libraries provide values for the descriptions for the laboratory, subsystems, station operation, tasks, and experiments. Because these libraries are not subject to frequent change, they may be called in block form. However, most of the entries may be changed by changing a few cards, if such changes are desired.

The planning mode is suited to a wide range of studies involving logistics requirements, crew analyses, resource analyses, and mission evaluations. Results for three typical studies are indicated in figure 19. The data for these studies were obtained from

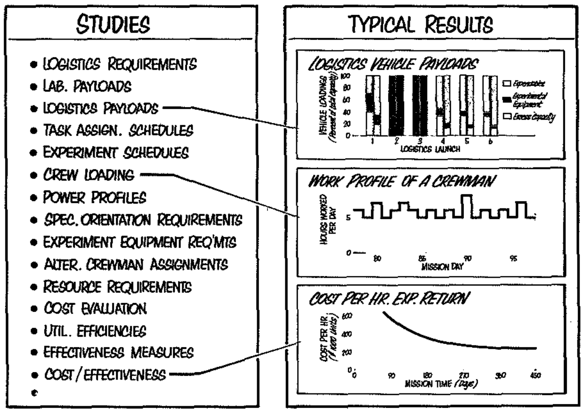

FIGURE 19.—Planning mode studies.

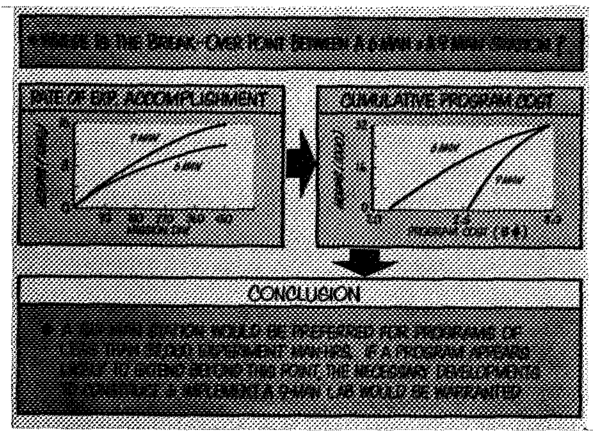

FIGURE 20.—Station size.

a run of the planning mode in which the mission duration was 450 days, the crew size was 6 men, and an experiments package consisting of 131 experiments was used.

The planning mode has extensive output of effectiveness measures and utilization efficiencies. This type of output capability makes it ideally suited for use on problems involving comparison between mission plans.

Planning mode example 1: station size.—A typical example of the use to which the planning mode can be put is that of answering questions such as the following: where is the breakover point between a six-man and a nine-man station?

The planning mode of the space station model was utilized in an analysis to determine the point (in a large mixed experiments program being performed in low Earth orbit) at which it would become profitable to have developed a nine-man station rather than a six-man station. The results in figure 20 indicate that the breakover point for this case would be at 32 000 experiment man-hours. Of course, the results obtained would be sensitive to such factors as type of laboratory, assumptions as to development requirements, types of logistics systems considered, and mission parameters.

Work is presently in progress with the planning mode to systematically evaluate the influence of these parameters on the breakover point. Information of this type is most useful early in a program when basic sizing decisions are being made.

Planning mode example 2: program efficiency.—Another typical example for the use of the planning mode would be to determine how to improve program performance to improve utilization efficiency.

Two candidate areas for improving operational efficiency were uncovered in some of the planning mode runs. It was found that the utilization efficiencies of some crewmen were significantly lower than overall crew averages. A closer inspection of the case illustrated in figure 21 revealed that crewman 13 was poorly utilized in the program because of the deficit of tasks suitable for him. This condition could possibly be improved by cross-training crewman 13 so that he may assume some of the burden of the

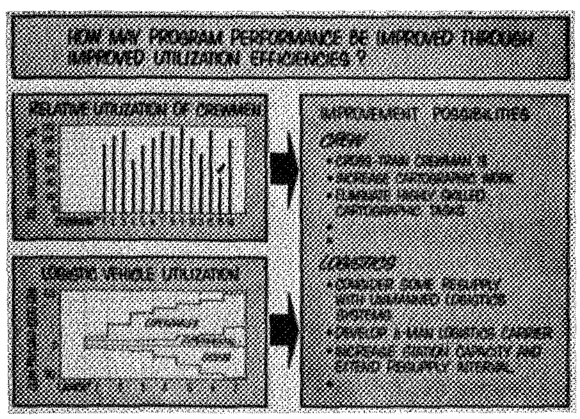

FIGURE 21.—Program efficiency.

other crewmen; increasing cartographic work (his specialty); or eliminating cartographic tasks requiring a high skill level so that other crewmen or automated equipment may perform these functions, thus replacing this astronaut.

Another area that appeared fruitful for improvement was in logistics vehicle utilization. Unused capacity was approximately 40 percent of total capacity. An investigation should give consideration to other resupply logistics systems or to better utilization of the vehicle capacity.

Models are well suited to studies of this nature. They provide an efficient, expedient means of isolating areas where improvement is most likely to be achieved.

Simulation Mode

The event controller noted in figure 22 is the central coordinator for the simulation mode. Because event-to-event simulation is applied in this model, the event controller advances to each event, processes it, and proceeds to the next event. The routing is sometimes rather extensive and, hence, the major subroutines are supplied with their own control programs.

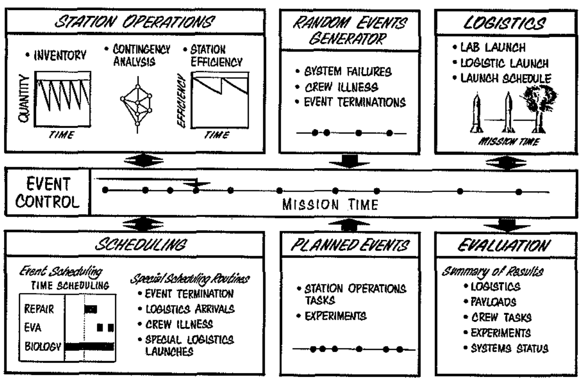

FIGURE 22.—Simulation mode.

After the last event (the arrival of a scheduled crew vehicle) is processed, if the mission has not been aborted prior to this time, the evaluation routine is called to supply a summary of the accounting and effectiveness measures.

It is necessary that the planning mode be run prior to the simulation mode. The planning mode prepares a tape of the mission plan along with data describing the mission, system, experiments, crew, expendable levels, etc. Whereas the planning mode treats the entire mission as a problem, the simulation mode examines each interval defined by crew arrivals as a problem. These intervals may, if it is so desired, be connected. Because most of the information is generated in other modes or in library storage, the problem deck for the simulation mode consists of only five cards (fig. 23). These cards describe five aspects: the output options, the probability of success of unmanned checkout, the probability of failure from miscellaneous causes, the delta efficiency allowed between present station efficiency and that which would be provided by a special logistics launch before ordering one, and the time differential from the end of a supply interval until crew safety would be threatened provided a supply was not effected.

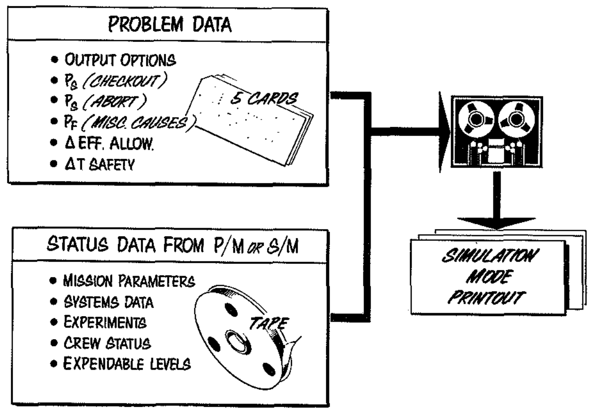

FIGURE 23.—Operating the simulation mode.

Events whose occurrence may be expressed probabilistically are accommodated by the simulation mode. The impact of system failures, crew illnesses, longer than expected task times, etc., may be viewed in a resulting mission history, which may be compared to a mission plan developed prior to simulation.

The examples shown in figure 24 were taken from a checkout problem in which four

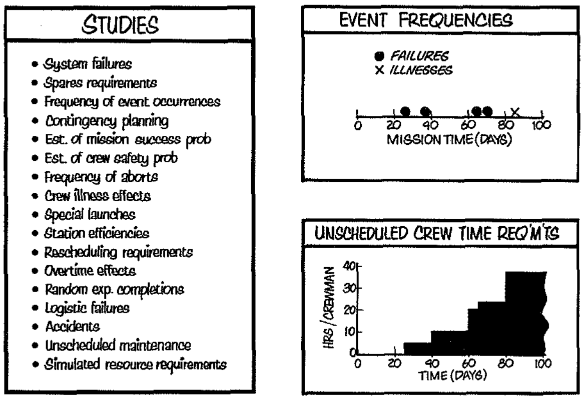

FIGURE 24.—Simulation mode studies.

system failures and one minor crew illness occurred during the first 90 mission days.

Simulation mode example 1: unscheduled logistics launches.—Because logistics resupply intervals will be selected to provide the best experimental return for the investment, subject to safety and other mission constraints, a reduction in the interval of time between logistics launches will directly reduce cost effectiveness as well as disrupt program timing. Unscheduled logistics launches may occur because of failures in critical systems without replacement parts, premature depletion of expendables attributed to random events, major crew illnesses that require that the crewmen be returned to Earth, or declines in station efficiency brought about by one or more contingencies.

Unscheduled logistics launches are considered to be of two types in the simulation mode: the next scheduled launch is moved to an earlier date, or a special launch is scheduled. The difference between the types rests in the payloads; the special launch carries only the critical items.

An examination of the plot containing the distribution of launches in figure 25 indicates that 76 percent of the time launches will fall within the regular scheduled interval, 10 percent of the time requirements may be satisfied by slipping the launch to an earlier date, while 14 percent of the time an additional launch must be superimposed on the logistics launch calendar. These results are, of course, indicative of a singular situation, and could be changed by most of the entries in the probabilistic phenomena libraries. However, on the basis of information of this nature, areas are now visible that offer promise of mission improvement.

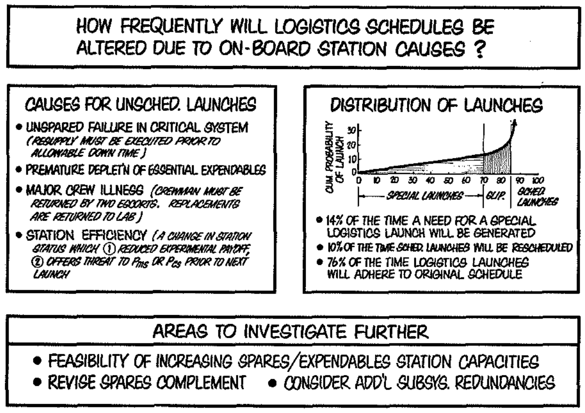

FIGURE 25.—Unscheduled logistics launches.

Simulation mode example 2: unscheduled crew time requirements.—Various unscheduled events may be expected to occur during a long-duration mission that will remove one or more crewmen from their experimental duties for a period of time. An assessment of the extent of scheduled experimental activity that can be expected to be interrupted during an interval allows adjustments to be made in mission plans. If the number of interruptions appears to be excessive, remedial actions may be incorporated after more penetrating analyses have been performed. For

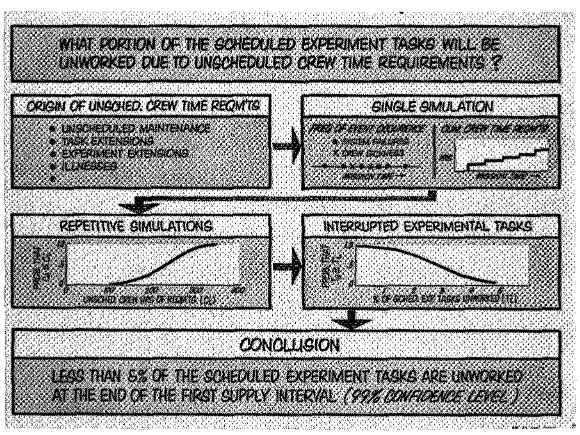

FIGURE 26.—Unscheduled crew time requirements.

the case illustrated in figure 26, it is shown that the crew usually spent between 100 and 400 hr in unscheduled activity during an interval of 90 days of mission time. These unscheduled activity requirements were caused by unscheduled maintenance, extension to scheduled experiment durations, or illnesses. Although several hundred hours of unscheduled activity may be accrued, the experiment hours lost are not of equal correspondence. For example, the simulation mode assigns repair tasks to alternate crewmen if the primary crewmen are occupied, or if necessary, assigns limited overtime to maintain schedules.

The data in figure 26 indicate that mission planners may be highly confident that greater than 95 percent of the scheduled experiment work will be accomplished under this plan.

FUTURE OF SPACE MISSION MODELING AND SIMULATION TECHNIQUES

The Need for Growth

In summation, it may be helpful to reiterate some of the prime factors that provide the impetus behind the growth of systems analysis in the space management field: technology continues to grow at a rapid rate; the number of alternatives to accomplish an objective are increasing; and more fundamental constraints on resources are apparent in terms of available men, material, skills, and in terms of the competition for the dollar. In such an intensifying environment, management technology and capability for improved decision processes must continue to be developed and must be better utilized.

To meet the increased management burden, the use of scientific procedures and methods must be accelerated; systematic procedures must be developed and utilized; organized and effective employment of systems analysis procedures and methods is a must. Management as an art has long dominated the managerial field; now it is necessary that management as a science have an accelerated growth so that managerial skill

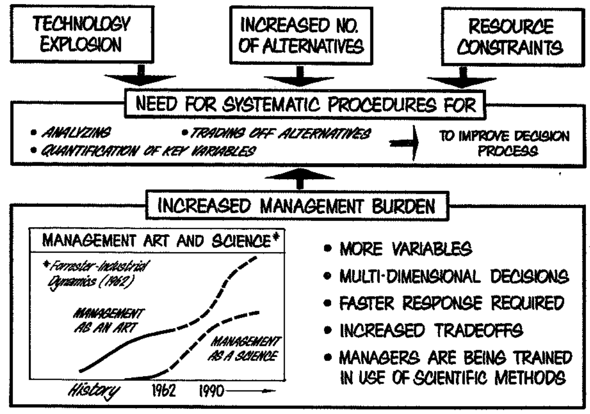

FIGURE 27.—Need for growth.

becomes both a science and an art. This necessity is depicted in figure 27.

More research in management methods must be accomplished to relieve and assist the management-decision process. We are sure to see a growth in systems analysis methods and procedures, and, in particular, we are certain to witness an increase in the use of mission modeling and simulation techniques.

Future Challenges

Insofar as they relate to space program planning and management, some of the principal needs of the future and the possible approaches to meet the challenges in the systems analysis field are summarized below and illustrated in figure 28.

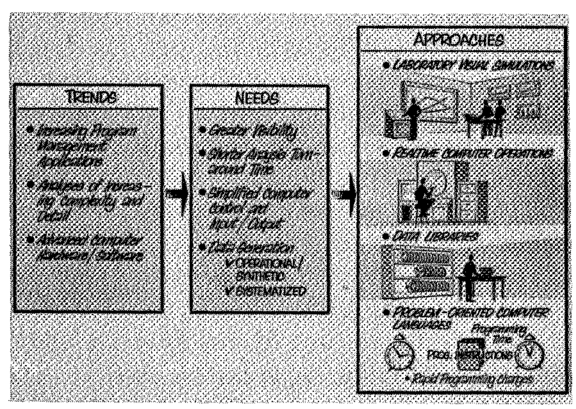

FIGURE 28.—Future challenges.

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(1) Greater visibility of the total program must be provided to the manager. Stacks of computer sheets are not satisfactory. The manager must be able to actually see the dynamics of the program and must be able to actually see the effects of changes and alternatives. With increased computer speeds, storage capacity, time-sharing improved modeling techniques, and improved communications and display devices becoming available, the results of large-scale simulations may be visually displayed to the manager. The impact of changes, comparisons of competing alternatives, and delta effects of alternate plans may be quickly and systematically displayed.

(2) Real-time computer operations with simplified input/output devices must be accomplished to make it possible to compare design and operational concepts in a timely manner. These operations will assist in problem visualization, cut down on analysis turnaround time, and provide a rapid assessment of key problems. All can be accomplished in the context of total program planning with minimized fear of suboptimization through large-scale mission models.

(3) Improved data, both in quantity and quality, must be generated in all technological fields. For example, detailed simulations of man's activities and his capabilities to accomplish specific tasks in the space environment must be accomplished. Such simulation can be justified on the basis of creating the need and understanding the requirements entailed in a realistic training program, not to mention the value to be realized from improved data banks for use in large program-level simulation to improve the management-decision process. Some particular areas of concentration are:

(*a*) Establishment of nominal astronaut workload

(*b*) Derivation of extended work policies

(*c*) Specifications for rest and recovery following periods of stress

(*d*) Selection of maximum tours of duty

(*e*) Prediction and quantification of crew efficiency throughout the mission

(*f*) Specification of crew habitability requirements

(*g*) Definition of man-machine relationships

(*h*) Establishment of crew safety policies

(*i*) Quantification of psychological and physiological factors in work scheduling

Quantified information from these and other areas of endeavor by the bioastronautics researchers will be effectively utilized by simulation technologists as it becomes available.

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ADVANCES IN SPACE SINCE 1958

One of the most healthy aspects of our democratic society is the participation of universities with industry and Government agencies in dealing with society's problems. In this country, we face new problems unlike any faced before. It is natural to turn to our universities for the knowledge, advice, and assistance needed. The space program is an excellent example of this. In February 1958 an experiment designed by James Van Allen of the State University of Iowa was flown in the first U.S. satellite. It led to the discovery of the band of energetic particles surrounding the Earth now known internationally as the Van Allen belt. This experiment, which involved the combined efforts of university scientists, industrial manufacturers, and Government agencies, set a pattern that has become standard.

Since 1959, the progress made by the university-industry-Government team in space exploration has been phenomenal. At that time, our technological experience was so limited that we had to endure several embarrassing failures before finally orbiting a comparatively small satelite.

Today, however, our technology is taken for granted. Meteorological satellites have been developed that produce photographs, used by 39 nations of the world, that reveal the cloud cover. This service contributes significantly to daily weather prognostication.

Communication satellite technology has developed to the extent that it is now a commercial venture, providing not only for continent-to-continent private phone conversations but also live global television transmission. The Comsat Corp. in 1965 inaugurated commercial 24-hr, transoceanic satellite communications capable of voice, Teletype, and TV transmissions. Comsat satellites have been used to provide TV coverage of such activities as the President's 1966 visit to Guam, the Russian May Day parade in Moscow, and the Australian Day demonstration from Expo '67.

Lunar orbital vehicles have provided excellent photographs of 99 percent of the Moon's front face and 89 percent of the backside. These pictures have a resolution 10 times better than that available with Earth telescopes. They have provided a hundredfold increase in discernible detail. Two Surveyor spacecraft have been soft landed on the Moon, and one has sampled the lunar surface to check its composition and to determine whether it will support Apollo astronauts and their spacecraft.

In 1964, a Mariner spacecraft flew close to the surface of Mars and sent to Earth 22 photographs of the Martian surface. This spacecraft is now approaching Earth after having been in flight for more than 33 months. It has traveled more than 1.3 billion miles in its orbit around the Sun, and its onboard controls and electronic systems are still operating.

Mariner 5, launched June 14, 1967, is proceeding toward Venus without complications. A midcourse correction on June 19 was successful. At 1:34 p.m. e.d.t., October 19, the spacecraft will pass within about 2000 miles of the surface of Venus.

In 1958 and 1959 there were many in the space industry who seriously doubted that extended manned space flight would be possible within less than several decades. Yet we saw John Glenn's three-orbit flight in February 1962, the completion of the Mercury program, and the successful completion of 10 two-man Gemini launches. Over 1900 astronaut-hours—almost one man work-year—have been spent in space. These flights have successfully demonstrated the rendezvous and docking of two spacecraft, the ability of astronauts to work outside their spacecraft, and the possibility of manned space flight for up to 2 weeks' duration. These flights have also demonstrated the reliability of life support systems capable of providing oxygen and water and handling waste for support of two men in the hostile 0*g* vacuum environment of space for periods of 14 days.

We have also seen space technology adapted to nonspace needs.

Improved X-rays.—A computer technique that was used by the Jet Propulsion Laboratory to enhance television pictures of the Moon and Mars from the spacecraft is being developed to clarify and sharpen medical X-ray photographs.

Walking chair.—A six-legged vehicle proposed as an instrument carrier for unmanned exploration of the Moon has been adapted by a California company as a walking chair that can carry crippled children over terrain and obstacles that would stop an ordinary wheelchair.

Biosensors.—Small biosensors used to monitor the astronaut's physical condition during flight are now being used in hospitals to permit one nurse, seated at a console, to monitor the condition of many patients at the same time.

Spray-on electrodes.—At the NASA Flight Research Center, a new technique for applying electrocardiographic electrodes to test pilots was developed. A liquefied, conductive mixture is sprayed over the ends of lead wires onto the patient's chest. The coating, which dries quickly, is thin, flexible, not uncomfortable, and can be easily removed but will keep the electrodes in contact with the skin during exercises causing perspiration. Clinical groups are now using the technique to gather data on patients and medical test subjects during exercise.

Thermocouple.—A doctor in a New York hospital is now using a commercially available microthermocouple probe in cryosurgery for patients with dystonia, Parkinson's disease, and other diseases causing abnormal muscular motion. Two doctors in a Boston hospital are using the same instrument in surgery to repair lesions of the eye by "welding" tissue at cryogenic temperatures. The microthermocouple probe was originally developed under contract to the NASA Lewis Research Center.

Such advances are notable primarily because they are indicative of what can be accomplished by a university-industry-Government team in a free nation where scientific knowledge and technical competence are combined in a cooperative effort and supported by the taxpaying citizen.

UNIVERSITY-INDUSTRY-GOVERNMENT TEAM

You may be interested in some statistics that reflect the investment and resources of the university-industry-Government space exploration team. Since 1959 the Nation has invested about one-half of 1 percent of the gross national product in the national space program managed by NASA. Over 20 000 firms and more than 200 universities have been involved in the effort, which at its peak employed about 420 000 persons. This number is now down to about 250 000 and is decreasing at the rate of about 5000 per month.

Over 90 percent of the total investment has gone to industry, but over \$½ billion (\$1½ billion if we include Caltech's Jet Propulsion Laboratory) has gone to universities. Our records show that about 10 000 university people (excluding JPL) are receiving some direct support from the space program, and we estimate there are at least twice this number who are associated with the program in one way or another.

Nearly 3700 predoctoral students in 153 universities are receiving direct support for their studies through the NASA Sustaining University Program; 49 universities have sustaining research grants that allow them to undertake space-related research that supports and strengthens the university. In addition, 35 research facilities have been built, or are being built, on university campuses across the country. During the past 6 or 7 yr, an additional $350 to $375 million has gone to support specific research projects or scientific experiments of university researchers.

As to the Government part of the team, NASA has about 40 000 scientists, engineers, technicians, and support personnel in 10 major Government laboratories and NASA Headquarters concerned with planning and managing the entire space program. They also carry out a substantial in-house research and development program.

THE UNIVERSITY'S ROLE

There is a wide diversity of opinion on the university's proper role in the space program. The major questions hinge on whether, or to what extent, universities should become concerned with immediate real-world problems. The question is not a new one—throughout history universities have been concerned about their proper role in society, whether they have a responsibility for dealing directly with society's problems or whether they should stand aside to remain unbiased in their search for knowledge.

Clark Kerr, in his book "The Uses of the University," reviewed some of this history. Bacon, in the 17th century, complained that men had withdrawn too much from the observations of experience; he believed that knowledge should be used for the benefit of men. On the other hand, in 1853, Cardinal Newman of the University of Dublin disagreed. He advocated careful and close protection of all knowledge in science, and expressed the view that useful knowledge was a "deal of trash."

Over the years, at various times and in various places, the pendulum has swung from one extreme to the other; there is historical support for both arguments. Kant, Hegel, and Newman would have sided with those who feel that the university must remain apart from the world of business, agriculture, or politics. Bacon, Franklin, Jefferson, and Einstein would support those who argue that universities have a direct responsibility for dealing with problems of their time.

In this country, advocates of the service role have had the better of the controversy. The Land Grant Act of 1862 was certainly aimed at creating universities to deal with real-world problems—teaching farming and manufacturing skills to farm boys (and city boys as well) who wanted to become more than country gentlemen. Kerr says this was "a dramatic break with early American tradition in higher education . . . which created a new social force in world history." He goes on to say that "the cloister and the ivory tower were destroyed by being thrown open to all qualified comers."

In any case, the rapid change in our society during the past two decades, paced by unprecedented advances in science and technology, and the national and international situation in 1967, are more relevant to the situation than all of university history and previous philosophy.

Because man is learning more about his universe, and stands to learn more about it in the next few years than in any other period of history, it would seem that if universities are to remain on the cutting edge of knowledge, they must become deeply and directly involved in the processes that are generating it.

This, of course, relates to the balance between the university's three roles: teaching, research, and service. The university's primary responsibility and, indeed, its reason for being, is education. However, research and service are vital because they are so closely associated with, and essential to, good teaching. Without continuous updating, revitalizing, and sharpening of knowledge through research, the process of teaching becomes stale; the teaching role becomes sterile. Similarly, research can become insipid or meaningless if directed toward artificial problems, if it mostly involves the honing and polishing of old familiar problems that have already been "researched to death," or if it consists merely of restating old knowledge in different or more complicated terms.

There is an unquestionable need for constant vigilance to see that a university's teaching responsibility, particularly at the undergraduate level, is not allowed to become degraded because of an overemphasis on research or service. Nevertheless, there is not only a place for, but also a clear need for vigorous research and service that balance and support teaching.

University participation in space exploration is essential to the space program and universities have much to gain. Our dealings with universities are based on recognition of the fact that the university's primary mission is teaching, and that research and service done on behalf of the space program should enhance and strengthen the university as a trusted and unbiased source of knowledge.

NASA's university programs are planned and managed to strengthen rather than weaken the universities participating in the space program. NASA's aim is that any university that does business with NASA should become a stronger university through the process than it would have been otherwise.

FUTURE POSSIBILITIES IN SPACE

If three-way university-industry-Government cooperation is continued, the future accomplishments of space exploration will be more spectacular than those of the past. For example, following the manned landing on the Moon, universities, Government agencies, and industrial firms working together can build the electrical power supplies, the life support systems, the surface vehicles, and the other systems necessary for long-term lunar visits and extensive exploration of the lunar surface. Semipermanent or permanent colonies can be established on the Moon. By so doing, greatly increased knowledge of the origin of the Moon can be anticipated: whether it was captured by Earth after being formed somewhere else in space or whether it was originally a part of the Earth that was thrown off and became a satellite.

With the cooperation and ingenuity, creativeness, and intellectual resources of its people, the Nation can develop the space vehicles and the life support systems that will permit men to land on the surface of Venus or Mars, to explore those planets and to return safely to Earth, even though many of the technical problems that must be solved may now appear insurmountable.

Further, in manned flight, future technological developments will enable men to take off in a more or less conventional manner from conventional airports, accelerate to orbital velocities, move into weightless space flight for various missions, and, upon completion of these missions, to return to landing fields of their choice on the Earth.

I am not advocating that all these things necessarily should be attempted, nor that they are the most important things that should be undertaken by the Nation. There are other important matters that are competing for national resources and demand the serious attention of our university-industry-Government forces. The choice of goals to be pursued is not a decision to be made by scientists or engineers alone. I am convinced, however, that the kinds of advances in space I mentioned, not only can be made but will be made in the future—if not by the United States, then by the Soviet Union or some other nation.

MACROSCOPIC PROBLEMS AND THE NEED FOR MULTIDISCIPLINARY APPROACH

There are other problems of serious consequence to the Nation in which scientists and engineers have considerable interest and to which they owe a measure of responsibility. These include the problems of water and air pollution, urban transportation and housing, control of crime, and the conditions that lead to riots in our cities. These problems I term macroscopic problems, to differentiate from the microscopic problems that usually confront engineers and scientists. The university-industry-Government combination that has shown the capability to deal effectively with problems of space exploration might also deal effectively with these macroscopic problems.

NASA is primarily responsible for the creation and maintenance of a national capability to operate in near and outer space, and for the advancement of aeronautics. The space effort is having a far greater impact upon the country and upon international affairs than are the mere technical accomplishments of sending men and machines into space or of landing men on the Moon. The agency is aware of and concerned with the second- and third-order effects of the space program upon society. I have already noted that we are concerned with not just what universities can do for NASA but also with what the NASA program does for universities. I have already noted some of the space-developed spinoffs identified by the Technology Utilization Program as being useful for applications outside the space effort. I would like to suggest, however, that the major and most important spinoff of the entire space program may be the demonstrated effectiveness and basic strength of the university-industry-Government mode of operation for dealing with complex multidisciplinary macroscopic problems. If we can develop a mode of operation that effectively deals with society's macroscopic problems, it will ultimately be of far more value to the Nation and to mankind than the more direct scientific and technical returns from space exploration.

These problems are heterogeneous, multifaceted, or multiparametered, as are systems engineering design problems. All the parameters must be explored to deal with the problem. Technical problems cannot be solved reliably or phenomena understood completely if important parts of relevant information are missing. For example, Mariner 5 could not achieve its objective if precise data had not been gathered and applied on hundreds of specific parameters, such as rocket motor thrust, burning time and fuel consumption, the gravitational constants of Earth and Venus, relative velocities and positions of Earth and Venus, aerodynamic drag coefficients, moments of inertia, instrument calibrations and drift rates, and even the effect of solar radiation pressure in altering the course of the space vehicle. Had any one of those important parameters been neglected, it is obvious Mariner 5 would never arrive at Venus. In prelaunch countdown, days were spent checking and rechecking thousands of instrument readings.

Our macroscopic real-world problems today are similar: they are complex, heterogeneous, and depend upon a large variety of closely interrelated but sometimes poorly defined parameters. And they cannot be dealt with successfully if we ignore those nontechnical aspects of the problem that are difficult to understand.

Unless all parameters of macroscopic problems are identified and their interactions with one another analyzed by groups of experts from many disciplines with experience in all facets of the situation, this Nation cannot hope to cope successfully with the problems of air and water pollution, urban housing, urban transportation, or control of crime.

Macroscopic problems are multidisciplinary in nature; they cannot be solved by science and technology alone. They are of a scope and complexity beyond the reach of one professional or scientific discipline—beyond the reach of either natural sciences or the social sciences. Society can no longer expect breakthroughs made by individuals or even groups of individuals within a single discipline to suddenly solve any one of these problems. They are not singly engineering problems, or sociological problems, or political problems. They are a most difficult combination of all of these. Neither can they be dealt with by any one industrial firm, or any one national industry, or any one Government agency.

Perhaps such problems will yield to the combined efforts of engineers, scientists, lawyers, doctors, sociologists, economists, anthropologists, psychologists, and philosophers, as well as managers, administrators, and politicians working together. That is, they might if we can develop the attitudes and administrative skills necessary to combine these efforts.

Some progress is being made. Universities especially have an opportunity to give faculty and students more of the attitudes, training, and experience necessary for dealing with complex multidisciplinary macroscopic problems as well as microscopic ones.

Many university scientists are by nature not interested in applying themselves in team efforts on large system problems; they are much more inclined to pursue knowledge in specialized fields. While this is true for many individuals, and their work has been, and should continue to be, supported by universities, there are many other creative and innovative people today who want to tackle some of the macroscopic problems we have discussed, who display an eagerness and an enthusiasm for working as part of a team effort on some of these problems, and who should be equally encouraged and rewarded by universities. Possibly more of these people would be attracted to graduate schools today if universities would provide recognition, promotions, and rewards for them on a par with the rewards offered to scientific research specialists in the classic disciplines.

The Nation must seek to develop minds that can apply to the human social problems of today the same kind of innovative thinking that made space flight possible. It must develop minds that can bridge the gap between technological solutions, on the one hand, and sociological problems, on the other, to solve the problems of air and water pollution, urban housing, urban transportation, and crime control. Universities, industries, and Government agencies must recognize that new attitudes and new approaches are needed to cope with current national and international situations.

President Johnson has said, "The test of our generation will not be the accumulation of knowledge. In that, we have surpassed all ages of man combined. Our test will be how well we apply that knowledge for the betterment of all mankind." Or, as Einstein put it, "The concern for man and his destiny must always be the chief interest of all technical effort. Never forget it among your diagrams and equations."

SESSION IV

Human Factors in Space Flight

Chairman: **M. A. GRODSKY**

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Physiological Hazards of Extended Space Flights

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N71-28541

As we approach the time of space flights lasting months or years, problems begin to loom up that have not yet been subjected to any sort of direct test. These must be considered, therefore, as potential hazards that require advance investigation. We must know everything to be known about the possible physiological contingencies that may arise, let us say, when the flight is 6 or 12 months from Earth, should an emergency arise that could not be handled by the crew. There will always be some unknown hazard, but we need not make each flight unnecessarily experimental.

There are three main sources of information available to us that can be utilized in reducing the uncertainties. One of these, used extensively in anticipation of the Gemini flights, is ground simulation of conditions aloft. The second is the mass of physiological data accumulated from the Gemini flights themselves. The third is the use of experimental flights with animal subjects that provide the opportunity to observe reactions directly under actual conditions, without human risk. This paper will review these briefly, attempting to evaluate information that relates to projected flights of several months or more, to point out the gaps in our knowledge that would lead to guesswork, and to suggest how the animal-experimentation approach may be utilized to handle certain crucial questions that cannot be answered in any other way, short of using human astronauts as experimental subjects, under conditions during which we cannot honestly promise they will be secure from unwarranted physiological peril.

INTRODUCTION

The space program has made possible great contributions to our basic physiological knowledge. Even greater contributions can be made by continuing the research supported by that program. The NASA program is, as it must be, essentially mission-oriented or applied research, but it is a well-known fact that programs that begin as strictly applied research inevitably are expanded as it becomes evident that many aspects of the applied problem cannot be solved without first filling the gaps in the underlying basic scientific information.

The physiological systems that seem to be mainly in question are the cardiovascular and the vestibular, and the questions revolve primarily around the enigma of prolonged weightlessness. The possible effect of truly extended periods in the weightless condition of space flight is the one great question that remains unsolved and unsolvable except by the direct test of prolonged flight itself. For this is a condition that cannot be replicated or simulated in all respects within the Earth's near-gravitational field, except for a very brief period of time. The Gemini flights and the imminent Apollo flights provide or will provide the answers to some questions, but there remain certain open, educated suspicions of effects that could not appear within the time limits of those flights. These are effects that present so much unpredictable hazard, both to success of missions and to well-being of the astronauts, that every effort to anticipate them by appropriate animal experiments must be made.

CONTRIBUTIONS OF SPACE FLIGHTS TO PHYSIOLOGICAL KNOWLEDGE

Physiological performance data from the Gemini orbital missions leave us with a generally optimistic feeling about man's ability to survive in space and in the weightless condition, for periods of time up to at least twice that of the longest flight, or about a month, and probably somewhat longer. The records of heart rate, respiration, and blood pressure show no significant deviation from the benign patterns expected or demonstrated in simulation experiments. In the longer flights, the heart rate and sleep cycle tended to settle into a clearly defined circadian rhythm, as the increase in heart rate associated with the excitement of liftoff gradually subsided. This was broken only by a gradual increase associated with preparations for returning to Earth. Blood pressure likewise showed no significant deviations from normal range, allowing for particular times and circumstances, such as exercise periods.

One of the consistent circulatory changes found in the Gemini astronauts was a time-related loss in red-blood-cell mass. The reduction in red-cell mass has been attributed to the high oxygen tension in the cabin atmosphere, a view that has received some support from laboratory data and experiments, although the observations are less than conclusive, and there remains an element of doubt. It seems unlikely that all of the facts can be explained as oxygen effects, or corrected by adjustment of the cabin atmosphere.

Similarly, decreases in plasma volume, a consistent finding among the Gemini astronauts, are not easily explained away by any simple, single-factor hypothesis. It seems probable that the weightless state contributes to both phenomena; therefore, there is an unpredictable element that can be resolved only by the actual experiment of prolonged weightless flight.

In the early phases of the space program, there was great concern about the possible effects of overstimulation, on the one hand, and, on the other, of partial deafferentation of the sensory input from the vestibular end organs. This concern centered initially on the expectation that astronauts would experience more or less severe handicaps because of vertigo and loss of equilibrium. It gave great impetus to research on the vestibular system and phenomena related to excessive or bizarre stimulation, on the one hand, or understimulation, on the other. Research on the activity of human vestibular sense organs has utilized the reflection of this activity in compensatory movements of the eye, in motion sickness, and in a few more lesser known phenomena that may be evoked by appropriate patterns of vestibular stimulation. The primary ocular manifestation, nystagmus, has been exhaustively studied with respect to fast and slow components, duration, and other factors, in response to stimulation of the three semicircular canals and otolith organs of either or both ears, in all the ways the ingenuity of the experimenters can contrive. Experimental subjects have been spun rapidly on a short radius and whirled rapidly or slowly on longer radii; external ear canals have been irrigated with hot water and ice water; subjects have experienced brief periods of 0*g*; they have been tilted, centrifuged, accelerated, decelerated, and generally disturbed by every means at the disposal of many ingenious investigators. They have been made sick by all of these methods, and also by rapid oscillation in the vertical axis and experimental voyages in round-bottomed ships deliberately guided into stormy seas. Every stage of motion sickness has been pitilessly scrutinized, photographed, and reduced to quasi-mathematical equations. The results of this kind of experimentation form a vast literature and lore of nystagmography, motion sickness, and related subsciences. The literature demonstrates the impressive degree of adaptability of the organism to much of the foregoing maltreatment and makes a number of material and procedural contributions to space-capsule design, astronaut equipment, and astronaut training. Perhaps the greatest of these contributions is that to the basic understanding of vestibular function. This is not to say that mission-oriented funds were improperly diverted to the support of amusement for scientists in their laboratories, but rather illustrates the point that applied research produced its inevitable byproduct in the form of contributions to basic knowledge. It may even be that this is as important a justification of the space program as would be the arrival of astronauts on the Moon in good health.

With respect to the mission contribution of vestibular research, thorough preflight examinations, functional testing, in-flight monitoring, observation, and postflight reexamination and reports have shown that the equilibratory consequences of the *g*-stresses of launching, weightless flight, and reentry were much less troublesome than had been feared as a consequence of wise planning, use of research data, and a prior knowledge of the realities of the situation. In fact, at present they pose no problems that are not rather easily offset. The Soviets have apparently been more impressed than we with the difficulties to be expected from this source, although the experience with Mercury and Gemini flights tend specifically to contradict the Soviet experience, perhaps as the result of more adequate planning, design, training, and related factors in the Mercury and Gemini programs.

Possible Physiological Problems of Long-Duration Flight

Much is known about man's immediate reactions and adaptability to brief overstimulation and brief partial-vestibular deafferentation. "Brief," in this case, means the timespan from 1 sec or less to 3 weeks in the laboratory and from a few seconds to 14 days in orbital flight. Although no insurmountable difficulties became apparent within these time limits, it must be questioned whether any would ever develop if weightless flight were extended to the time required, for example, for flight to Mars or Venus. It would be justifiable to assume that none would develop only if it were certain that there were not some point in time between 14 days and this limited infinity (time required for the long-duration flight) at which an endpoint would be reached in a physiological or anatomical deterioration process, beyond which what had been true before would no longer be true. Extrapolation is a mathematically valid process, only when dealing with a continuum in which there are no such breakpoints or thresholds.

Weightlessness, sufficiently prolonged, may produce effects that, while having no premonitory manifestations, once the critical point is reached, would be irreversible, at least for the subsequent duration of the weightless state. One such effect would be the direct result on the vestibular system of prolonged deafferentation of the otolith organs. The other would be an indirect result on autonomic and somatic mechanisms having to do with vascular function, and induced by the prolonged interruption of the vestibular input to spinal and visceral tonic motor control.

The direct effect on vestibular structure and function is one for which there is little direct evidence from vestibular studies but several significant lines of information from other neural systems. These have to do with a curiously neglected area of neuropathological research; namely, that of the anatomical effect on synaptic mechanisms of functional deprivation of afferent input. Two phenomena are involved, presumably sequentially: retraction of axonal endings and degeneration of the second neuron in a sequential chain, a process known as transsynaptic or transneuronal degeneration. One of the clearest examples of this is found in studies of the lateral geniculate body after severance of the optic tract or enucleation of an eye. In this system in primates, the optic tract is made up in nearly equal proportions of the axons of retinal ganglion cells from the ipsilateral halves of the two retinas. The lateral geniculate body is the nucleus of termination of the optic tract, and is bilateral; i.e., one lateral geniculate body for each optic tract, which means for the opposite half of the visual field. It is made up of six layers of cells. The odd-numbered layers receive axons from the ipsilateral eye; the even-numbered layers from the contralateral eye. Destruction of the ipsilateral retina or optic tract results in degeneration of the cells of the odd layers of the lateral geniculate body, whereas destruction of the contralateral retina or optic tract leads to degeneration of the even layers of the geniculate cells.

In a somewhat different sort of neural system within the brain, experiments in our own laboratory have shown that destruction of a tract called the fornix produces about a 10-percent depopulation of cells in the nucleus of its termination, the mammillary nucleus of the hypothalamus. It is to be noted that this example represents a partial depopulation.

Experiments on animals have shown that destruction of the cochlea (hence, of the cells of the spiral ganglion, the cells of origin of the axons that compose the auditory nerve), followed by survival periods of 60 to 359 days, results in degeneration of certain cells in the dorsal and ventral cochlear nuclei. An incidental finding in one animal was that inadvertent damage to the vestibular nerve produced degeneration in the medial and descending vestibular nuclei. These experiments provide evidence that the cells of the cochlear and vestibular nuclei that receive synaptic terminations from the primary afferent fibers of the auditory and vestibular nerves respond to anatomical deafferentation by selective degeneration. The question of whether similar reactions would occur in response to functional deafferentation remains to be answered. The degenerative reactions seen in the auditory brainstem nuclei, in their similarity to those of the lateral geniculate body, in the case of the visual system suggest that degeneration after functional deafferentation would be likely. The experimental conditions that would test this hypothesis in the laboratory are extremely difficult if not impossible to design. Prolonged weightless flight should provide the crucial test in the case of the vestibular system.

The process by which this kind of cell degeneration is produced has come to be called transneuronal or transsynaptic degeneration. It occurs when a neuron is deprived of its input from the axons of neurons that precede it in a synaptic chain. It is not known what proportion of input to multiconnected neurons must be destroyed to cause their degeneration nor what proportion retained to maintain their integrity. Complete deafferentation of nerve cells, wherever this phenomenon has been searched for, causes their degeneration. This phenomenon is most likely to be observable in situations where certain neurons receive all, or virtually all, of their input from a single source, and when that source is disconnected or functionally silent. Neuronal degeneration caused by deafferentation is not detectable in much less than 6 months, nor complete in much less than 12 months, which is of crucial importance in the present context.

Putting together all of these facts, it is apparent that the vestibular system and the temporal scale of projected long-term weightless flight become a logical field in which to anticipate possible trouble. The widespread pattern of secondary vestibular projections, both anatomically and physiologically, gives us many hints of the possible consequences of vestibular deafferentation. All must be explored and included in calculations for future extended flights.

VULNERABLE ANATOMICAL SITES

The first locus of vulnerability is in the vestibular receptor organs themselves, the hair cells of the maculae of the utriculus and sacculus and of the cristae of the semicircular canals. (Anatomical descriptions of the microscopic structure and ultrastructure of the inner ear are available in many standard texts and in publications of several recent symposia.) The hair cells are in synaptic contact with the endings of afferent nerve fibers of the vestibular ganglion and nerve. It is especially in the ultrastructure of these synaptic contacts that the earliest effects of functional deafferentation may be manifested. Some early indications of change in synaptic junctions between auditory hair cells and afferent nerve endings in response to noise exposure have appeared. Even though this is an inversion of the circumstances envisioned for vestibular hair cells in prolonged flight, it seems to provide reasonable basis for the hypothesis that such synaptic regions are sensitive to modification of functional input.

The second locus in which pathological change might be expected is in the cells of the vestibular nuclei of the medulla. This is the site of the first interneuronal synapses (as distinguished from sensory-neural synapses) in the vestibular system. It is well established that the comparable second-order neurons of the auditory pathway undergo transneuronal degeneration upon being surgically separated from their input. There is a lesser, but nevertheless significant, amount of evidence that the same rules apply to the vestibular system as well. It is apparent that this is an area that urgently requires further research within the limitations of the laboratory situation prior to possible future testing in a prolonged flight experiment. This is, in fact, one of the lines of research currently being studied.

Beyond the second-order neurons, any further pathological changes in the vestibular system resulting from deafferentation are entirely conjectural. There is no evidence to support a hypothesis that transneuronal change beyond the vestibular nuclei would have an input limited to that from the vestibular end organs or primary nuclei; therefore, it would be reasonable to assume that any physiological effect of vestibular deafferentation beyond the primary vestibular nuclei would be the result of a physiological deficit in vestibular contribution, but not to extension of the transneuronal degeneration to motor nuclei that receive secondary projections from that system.

METHODS FOR COUNTERING THESE PROBLEMS

The effects of irreversible changes in vascular constituents and in neural systems that are, directly or indirectly, important to circulatory physiology may interact with other factors in such ways as to prevent astronauts from functioning or even surviving on flights of a year or more unless these are anticipated and appropriately neutralized. The way to offset the $0g$ condition is to provide an artificial gravity. This entails, under present circumstances, a substantial sacrifice in payload. There are those who believe that prolonged weightlessness poses no problems that have not already been answered by the Mercury and Gemini experience. They feel that it is unnecessary to consume weight allowance with the elaborate equipment for providing artificial gravity. That these same people, however, are not quite sure is bespoken by their contention that an incremental approach to longer flights will provide a hedge against the possibility that there may still be some unsolved problems.

The incremental approach is indeed the basic pattern followed through the Mercury, Gemini, and Apollo phases. Basically it is a sound plan that has paid off in terms of safety and in showing the way for each succeeding flight. But, like all plans, it has its limitations. The time has come when, to make further progress on a feasible time schedule, the increments must become successively and rapidly greater. An incremental pattern is often used in research, but only if the research is of such nature that there is no possibility that one increment will reach and go beyond some threshold or breaking point that spells disaster. So long as human subjects are used as elements in an experiment, there must be no such increment. This paper has indicated areas dealing with thresholds of irreversible physiological failure. To approach these incrementally with human astronauts is an invitation to trouble. Fortunately, there is an alternative that not only avoids this difficulty but also offers acceleration of the whole program. This consists of inserting animal flights of suitable duration and appropriate plan into the program so that prolonged weightlessness constitutes the sole variable. Such flights and the experimental subjects should provide for exhaustive preflight testing, in-flight observation, parallel ground simulation of all features except 0*g*, and complete postflight physiological and pathological examination of the subjects and ground controls. The flight-duration increments in such experiments can reasonably be pushed beyond the hypothetical breaking points and so may identify these unmistakably before risking human astronauts. There is no other way to give these people the assurance they are entitled to expect before they are launched into prolonged weightless flight.

The 1000-Day Mission: Null Gravity and Man

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Existing biomedical information, in terms of 1000 days in space, is insufficient for extrapolation. This paper discusses the need for realinement of research and development and the need for data that have significance for vehicle design. The roles of Earth and orbiting laboratories in qualifying man for long-duration missions are presented. Finally, fault-tree analysis is introduced as a means of orienting biomedical research in the direction of mission parameters.

THE SPACE PROGRAM FOR THE 1970'S

The achievements of Mercury and Gemini have been remarkable in every sense; yet, in terms of 1000 days in space, especially in terms of biomedicine, they might almost never have been; we are starting nearly from scratch. Until now, the best utilization of man in the spaceship environment has not been a major consideration; it has been more important just to get him into and out of orbit safely. Previous missions have shown the drawbacks of certain atmospheres for breathing and safety, the handicaps of spacesuits, and the difficulties of feeding and hygiene. The areas of metabolic process and contamination control have been identified as areas in which there is insufficient information for extrapolation. In short, the present state of biomedical art is principally based on qualitative data from a few pilots under limited conditions of every kind—time, novelty, and confinement.

Some of the information needed in planning long-duration missions can be provided by quantitative measurements in ground-based laboratories. It is quite possible, for instance, to keep enough people at bedrest, in mixed-gas environments, or in close quarters over long-enough periods of time to obtain reasonable data with which to make safe predictions. Other questions will most certainly be answered empirically as flights of longer and longer duration occur. Yet, in preparation for each specific mission, there occur the mixed problems of engineering design, safety, performance, and utilization of crewmen as well as the inevitable trade-offs to be made in solving these problems.

In recent months, the President's Science Advisory Committee and other bodies have reported the need for intensive biomedical research, the urgency of the need, and their criteria for such research. There is general agreement on the need for new techniques of prediction in relation to flights of long duration and, in particular, the need for data that have significance for vehicle design. This is a different problem from that of planning experiments that contribute quantitative data toward a better understanding of human physiological and behavioral mechanisms.

In this paper, the need for predicting the effects of long space flight on man is discussed, and two different approaches to the collection of data, in terms of vehicle and mission parameters, are outlined. The concept of fault-tree analysis, a method for turning qualitative objectives into quantifiable requirements, is also presented.

QUALIFICATION OF MAN

Both Government and industry spend considerable effort in the analysis and study of systems at the conceptual level. The purpose of these studies is to help select those few systems that will be carried through development and added to the inventory. Normally, these studies are of a parametric nature and are directed toward showing the optimum of many possible system configurations for achieving mission objectives. In making such studies, man's capability is frequently a critical factor. Obviously, the system analyst cannot factor the human requirement unless data are presented quantitatively and in terms of vehicle and mission parameters. One such study, now in progress, concerns the need for artificial gravity and how it is to be provided.

The search for assurance that man can weather long-term space flight without cardiovascular adaptation to $0g$ is producing a variety of gravity substitutes. These substitutes are directed toward increasing tissue pressure, increasing arteriolar and venomotor tone, maintaining blood volume, and maintaining cardiac work capacity. Elevated tissue pressure can be achieved by use of elastic garments and by increasing muscle tone with exercise. Maintenance of venomotor tone is being attempted through the use of lower body negative pressure, the oscillating trampoline, the short-radius centrifuge, pressure cuffs, exercise, and drugs. Antidiuretic hormones (Vasopressin), aldosterone (9-α-fluorohydrocortisone), exercise, hypoxia, and lower body negative pressure are being used in attempts to maintain plasma and red-cell fractions of blood volume. An increase in cardiac work capacity can be brought about by exercise.

Substitutes for gravity may be summarized as follows:

(1) Exercise:
- Isotonic
- Isometric
- Ergometers

(2) Pressure:
- Positive-pressure cuffs
- Lower body negative pressure
- Pressure breathing
- Hypoxia
- Elastic leotard
- Cardiovascular suit

(3) Acceleration:
- Space-station rotation
- Centrifuge
- Trampoline

(4) Drugs:
- Aldosterone
- Antidiuretic hormones
- Plasma expander

This cornucopia of substitutes poses an impossible problem for the system analyst in that weight, power, volume, and cost cannot be brought into perspective. Yet, in the near future, a decision must be made between purchasing a pair of elastic leotards and financing the rotation of a space station. The problem of financial resources prohibits proceeding along two or more approaches simultaneously. The lack of a solution clearly shows that research and development must be realined and directed toward vehicle and mission parameters.

DATA COLLECTION

The Basic Approach

At the present time, the biomedical specialist is in possession of quantities of assorted data about man and his requirements in the space environment. In the early stages of space achievement it has been necessary to build studies in areas of suspected importance. For example, reams of tilt-table data defining orthostatic tolerance are available, but the usefulness of these data is questionable. The crewman of the 14-day Gemini mission who lost the least weight and whose blood volume was normal was the one who fainted on the tilt table and took as long as

3 days to return to his preflight status. There are many other examples that raise serious question as to the relation between some of our physiologic tests and the operational demands faced by the flightcrews. Left to welter on this sea, one may choose to either proceed on intuition or to direct oneself to mission objectives.

The next generation of atmospheric entry systems will impose an exacting and difficult task upon flightcrews. The trajectory of a lifting-body vehicle is very sensitive to crew performance. Any guidance error produces a higher-than-nominal acceleration or lengthens the time spent at a lower acceleration. In the final analysis, the skill of the crew determines the point of hard touchdown. The system analyst's paramount interests concerning crew safety are the ability of the crew to tolerate a nominal acceleration-time profile without blacking out or exceeding a medically established maximum heart rate, and the guidance precision that can be expected of the crew if their last reentry practice was 6 to 12 month earlier. Answers to these questions dictate the degree of automatic control to be designed into a vehicle and the type of onboard refresher training needed to maintain crew proficiency. In the proposed realinement of research and development, much more attention must be given to answering design questions and to presenting data useful to the engineer and system analyst.

On the Ground

A space laboratory is no substitute for the versatility and precision of a ground laboratory. The choice among gravity substitutes (or perhaps even the determination of the need for such substitutes) will come from a series of bedrest studies performed on the ground in a space-cabin environment with human subjects performing realistic mission tasks. Considering the present state of knowledge, it is not unreasonable to plan for progressively longer periods of bedrest (with a maximum of 1000 days) in the space-cabin simulator. Primates are not an adequate substitute for man in these studies; for instance, the difference in length of hydrostatic column precludes extrapolation of cardiovascular data from such a source. There are no sophisticated shortcuts in the qualification of man for long-duration flights.

Although the conduct of these studies is of national concern, the first goal should be an assessment of the effectiveness of gravity substitutes in preventing cardiovascular adaptation to $0g$. Some indication of the potential of gravity substitutes can be given now, but it must be remembered that large variability in data collection, dosage pattern, and experimental conditions characterize such judgments. For example, diametrically different approaches have been taken in the study of two gravity substitutes: the rotating space station and the onboard centrifuge.

The major biomedical problem with station rotation is "canal sickness." Many ground-based studies have been made of the design parameters for a rotating space station (fig. 1). Because any level of artificial gravity can be achieved by regulating the

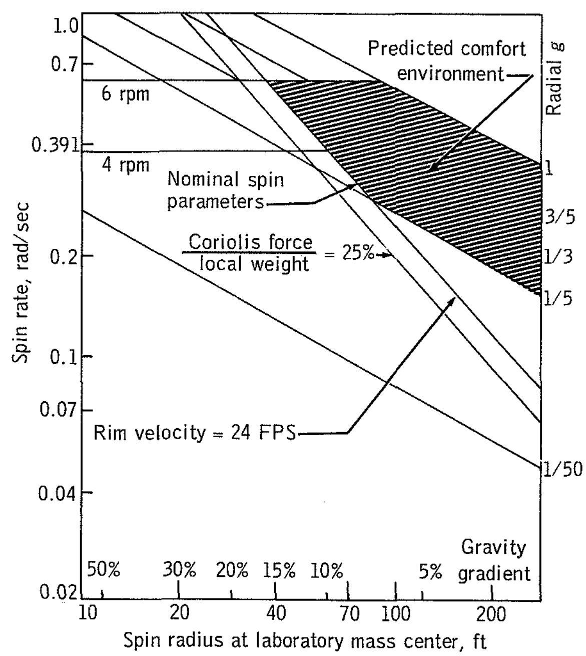


FIGURE 1.—Artificial gravity parameters.

radius and velocity of rotation, suggestions have been made as to the lower and upper limits for effective human performance. Reasonable lower and upper limits for the operating envelope are $0.3g$ and $1g$. The most recent data show that 6 rpm would be tolerable for trained crews making nominal head movements (225 deg/sec head rotation) in a rotating vehicle. These estimates would result in a vehicle with a 48-ft radius, rotating at 6 rpm and providing 58 percent of Earth gravity. Although the concept of partial acceleration is advanced as a means of maintaining homeostasis, there are no studies to show what level of partial acceleration is required to minimize cardiovascular adaptation.

The potential of the centrifuge in this regard is better studied. With as few as four 7.5-min rides on a short-radius centrifuge, the symptoms of orthostatic intolerance are largely prevented. Oddly enough, the steep heart-to-foot acceleration gradient of 256 percent created by this measure did not preclude movement of the head, arms, and legs, and motion sickness was not a problem for the well-trained individual exposed to high angular rates and modest head or limb movements. Also, exposure to lower body negative pressure appears to be a feasible measure for restoring orthostatic tolerance while in space. However, the 8-hr-per-day dosage pattern for this measure is a serious limitation on crew time. It is apparent from this discussion that "figures of merit" need to be established for the effectiveness of gravity substitutes. The resulting biomedical and engineering trade studies would show the adequate system for achieving mission objectives.

In Space

There is, on the other hand, no substitute for space. Within the decade, current manned spacecraft programs will provide an opportunity for comparing the actual effects of space flight with predictions of these effects. NASA's Langley Research Center is currently studying the engineering feasibility of a centrifuge experiment for the Apollo Applications Program. The purpose of the centrifuge is to reproduce, in $0g$ environment, a valid physiological stimulus to study tolerance to acceleration, threshold levels of sensitivity to acceleration, oculogravic illusions and eye counterrolling, semicircular canal stimulation, measurement of body mass, reentry simulation, and cardiovascular countermeasures. Repair and maintenance functions and hygienic functions that require elaborate airflow devices in a weightless environment may also be studied. Various methods of installing a modular centrifuge, transverse and axial, are being studied in terms of roll-and-yaw dynamics (fig. 2). When treated as an experimental device, it is just this kind of approach that will permit the biomedical community to state, without reservation, the level at which man can function effectively during extended time in space and still fully readapt to terrestrial conditions on return.

FAULT-TREE ANALYSIS

Crew safety and mission performance are twin criteria for the allocation of resources in the design, development, and operation of a space system. A singularly effective, analytic method is evolving for turning qualitative objectives into quantitative requirements. "Fault-tree analysis" was developed by Bell Telephone Laboratories for the Minuteman missile system; it has been used for assessing an undesirable event (a safety hazard, for example) and providing a mathematical treatment for estimating the probability that such an event will occur. Bell engineers discovered that the method used to describe the flow of "correct" logic in data-processing equipment could also be used to analyze the "false" logic that resulted from component failure. Moreover, such a format was ideally suited to the application of probability theory to numerically define the critical fault modes.

The starting point in the development of a fault-tree diagram is the identification of the undesirable event. Subevents contribut-

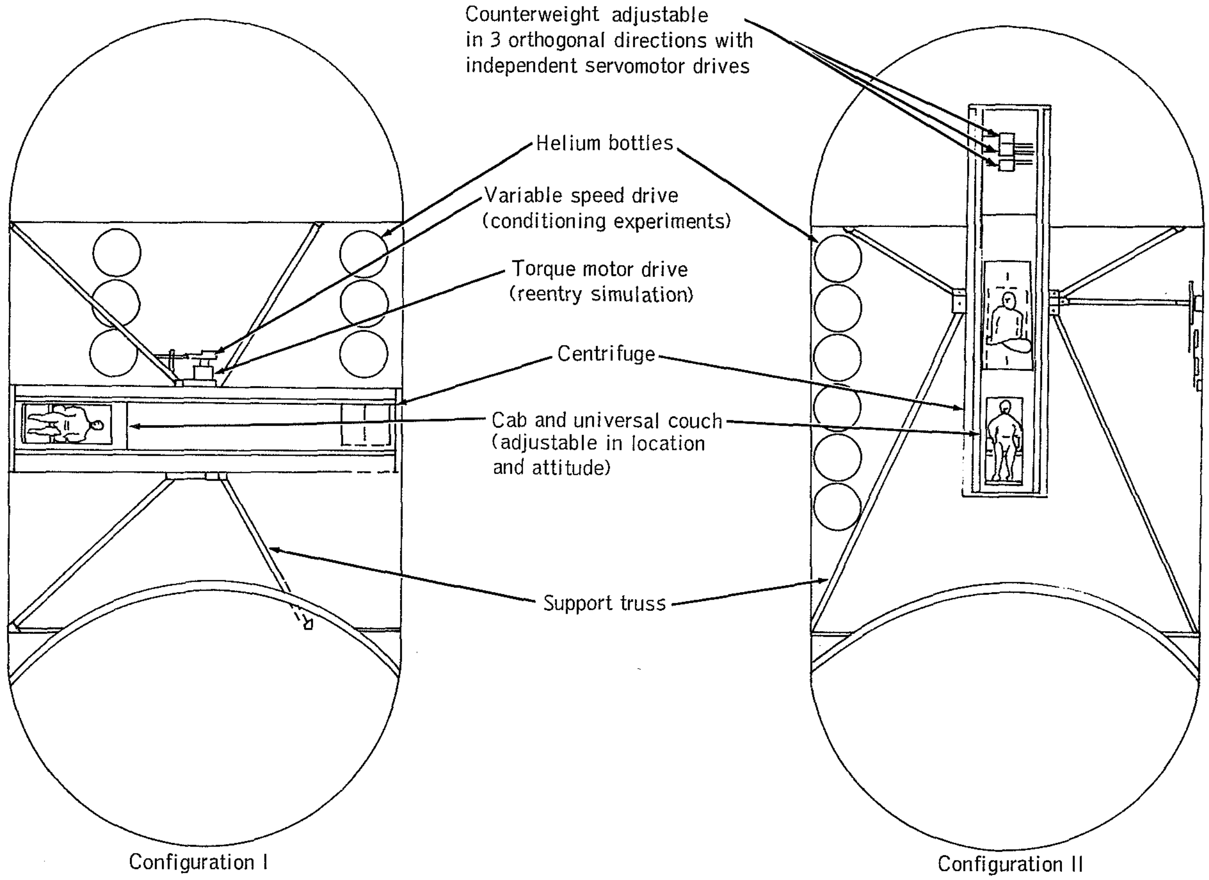


FIGURE 2.—Saturn IVB intratank installations.

ing to this event are identified, and Boolean algebra is used to formulate precise equations that express the relation of fault-producing events to each other. The arrangement of the diagram shows the events that coexist and those that exist on an either/or basis: the OR gate (+) indicates that the output event will exist if any or all of the input events are present; the AND gate (·) indicates that the coexistence of all input events is required to produce the output event. A rectangle (□) encloses an event that results from the combination of fault events through logic gates; the diamond (◇) encloses an event that is basic in a given fault tree.

In the analysis, probability values must be budgeted among the events to establish a failure goal for each of the subevents contributing to the end or top event. The hypothetical analysis diagramed in figures 3 and 4 assumes an equivalence of probabilities for each mission phase. Point-by-point budgeting of probabilities is continued throughout the tree. An interesting facet of the analysis is the budget-assigned events for which corrective or repair action is possible. In the example diagramed in figures 3 and 4, the analyst depends more on correcting a critical event than on prevention. A recent development that reflects correction of critical events is the constant repair or "lambda-tau" method of fault-tree evaluation. This method considers the probability of coexisting failures in repairable items and defines the time that a function can be inoperative without impairing crew safety (fig. 5). The Boolean and probability equations resulting from the analysis introduce a solid engineering basis to the field of crew safety.

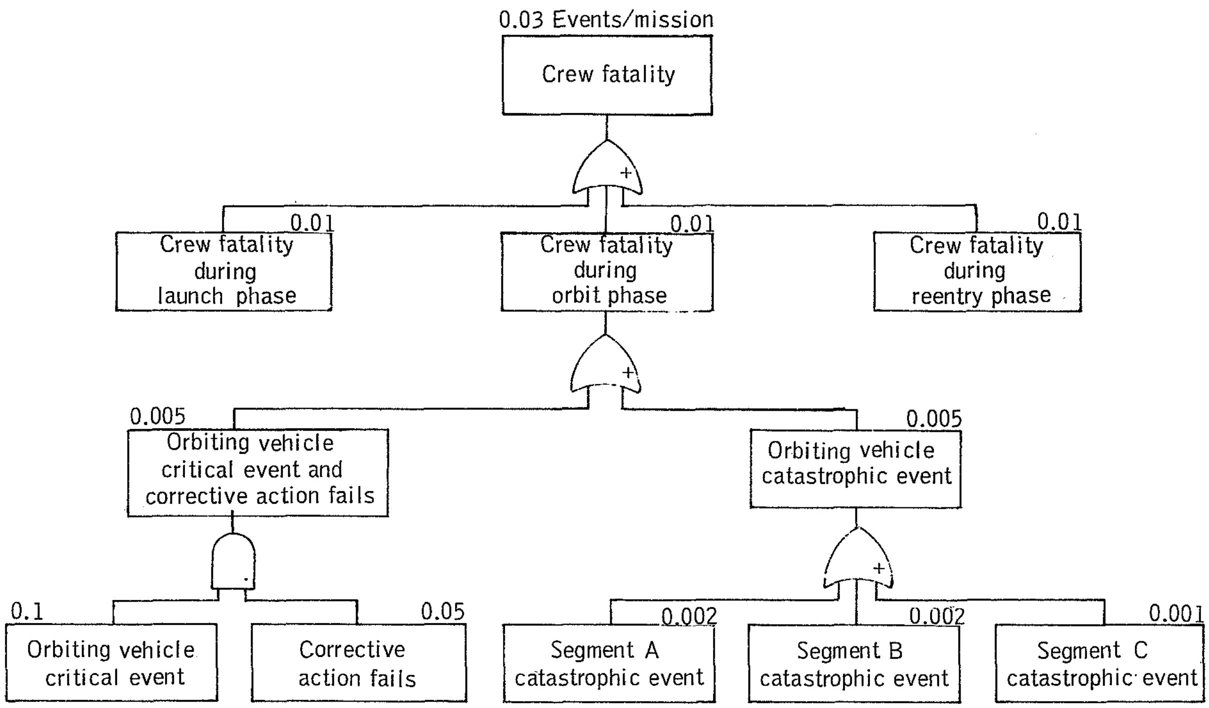


FIGURE 3.—Top-level fault tree.

Another requirement of the analysis is that of applying predicted or empirical failure probabilities to the Boolean equations describing the tree. Ultimately, the analysis consists of comparing the budgeted and predicted probabilities at each branch through to the top of the tree. When the predicted probabilities are less than the budgeted probabilities, a fault is considered acceptable. If the predicted value at the top is greater than the budgeted value, there is cause for concern and corrective measures are required. Thus, a method for computing and controlling quantitatively the safety of any system is realized.

SUMMARY

There is agreement within the biomedical community regarding the need for research, techniques of prediction, and data that have significance for vehicle design. The problem for the systems analyst in evaluating the different methods of qualifying man for flights of long duration is complicated by considerations of weight, power, volume, and cost. Further, there is the question of the relations between our current physiologic tests and the operational experience or demands of flightcrews; much more attention must be given to relating these factors to each other.

It is mandatory that we look to new analytic methods for turning qualitative objectives into quantitative requirements. Fault-tree analysis in its present application on manned systems has proved to be an effective means of specifying crew safety, mission performance, and vehicle and mission parameters.

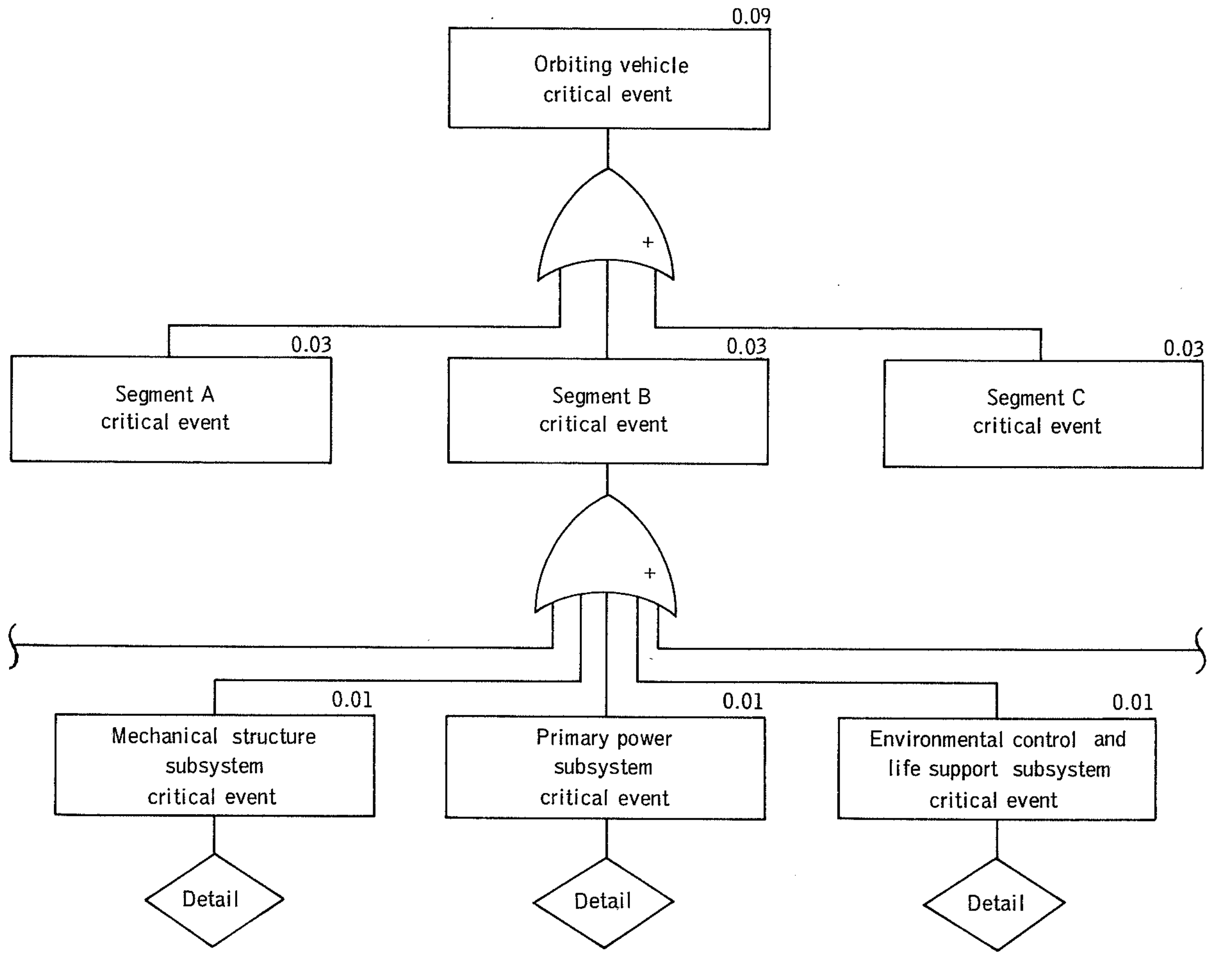
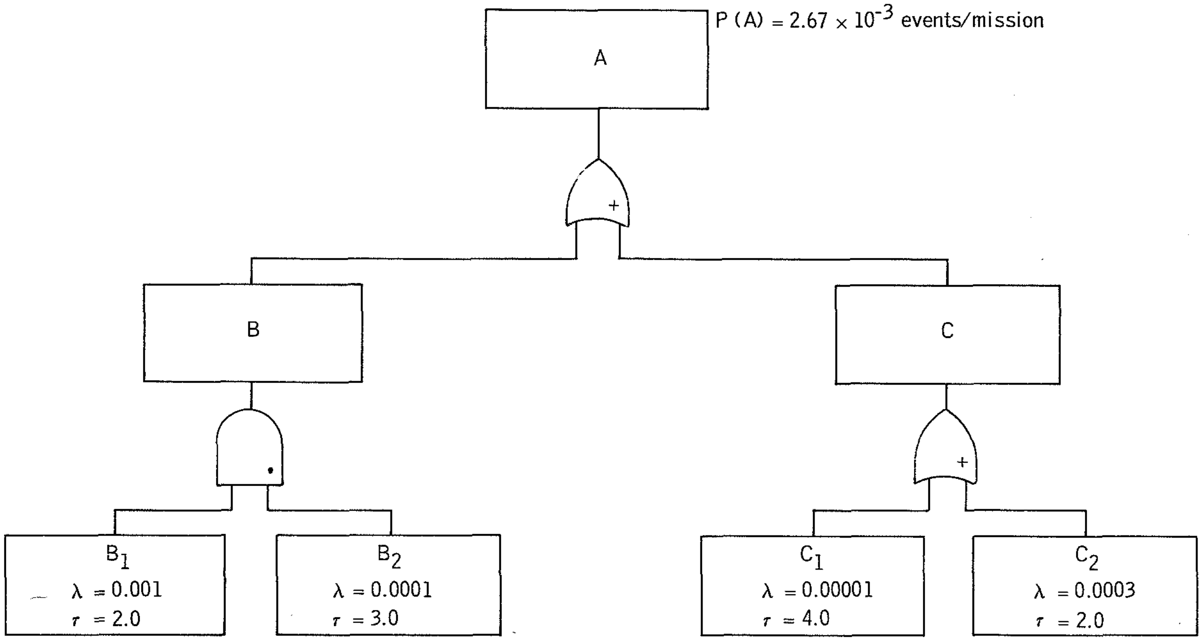


FIGURE 4.—Intermediate-level fault tree.



λ=Primary failure rate (events/day)
τ=Mean hazard reaction time (hours)
T=Mission length=100 days

$$A=B+C$$
$$A=B_1B_2+C_1+C_2$$
$$P(A)=P(B_1)\ P(B_2)+P(C_1)+P(C_2)$$
$$P(A)=[\lambda_{B_1}\tau_{B_1}\lambda_{B_2}\tau_{B_2}+\lambda_{C_1}\tau_{C_1}+\lambda_{C_2}\tau_{C_2}]T$$
$$P(A)=[(0.001)\ (2.0)\ (0.0001)\ (3.0)+(0.00001)\ (4.0)+(0.0003)\ (2.0)]\frac{100}{24}$$
$$P(A)=2.67\times10^{-3}\ \text{events/mission}$$

FIGURE 5.—Fault-tree probabilities.

Man's Role in Mission Reliability

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N71-28543

For centuries man has been building machines to be operated by man. As technology has advanced, he has built more and more complex machines and equipment that have required the performance of more complex roles or functions by man. In some machines man has a very simple role and performs that role without training or instruction. Other equipment is being built that may require years of training and preparation before a particular man is qualified to operate it. The case of the highly complex man/machine system is nowhere better demonstrated than by manned space flight. Man has a similar role in modern aircraft, ships, submarines, and other equipment used in the military and industrial world.

Prior to World War II, designers were concerned primarily with the hardware characteristics of the system or equipment that they were designing. Since that time there has been an increasing tendency for designers to consider man as a component of the systems they are designing and developing. They now consider man in the same way they consider hardware elements of new systems. Frequently the question is asked, "Should this be a manned or an unmanned system?" This is not the proper question. Designers and planners should ask, "What system or equipment output or performance is called for, and which system functions can equipment perform best and which functions can man perform best to improve system output?" Frequently the problem is oversimplified by saying that man should be assigned those functions that require planning, reprograming, and rational processes; equipment should be assigned those functions that require routine and repetitive actions.

In the space-flight community and the Department of Defense, we now operate under a design-and-development philosophy that requires at least two things: (1) At any time in the design-and-development process we must be able to assess and predict the cost and effectiveness of the equipment and manned aspects of the systems that we are developing; and (2) as the equipment or hardware is being planned and developed, there must be a concurrent effort to select, train, and prepare those personnel who will man, operate, and maintain it. These two requirements assume that we have the same capability to quantify and predict the cost and effectiveness and the technical contribution of man as a component of the system under development. Unfortunately this is not often the case.

PURPOSE

The intent of this paper is to examine the results of several studies that demonstrate the role that human performance contributes to system reliability and effectiveness. Keep in mind the fact that human reliability as a concept is an aid to the system planner at the time of the selection of a system concept and is also an aid to the designer and developer as he makes decisions concerning specific man/machine functions. In addition, it can be an aid to the manufacturer of the system as he establishes and carries out the

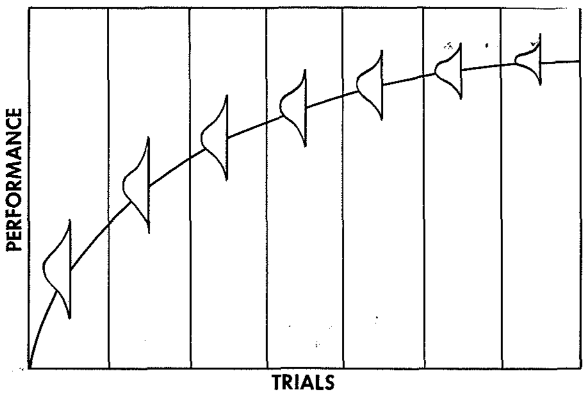

FIGURE 1.—The learning curve and human reliability.

fabrication of the system. The major message of this presentation is summed up in figure 1. This is the well-known learning curve and underlies the concept of human reliability. Human performance is indicated by the ordinate, and in the man/machine system context this can represent human performance ranging from the highly skilled performance of the pilot in an aircraft or space-flight system or it can be the very simple and untrained performance of an individual following the written instruction on a coin-operated vending machine. Although these are skilled performances at extremely different levels, they represent the same logical problem to the man/machine equipment planner and designer. The distribution curves that are turned 90° and are superimposed on the learning curve portray the improvement in level of performance and the decrease in variability as training progresses and reaches or approaches the asymptote. Simply stated, this means that when a system planner or designer is assigning system functions to be performed by man, the level of expected performance during system operation should rest well below the range of performance represented by the distribution curve describing performance at the end of training. Let us now look at the results of some studies of the contribution of human performance to overall system performance and operation.

STUDIES OF HUMAN PERFORMANCE RELIABILITY

One of the best known studies in the area of malfunction data collection was conducted by Shapero, Cooper, Rappaport, Schaeffer, and Bates (ref. 1). They surveyed the malfunction and hold data of nine operational Air Force missile weapon systems. They examined all of the available malfunction and hold reports to determine whether human performance initiated the series of events that led to a failure or a hold in missile checkout or launch. Their analytic study involved reviewing all types of failure reports, including coded failure reporting systems and failure reporting systems in which cognizant personnel reviewed the individual failures in a verbal report. The first step in their study was to separate those equipment or system failures clearly not initiated by humans. Examples of such failures include those initiated by events such as microphonic, fungus effect, or loss of residual magnetism. Examples of reports that were identified as human initiated include those identified as human error, reversed leads, wrong part, torque incorrect, etc. An overall summary of their data is included in figure 2, and it can be seen that of a total of 3829 equipment failures, 1092, or 29 percent, were human initiated. Of the 419 equipment holds, 75, or 20 percent, were human initiated. Figure 3 shows part of this information subdivided into human-initiated errors per par-

	HUMAN-INITIATED EQUIPMENT FAILURES AND HOLDS	NOT HUMAN-INITIATED EQUIPMENT FAILURES AND HOLDS	TOTAL EQUIPMENT FAILURES AND HOLDS
FAILURES	1,092	2,737	3,829
HOLDS	75	344	419

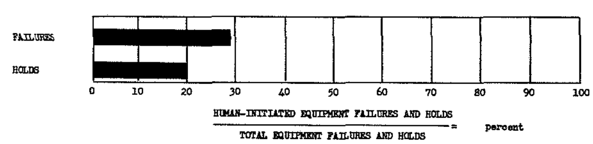

FIGURE 2.—Human-initiated equipment failures and unscheduled holds as a percent of total equipment failures and unscheduled holds during missile launch and prelaunch activities for seven missile systems.

ticular missile system. It can be seen that human-initiated failures per missile system range from 53 percent for missile system F to 20 percent for missile system B. In the case of holds, information was available for only two of the missile systems. In figure 4 it can be seen that 23 percent of the unscheduled holds for missile system I were human initiated and 16 percent were human initiated for missile system H. Figure 5 demon-

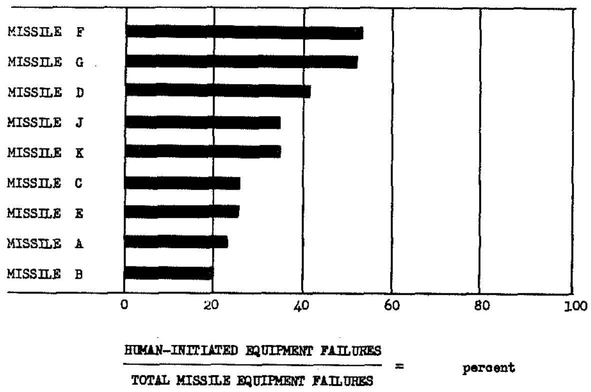

FIGURE 3.—Human-initiated equipment failures as a percent of total equipment failures during missile launch and prelaunch activities.

strates different operations during which human-initiated failures occurred. The authors of the study felt that this classification was incomplete because it did not include procedural failures that were detrimental to system performance but did not lead to system failure. In most failure reporting systems, such procedural failures are not reported.

One of the very important findings of this study was the fact that the forms and reporting procedures for identifying human-initiated failures point the finger of guilt at

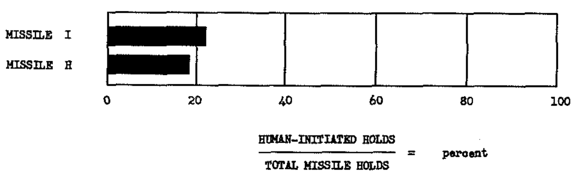

FIGURE 4.—Human-initiated unscheduled holds as a percent of total unscheduled holds during missile launch and prelaunch activities.

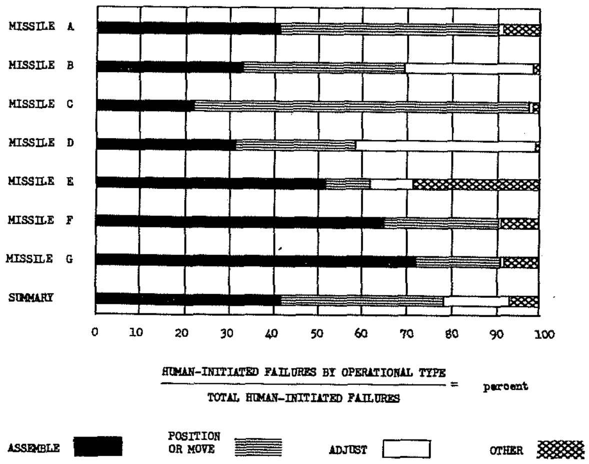

FIGURE 5.—Human-initiated equipment failures during missile launch and prelaunch activities, classified by operation, for seven missile systems.

system personnel; and, therefore, there is reluctance to report human-initiated failures when the operator is "guilty." This was true even when the human-initiated failure was caused by faulty design of equipment or procedure. In interviews with contractor personnel, it was found that at least one disastrous launch or flight failure occurred in each of the missile systems investigated. However, to avoid the implication of guilt, this fact was seldom reflected in failure, malfunction, or hold reporting systems. Although this study was completed several years ago, we have no reason to believe that this characteristic of failure reporting systems has changed.

This has been reviewed in this discussion for three reasons: it is a classic study of the effect of human performance or human reliability contribution to system performance; it demonstrates a method that can be used to determine these effects in operational systems; and although these missile systems are not manned space-flight systems, it demonstrates that all human components of the ground-support system must be evaluated as well as the flightcrew to determine the overall effectiveness of that system.

Expert Judgments of Human Reliability

During Project Mercury, analyses were

performed by Grober, Jones, Felker, and Glaenzer (ref. 2) and Wolman and Okano (ref. 3) on the effects of an astronaut upon the reliability of the Mercury spacecraft mission. The Mercury system was originally intended to be an automatic system and man was included as a backup only. In these studies the approach was to make a thorough analysis of possible system failures, determine the sensory cues by which an astronaut would detect such failures, determine the corrective action required, determine the environmental conditions under which the corrective action would be taken, and evaluate the applicability of existing experimentally derived human-performance data to this problem.

On the basis of this information, a group of five experts made judgments of the probability that the astronaut would perform the necessary corrective actions when called for under conditions of flight. These estimates were then entered into reliability nets that included estimates of equipment reliability and information concerning the alternate paths that would be followed in case of failure.

This approach indicated that the inclusion of man in a spacecraft can increase reliability of performance of certain systems. However, these studies left two elements open: They did not address the entire set of mission tasks that the astronaut must carry out during the duration of the space mission (only identification of failures and their corrections); and they did not satisfactorily establish that expert judgment of crew performance can be accepted as a valid predicter of actual performance.

Two other studies using the judgment of experts to assess flightcrew reliability were carried on by Boobar (ref. 4) and Grodsky (ref. 5). These were parallel studies carried on concurrently and independently to assess the relative effect of human reliability upon overall system performance for lunar landing by direct flight versus lunar landing by the lunar orbit rendezvous mode. In other words, the problem was to determine whether human aspects of reliability would affect the overall reliability of the two modes differently. The direct flight mode is one in which the astronauts go directly from Earth to Moon, land on the Moon, launch and return to Earth in the same spacecraft or command module. The second mode, which was the selected mode for the Apollo mission, is one in which three astronauts launch from the Earth and travel to lunar orbit in a command module. Two astronauts then descend to the lunar surface in a lunar excursion module, land, launch from the lunar surface, and rendezvous with the third astronaut who has remained in lunar orbit in the command module. Then the three return to Earth in the command module.

Although Boobar and Grodsky used study approaches that were different in detail, they used similar research strategies. Each went through the following steps:

(1) Determination of crew tasks for the entire mission for both modes. These tasks ranged from flight-control tasks through switching, monitoring, communications, and systems management.

(2) Assessment of the difficulty of various tasks and the accuracy with which they had to be performed.

(3) Determination of the various conditions that would be acting upon the astronauts at the time of the performance of each of the specified tasks. Included and considered, and of varying degrees of importance, were such factors as display and control characteristics; available volume and its utilization; visual problems of landing, rendezvous and docking; psychological stress; task complexity; workload, and sensory deprivation.

(4) Judgment by experts of the likelihood that the astronauts would perform the tasks at the required level of accuracy.

(5) Entrance of the judged reliabilities into mission sequences to determine overall mission reliability.

One last step in the Boobar study included a computer reliability analysis employing a Monte Carlo technique that by means of digital simulation "flew" 5000 missions in each configuration.

The results of these two studies disagreed, one indicating that a manned lunar landing by direct flight was more reliable than a landing by the lunar orbit rendezvous mode. Subsequent comparison of the two studies shows that the difference in their conclusions rested upon assumptions regarding the effects of restricted volume upon flightcrews. In other respects, the studies were in general agreement as to the effects of space flight upon crew performance.

The studies of judged human reliability show clearly that the generalizations and judgments that are necessary to estimate crew reliability are not satisfactory because there is no way to determine the discrepancy between judged crew reliability and actual reliability.

Assessment of Crew Reliability by Manned Simulation

Manned simulation of crew performance can provide reliability data of higher validity than that provided by expert judgment by utilization of displays and controls as similar as possible to those planned for the actual mission, by performance of tasks in the appropriate temporal sequence for the mission under study, by utilization of a subject population similar to the actual astronauts who will be involved in the mission, and by performing the mission in real time with all the operations in normal sequence. This approach can provide improved estimates of flightcrew reliability for lunar and other space missions until actual space-flight data are recorded in a form usable for reliability prediction.

Such a study was conducted by Grodsky, Mandour, Roberts, and Woodward (ref. 6). They trained five flightcrews composed of three pilots each. Each crew was trained for a 5-week period, after which it participated in a 7-day real-time manned simulation of a lunar landing mission. Characteristics of the teams are noted in table I. All of the subjects were graduates of the U.S. Air Force Aerospace Research Pilots' School at Edwards Air Force Base, and each held at least a baccalaureate degree in either engineering, physical science, or military science. All but two were married; their average age was 31.7 yr; they averaged 368.6 hr of bomber flight time and 2292.6 hr of fighter flight time; and they had an average of 10.03 yr of military service.

One crew at a time was trained. Each crewmember was trained on all mission flight tasks during the 5-week training period. Training was carried on 8 hr per day, and an additional 2 hr were spent daily in physical conditioning. The approach utilized during the training period was to lecture each crew on the system concepts and the operation of the system, demonstrate the operation of the simulator, perform part task training of individual phases of the mission, perform whole task phases, and then perform an integrated fast-time mission (the complete 7-day mission with coast phases was eliminated to

TABLE I.—*Pertinent Data on Pilots*

Crew	Average age, yr	Marital status	Average flight time, hr		Average military time, yr	Average college time, yr
			Bomber	Fighter		
1	33.6	3M	336.6	2498.3	11.8	5.0
2	32.0	3M	786.6	1905.0	10.5	4.0
3	31.8	3M	635.0	2608.3	10.2	4.1
4	30.5	3M	33.3	2040.0	9.0	4.3
5	30.6	1M, 2S	51.6	2411.3	8.6	4.0
Total average	31.7	13M, 2S	368.6	2292.6	10.03	4.3

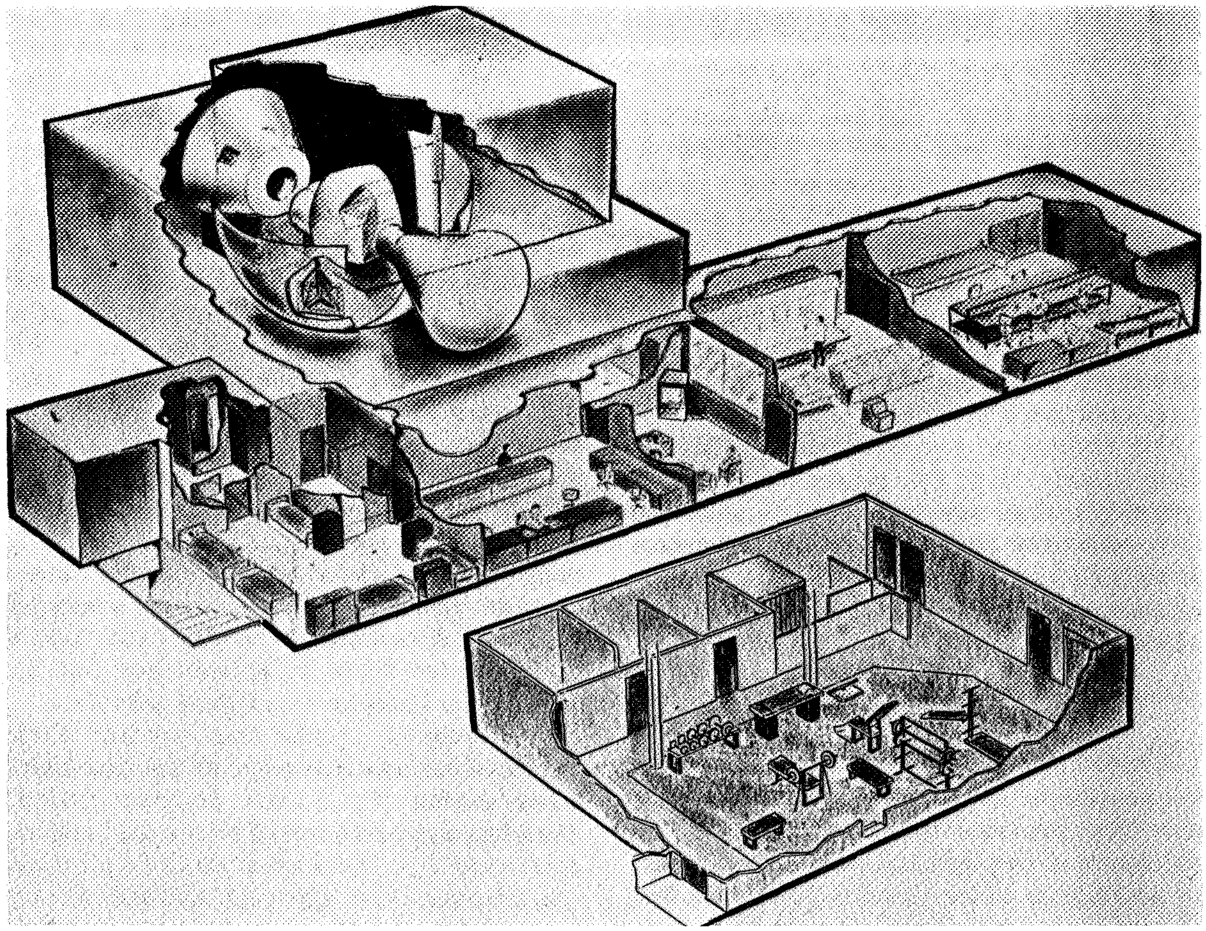

FIGURE 6.—Simulation laboratory.

shorten time required). During the course of the training period, the crews were also required to participate in the physical conditioning program, learn in-flight checkout and maintenance procedures, and attend lectures and training for simulated lunar-surface exploration tasks.

The mission performed was the lunar landing mission as planned by NASA at the time this study was conducted (1964–65). There were two deviations from mission realism during the 7-day real-time simulation:

(1) All dynamic phases were repeated three times (except Earth launch and midcourse corrections) to collect data from each pilot for performance of each phase. In this way as much data as possible were collected from each crew.

(2) Because the purpose of this study was to obtain pilot performance data, it was necessary to put the pilot into the system loop in as many systems and mission phases as possible. Therefore, some of the mission phases and operations that would normally have been automatic were flown or operated in manual mode to collect data on human performance of those operations.

The basic experimental facility for this study (fig. 6) included a simulator room, housing simulators of the Apollo command module and the lunar excursion module, a mission control room, and an analog computer facility that provided signals for the flight instruments and out-the-window displays.

The interiors of the command module

(CM) and the lunar excursion module (LEM) (including instruments and controls) were essentially like those designed for

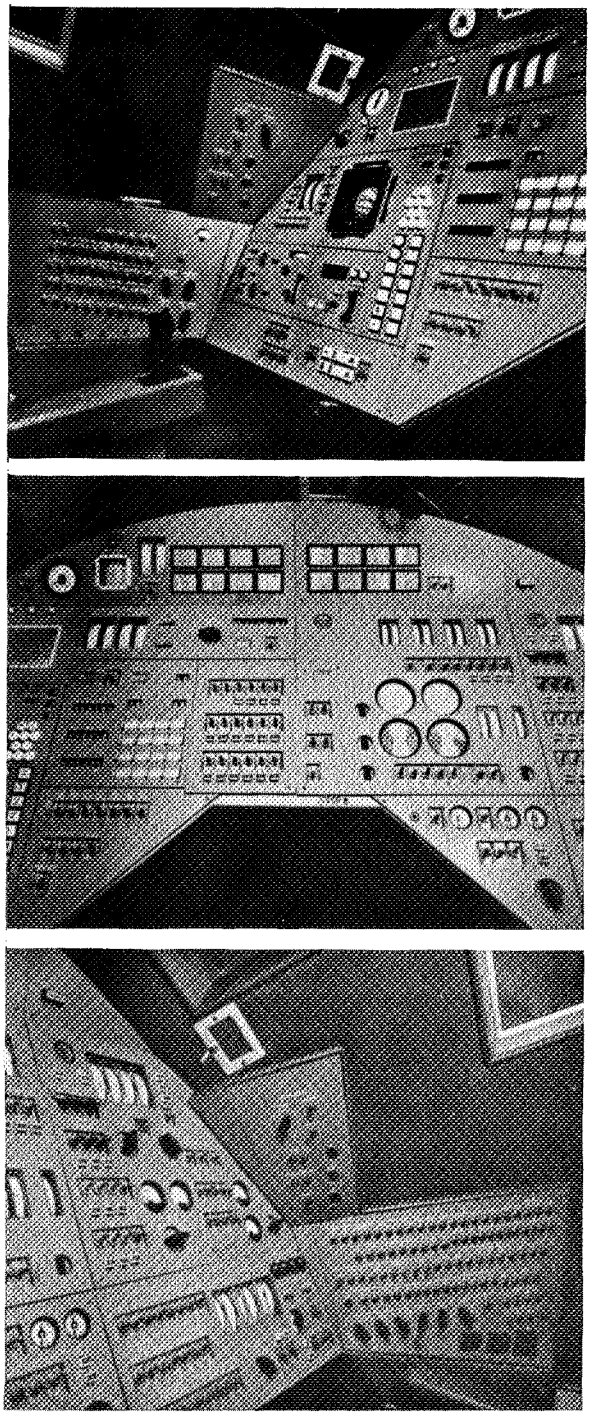

FIGURE 7.—Interior views of command module instrument panels.

the Apollo mission (fig. 7). The CM had three-abreast seating for the command pilot, the navigator, and the systems engineer. It also included a navigation station (fig. 8). The LEM simulator seated two abreast in harnesses in semierect position as in the Apollo LEM.

The control room contained the following consoles:

(1) The flight director's console, which contained duplicate displays and control monitors for all of the primary flight systems in the CM and the LEM.

(2) The capsule communicator's console, which contained communications equipment to allow the capsule communicator to maintain constant surveillance over and communication with the flightcrew during mission simulations.

(3) The system operation console, which contained displays and controls that allowed control-room personnel to monitor crew and system performance and to insert system responses (other than flight control) or malfunctions according to prepared scenarios of the missions.

(4) The data recording console, which included four 100-channel brush recorders that were used to record switch position and warning light status. It also included three 50-channel oscillographs, which were used for recording of motion of navigation optics.

The computing facility included three ana-

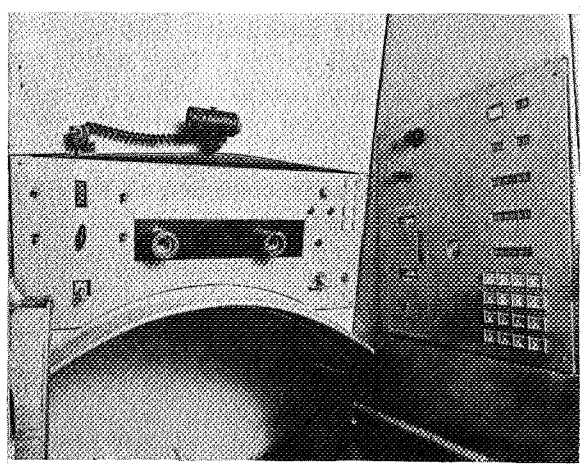

FIGURE 8.—Navigation station.

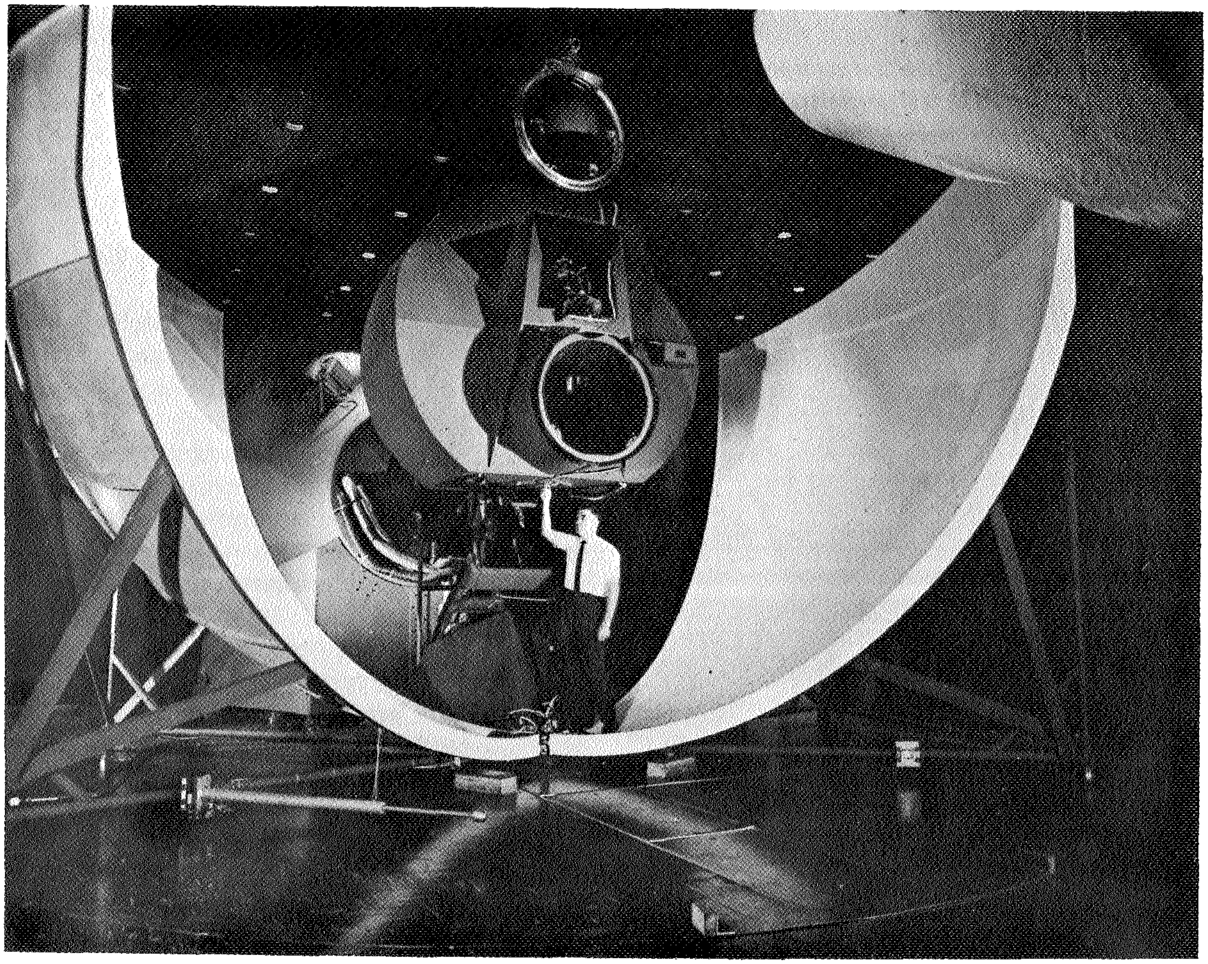

FIGURE 9.—Simulator room.

log computers with a total of 360 operational amplifiers to drive instrument displays and to solve spacecraft moving base simulator dynamics. Recorders and plotters for recording flight performance and terminal conditions were also included.

With this simulation complex, all subjects were trained to perform all mission flight tasks for the entire lunar mission, for CM and LEM (fig. 9).

After 5 weeks of individualized training, during which each pilot was able to review his performance daily, each three-man team "flew" an integrated "fast-time" mission that included all mission dynamic phases with all coast phases eliminated. Then the integrated 7-day real-time lunar landing mission was flown. The three men remained in the CM and performed all flight tasks for Earth checkout, Earth launch, Earth ascent, Earth orbit, translunar insertion, transposition of the LEM, position determination, midcourse corrections, and lunar-orbit insertion. Then two men entered the LEM and performed LEM separation and deorbit, coast descent, brake, hover, touchdown, lunar-surface tasks, lunar launch, coast ascent, and rendezvous and docking. Then mission procedure was altered so that all pilots performed all tasks of all dynamic phases—the pilot who had remained in lunar orbit completed the lunar landing phases up to rendezvous and docking in company with one of the pilots who had already completed those phases. Following this, transfer was made to the CM and all pilots completed the transearth entry and landing phases of the mission.

All out-the-window displays were as realistic as possible. There was a star-field projector and Earth and Moon models, driven appropriately to simulate all optic and spacecraft controls used by the pilots during navigation tasks and midcourse correction. The lunar horizon and star field were projected on a clamshell screen in front of the LEM to simulate spacecraft attitude and position during lunar orbit and coast phases. During rendezvous, a simulated CM beacon flashed on that same screen and increased in size as position of the CM and LEM closed. When they were calculated to be approximately 12 ft apart, the clamshell screen opened. The CM model, moving in three degrees of translation, and the LEM, moving in three degrees of altitude, simulated the six-degree-of-freedom visual-docking problem and allowed physical docking of the LEM and CM model.

The flight-control performance measures that were taken on each pilot and analyzed for each training trial and mission phase are:

(1) Translunar insertion, lunar orbit insertion, and transearth insertion:
  (*a*) Imparted velocity increment error,[1] ΔV_e
  (*b*) Average pitch error,[1] θ_e average
  (*c*) Pitch error standard deviation, θ_e SD
(2) LEM transposition:
  (*a*) Closing rate,[1] $\dot{X}$
  (*b*) Reaction control system (RCS) fuel,[1] Δm RCS
  (*c*) Displacement at docking,[1] D
  (*d*) Displacement rate at docking,[1] $\dot{D}$
(3) Midcourse correction:
  (*a*) Imparted velocity increment error,[1] ΔV_e
  (*b*) Pitch error,[1] θ_e
  (*c*) Yaw error,[1] ψ_e
(4) Separation and deorbit:
  (*a*) Imparted velocity increment error,[1] ΔV_e
  (*b*) Pilot roll error,[1] ϕ_e
  (*c*) Local pitch angle error,[1] ϵ_e
(5) Break and hover:
  (*a*) Percent main engine fuel remaining,[1] percent MEF
  (*b*) Pilot roll error,[1] ϕ_e
  (*c*) Local pitch angle error,[1] ϵ_e
  (*d*) Distance from landing site,[1] SR
  (*e*) Vertical touchdown rate,[1] $\dot{S}_z$
  (*f*) Lateral touchdown rates in *X* and *Y* planes,[1] S_{xy}
(6) Lunar-powered ascent: Imparted velocity increment error,[1] ΔV_e
(7) Rendezvous: Percent RCS fuel used,[1] percent RCS
(8) Docking:
  (*a*) Closing rate,[1] $S_{\dot{z}}$
  (*b*) Displacement at docking,[1] D
  (*c*) Displacement rate at docking,[1] $\dot{D}$
(9) Earth entry:
  (*a*) Distance from landing site,[1] D
  (*b*) Average altitude error,[1] H_e average
  (*c*) Altitude error standard deviation,[1] H_eSD
  (*d*) Average cross-range error,[1] Y_e average
  (*e*) Cross-range error standard deviation,[1] Y_eSD
  (*f*) RCS fuel used, Δm RCS
  (*g*) Pitch error at 0.05*g*, θ_e 0.05*g*
  (*h*) Average pilot roll error, ϕ_e average
  (*i*) Pilot roll error standard deviation, ϕ_eSD

Analyses of these data first required dividing the training trial performance into two parts: training trials in which performance was improving significantly and baseline or asymptotic trials in which improvement had dropped to very low increments between trials.

This was done through statistical tests (*F* tests) of variability between all possible cuts between training and baseline trials on each flight parameter. In this way baseline trials represented those in which variance was as low as possible in comparison to the training trials.

A determination also had to be made as to

[1] Displayed to the pilots each day during training.

criteria of successful performance on each flight parameter. For analysis purposes, two such criteria were established: (1) baseline mean $+3\sigma$ and (2) mission or gaining goal criteria based on Apollo system limits.

After accomplishing the above, it was then possible to simply count those cases in which performance criteria were exceeded and determine discrete reliabilities therefrom by simple computation of numbers of errors made versus the number of possible errors. On this basis, determination of baseline performance reliability and real-time mission reliability was accomplished. As shown in figure 10, mission reliability fell off significantly for crews 2, 4, and 5 when successful performance was considered to be the baseline mean $+3\sigma$.

The use of the baseline mean $+3\sigma$ is a much more stringent criteria than the training goal criteria. This is shown in figure 11. When using the mean $+3\sigma$ criteria, both crews 4 and 5 indicated significant degradation of performance reliability during the mission, whereas only crew 5 displayed such degradation when the comparison was made on the basis of the training goal criteria.

The effect of the use of the two different criteria is further demonstrated by comparing normalized reliabilities (mission reliability/baseline reliability) on the basis of mission phase or mission time (fig. 12).

Switching data were simple but tedious to analyze. It merely required a count of the two kinds of incorrect switch operations possible, including switches thrown when not required and switches not thrown when required.

The same assumptions were used in the analysis of switching data that were used with flight control data; namely, that variance would decrease and performance would improve as trials progressed. Therefore, the same technique of comparison of variances was used to determine the cut points between training and baseline trials. Having determined baseline reliabilities for switching performance, normalized reliabilities were computed and were plotted by mission time and phase in figure 13. These plots indicate

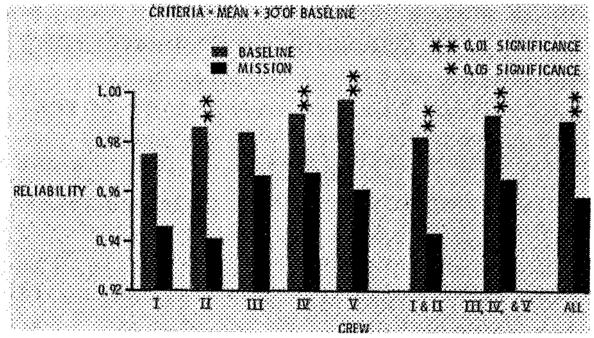

FIGURE 10.—Flight control: mission and baseline reliability, by crew.

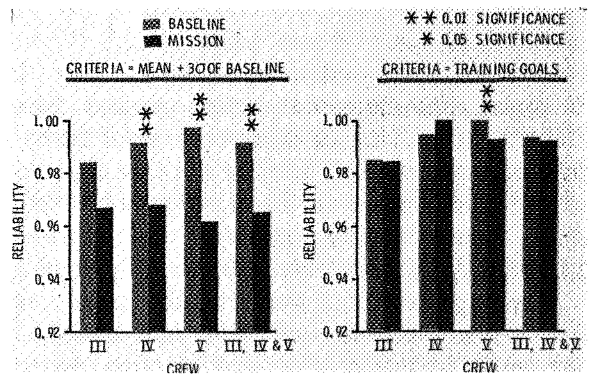

FIGURE 11.—Flight control: effect of criteria on crew reliability.

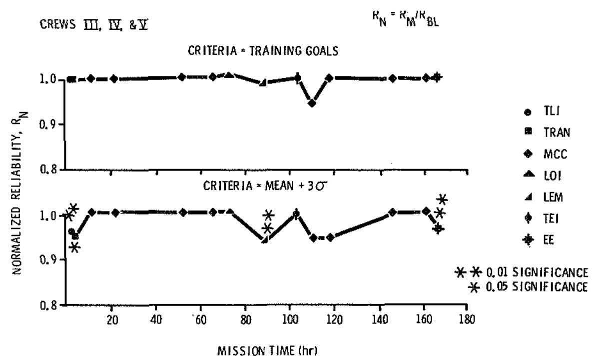

FIGURE 12.—Flight control: mission reliability normalized to baseline mission time effect.

general improvement in switching performance up to about the 70th hour, with slight degradation after that point.

Further analysis of these switching errors indicated that only 59 of 326 (18.1 percent) of mission switching errors occurred in sys-

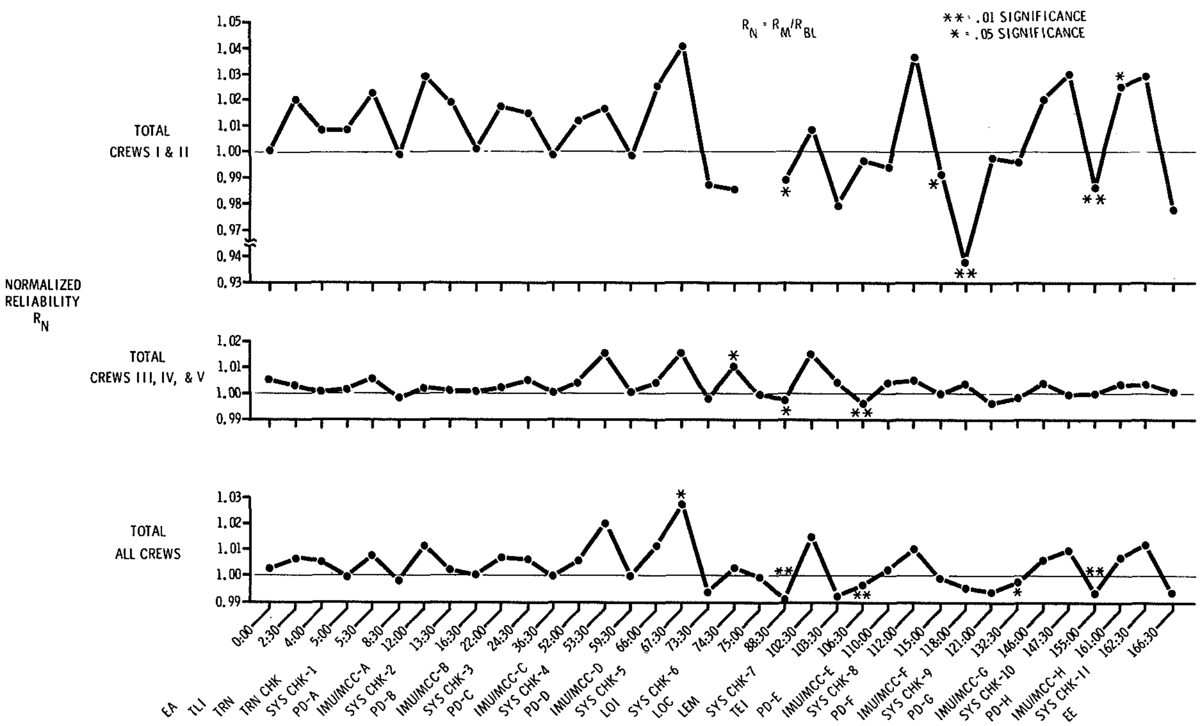

FIGURE 13.—Switching performance.

tem or circumstances that could have caused abort or catastrophe. However, there were no aborts or catastrophic errors.

Grodsky, Roberts, and Mandour (ref. 7) conducted many other analyses of the data we have reviewed and other data they collected. However, for our purposes the major point to be gained by review of this study has been to demonstrate the use of real-time manned simulation as a technique for assessing human or flightcrew reliability. It has application for both ground control and flight personnel, if we truly become serious about man/machine and man/man comparisons of reliability. This study demonstrates that, for the mission defined, there was only a minimal loss of crew-performance reliability during missions and that this reliability loss can be interpreted in terms of operational needs as was done here by comparing two forms of criteria (i.e., training goal criteria and Apollo mission criteria). This technique (that is, comparing man and equipment reliability) offers an analytic technique to integrate human performance criteria into space-flight vehicle development by verifying that crew performance will meet mission objectives.

Crew Performance in Long-Duration Missions

In the realm of human performance, one of the major questions for both NASA orbital, lunar, and planetary missions and DOD–USAF orbital missions relates to the retention of flightcrew skills to perform critical flight-control tasks after long periods away from training facilities or performance of specific operational tasks.

To test this question relative to missions of up to 3 months, the U.S. Air Force sponsored a follow-on study to the one described above, using the same facilities and already trained flightcrews (refs. 7 and 8). They returned four of the five crews to the training facility at such a time as to provide 4, 8, 9, and 13 weeks of skill retention or forgetting time.

In their review of the Grodsky data and in their analysis of the retention data, Cotterman and Wood developed a less optimistic position regarding performance reliability in the training described previously. Simply stated, they computed the mean and standard deviation for the last four training trials on each of the mission applicable parameters for each mission phase. The distributions thereby described were used to make likelihood statements as to whether the pilot or crew could meet or surpass predetermined performance criteria for each mission parameter. These reliabilities were combined to assess the joint reliability of performing adequately on all mission parameters of a particular phase. The reliabilities for a particular parameter ($\bar{p}$) and for all parameters ($\bar{\bar{p}}$) for all phases of an entire mission are shown in figure 14. Results are combined for the crews whose retention performance was assessed at 4 and 9 weeks (c–4 and c–9, respectively) after completion of the initial training. They were combined because their performance on final training trials was judged (on the basis of variation in predicted performance) to represent comparable end-of-training skills. The two crews with retention assessment at 8 and 13 weeks (c–8 and c–13, respectively) were combined on the same basis.

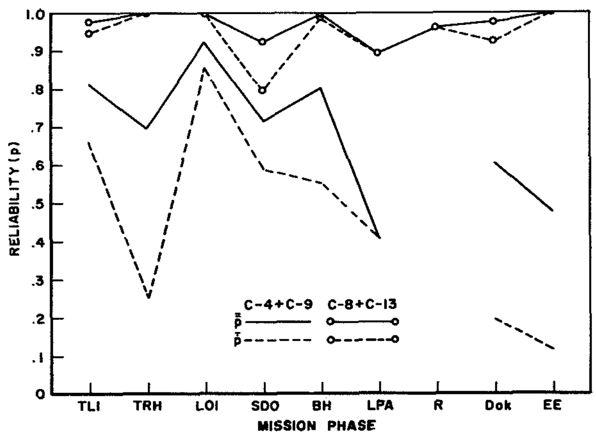

FIGURE 14.—Crew reliabilities for single parameters and combined parameters by mission phase.

Figure 15 demonstrates two points that Cotterman and Wood consider important in evaluation of crew reliability: End-of-training skill can be translated directly into reliability terms, and, in this case, indicates that crews c–4 and c–9 were better trained, i.e., more reliable than crews c–8 and c–13; and this difference in performance reliability represents a difference in training levels, not capabilities.

To clarify what actually happened to a pilot's reliability as training progressed and during periods of nontraining or rest from training, Cotterman and Wood plotted the performance scores (x), means of performance scores by four trial blocks ($\bar{x}$), and based on those four trial blocks the predicted limit within which 95 percent of all performance measures would fall ($\dot{\bar{x}}$). Selected plots for one pilot in selected mission phases in the 13-week retention group are shown in figures 16 through 21. These figures indicate that actual mission performance parameters can be used as measures of crew performance levels (therefore, as measures of pilot

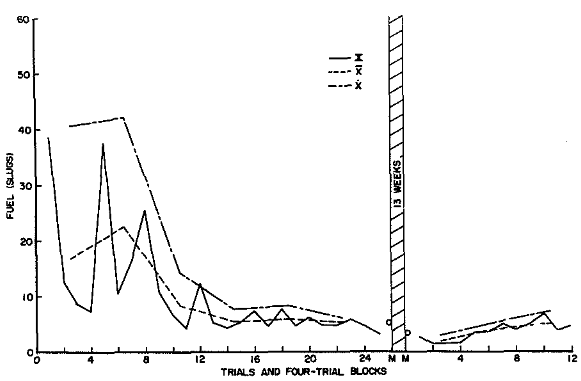

FIGURE 15.—Transposition: fuel consumed.

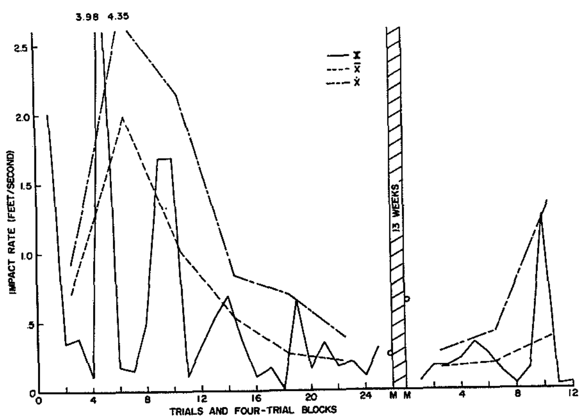

FIGURE 16.—Transposition: impact rate.

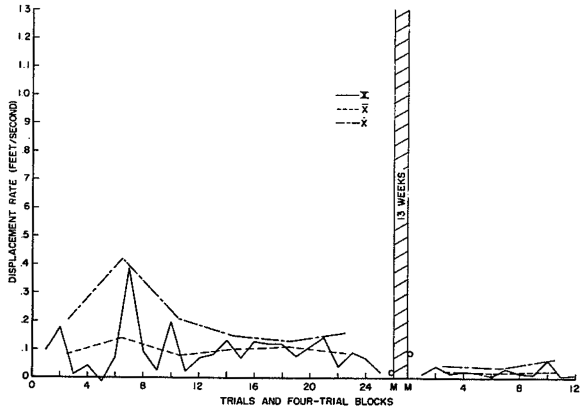

FIGURE 17.—Transposition: displacement rate.

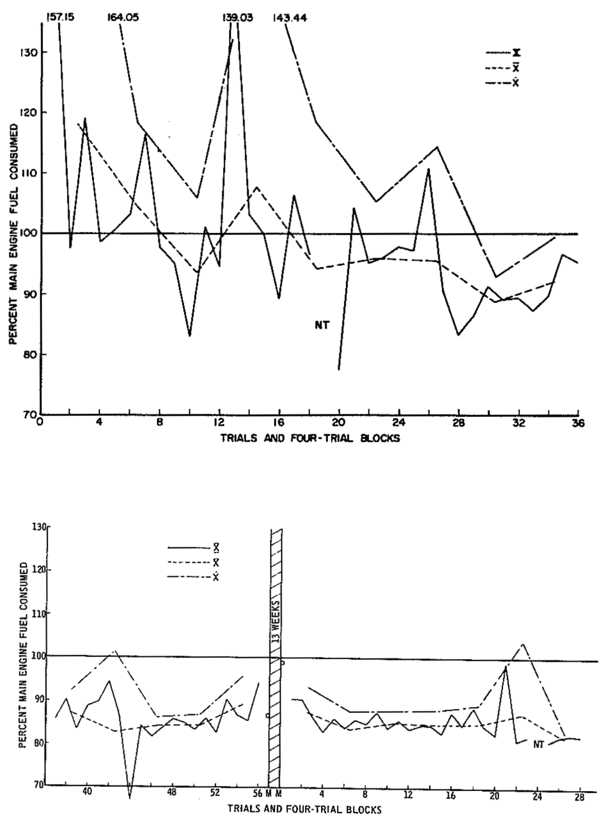

FIGURE 18.—Brake and hover: percent fuel consumed.

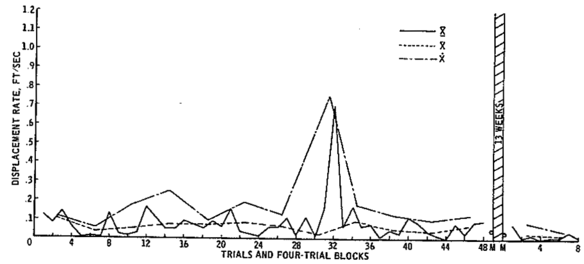

FIGURE 19.—Docking: displacement rate.

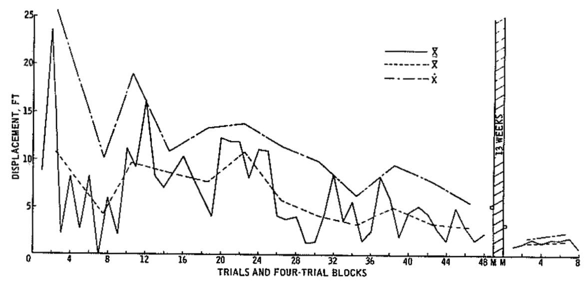

FIGURE 20.—Docking: displacement.

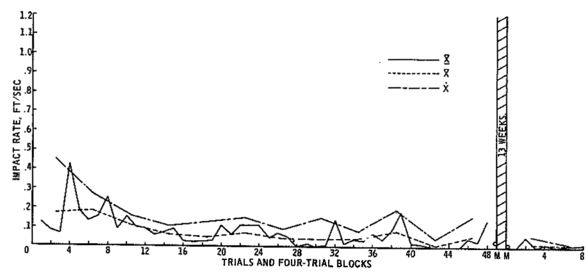

FIGURE 21.—Docking: impact rate.

or crew reliability). By superimposing mission performance criteria on these figures, it would be possible to state the likelihood that system limitations or reliability limits would be exceeded because of human performance.

CONCLUSIONS AND OBSERVATIONS

In planning for future space-flight systems, groundcrew and flightcrew reliability must be addressed, not just as an interesting aspect of human performance, but as an important system characteristic. Humans who perform in space-flight systems are scarce national resources and should be evaluated and assigned accordingly.

Objective data, not expert opinion, on flightcrew or groundcrew performance should be used as the basis for crew selection, mission mode decisions, and design concepts. Engineers do not usually select materials on the basis of individual judgment; instead, they rely on trade studies regarding materials that may meet the system need. We should do the same where decisions regarding human components or subsystems are concerned.

The Department of Defense now demands cost and effectiveness analyses, and steps are being taken at that level which will require analyses of human contribution to system reliability and system effectiveness. When this program reaches maturity, prediction of cost and effectiveness for the entire life cycle of DOD systems will include and require measures of human-performance reliability.

RECOMMENDATIONS

To this author's knowledge no studies are being conducted in manned space flight to follow up the studies of human-initiated failures and holds in missile systems. Furthermore, none are being conducted following the crew reliability for lunar landing study or the studies of pilot skill retention for longer period missions.

Therefore, it is appropriate that the space-flight community should develop data banks of flightcrew and groundcrew reliability for application to future generations of space-flight systems and verify and update these data by collection of performance data on crews in flight and on operational groundcrews at manned launches.

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Capsule Society—New Problems for Man in Space on Long-Duration Missions*

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In the last decade, the course of powered flight has advanced to new dimensions of altitude and speed, inaugurating the aerospace era. The major focus of this conference is on life support and human adaptation in space flight in this era, which will reach a significant goal in the Apollo-class mission. However, further goals lie ahead, in the solar system and beyond, and the next important transition will involve missions of such distance and duration that they may very well identify the beginning of the next era, that of space travel. This paper is concerned with new problems peculiar to space travel, in which emphasis will be placed not only on navigation and operation of the vehicles, as at present in the relatively short missions in Earth and lunar space, but also on living for significant periods, initially 1 or 2 yr, under unprecedented conditions of isolation and close confinement. Early missions to Mars and Venus may be attempted in the 1980's; it is not too early to give them serious consideration.

Our area of concern is human behavior, which involves the composition and organization of the crew, matters of individual adjustment and satisfaction, group coordination and effectiveness, management of reactions to stress, and a host of topics related to these fundamental issues. There are, of course, other problems, in engineering, celestial mechanics, life support, programing, and mission planning, that are beyond the scope of this discussion. The focus of this paper will be on problems of interpersonal interaction of crewmembers on board the long-duration spaceship.

Popular discussions of these problems have tended to exaggerate or distort the putative effects of isolation and confinement on sanity, self-control, and social adaptability. Such accounts too frequently represent rank speculation or uncritical acceptance of vague, anecdotal, or imagined happenings involving persons and situations remote from those to which they are generalized. Isolation and confinement are believed to be important sources of stress, but these are general terms and the scientific information on their role in the present problem is limited. At this time, it is necessary to identify the important questions, to find relevant data in the literature, to plan significant research where information is not available, and to get on with the research. An indication of the importance attributed to this problem is the recent creation by the National Academy of Sciences, at the request of NASA, of a committee on long-duration space missions.

A SOCIAL SYSTEM MODEL FOR CAPSULE SOCIETY

Because the crew of the spaceship is a small group and there has been extensive research on small-group behavior, it is natural that scientific investigators seeking data to extrapolate to the spacecrew would

*In the preparation of this report, data and files were used from NASA grant NGR 44-009-008.

turn to the small-group literature. There are also significant literatures on human behavior in shipwrecks and disasters, remote-duty stations, prisoner-of-war camps and other prisons, mental-hospital wards, ships, submarines, bomber crews, and still other human situations involving aspects of isolation and stress.

Our staff spent considerable time searching these literatures and put together a vast array of empirical information, much of which is interesting and important. As experience accumulated, it became increasingly apparent that the appropriateness of generalization depends on the degree of similarity between the situations used as sources of information and those to which the information is extended. Objections could readily be raised against the artificiality of many laboratory situations and their unsuitability, in regard to personnel, environment, technology, and other critical aspects of most of the natural and emergency situations surveyed, as a basis for studying spacecrew problems.

This line of thinking led to the examination of approaches to the analysis of situational similarity and, eventually, to realization of the holistic nature of each type of situation with respect to its defining variables, which is most appropriately described in system terms. Thus, attention turned to consideration of the spaceship situation as a miniature social system or microsociety and the various comparison situations as social systems having varying degrees of similarity to the spaceship, on the basis of profiles involving common variables. To perform a similarity analysis, it became necessary to construct a basic social system model and to conceptualize the system profiles for different prototype social systems, using this model. This was done, and the results of such a study were reported in *Aerospace Medicine* (ref. 1).

Description of the Model

For a more detailed summary of the social system model, I must refer you to the published paper. However, the major dimensions and results of the comparative study are shown in tables I and II.

This version of the social system model has 7 major dimensions and 56 descriptors. The major dimensions include:

I. Objectives and goals
II. Value systems
III. Personnel composition
IV. Organization
V. Technology
VI. Physical environment
VII. Temporal characteristics

An eighth dimension, social and cultural environment, has been included in a general formulation, but was omitted here, perhaps incorrectly, on the grounds that such factors would show minimum variation within a more or less homogeneous culture. Each of the 56 descriptors involves an important facet of a social system that can be ordered, to some extent, on continua conducive to comparative analysis.

The seven factors listed under "Objectives and goals" refer to aspects of structure rather than content, which is implied by other dimensions. The importance of these, as they have implications for behavior, can be appreciated when one compares an operational spacecrew with a simulated group in a laboratory. Factors such as those included here might readily explain why many real-life situations are difficult to simulate productively.

The "Value systems" of an organization and its members, described tentatively in descriptors 8 through 13, have fundamental importance with respect to policies concerning risks taken, attitudes toward goals, attitudes relating to authority, cooperation, trust, and other matters permeating every aspect of the program. It is known that organizations and groups vary on these factors. It is our belief that the specification of such factors is essential to the understanding of a social system and to strategies of management.

"Personnel composition" factors (14 through 26) are most familiar, perhaps because of widespread interest in selection. The inclusion of six dimensions, in addition to the personnel dimension, should be a reminder that there is more to crew effectiveness than selecting the "right" people. Nevertheless, it should be apparent that the seven dimensions overlap considerably; for example, values, personnel, and technology involve obvious interdependencies. For the purposes of the present discussion, however, it is advantageous to include the complete list, regardless of conceptual redundancy, to illustrate the range of relevant factors. The personnel composition of a social system includes experience, training, and social factors that are critical in distinguishing astronaut crews from other social groups with comparable intellectual and educational backgrounds.

"Organization" (factors 27 through 37) refers not only to the role structure and division of labor but also to the manner in which the social system is governed. Organizations vary in the extent to which roles are assigned, as compared to laissez faire emergence of roles, in degree of subdivision, lines of authority, degree of centralization of authority and decisionmaking, use of various sanctions, provision for succession, control of member behavior, participation by members in government, degree of stratification by rank, and numerous other respects. It is believed that the items listed afford a satisfactory description of this complex dimension.

"Technology" (factors 38 through 44) is crucial in distinguishing among various specialized task groups in contemporary society. The technological factors not only define many aspects of individual roles and role relations but also define goals, characteristics of site and environment, specific nature, complexity, characteristic operations, problems, and traditions (or customs) of the group. The technology not only emphasizes equipment distinctions, such as between jet and earlier piston aviation, with the attendant differences in speed, altitudes, schedules, and payload, but also emphasizes differences among personnel, customs, training, and other significant factors determined by the respective technologies.

"Physical environment" (factors 45 through 53) includes descriptors of the distinctive features of the task or situation and has implications both for the level of risk involved and the nature and magnitude of the various stresses to be encountered. Attention is paid in item 52 to the distinction between maneuvering situations, such as mountain-climbing expeditions, and static situations, such as remote radar outposts. The term "Embedded environmental stresses" (item 53) refers to stresses embedded in certain environmental situations, subject to failure of specific protective measures, such as the anoxic environment of space.

Finally, items 54 through 56 represent the important "Temporal" dimension. The first item (54) refers to the duration of the social system (organization or activity). The term "total" in item 55 is from the sociologist Goffman (ref. 2) who described a total group as one in which the individual remained continuously without the relief of discontinuities occasioned by leaving and reentering. A hospital ward or prison might be a total group situation in this sense. This item describes the percent of time, on a 24-hr basis, that the individual remains in the group. An effect of total environment, observed in hospital studies, is the magnification of interpersonal stresses generated by enforced close contacts. This can be mitigated to some extent by the provision of opportunities for solitude and privacy. The last item, "Remoteness of goals," is related to duration of the activity. In general, the more remote or distant the goals, the greater the need to sustain individual motivation over long periods of operation. Remoteness must interact with uncertainty (item 7), but the relationship is believed to be complex.

Application of This Model to the Long-Duration Spaceship

If all of the information needed were presently available to specify parameters of this social system model for optimal conditions in long-duration space missions, we would be further ahead than we are now. The suggestions presented below are, in most cases, difficult to document and, in all cases, are viewed as hypotheses subject to empirical verification rather than as pronouncements by an authority. However, the enumeration of some information concerning the 56 descriptors is useful to indicate significant research problems and to help assess our readiness to embark on long-duration missions. In view of the time limitations for this presentation, many of the points cannot be developed in detail.

Objectives and Goals

On the basis of general acquaintance with the views expressed by NASA officials, astronauts, and others, I expect, at present, that the objectives of space missions of long duration will be (1) formally prescribed in the elegant detail of past announcements, (2) mandatory, and (3) set by the duly constituted organizational directorate. Polarization (4), which refers to the degree to which group members work together for the achievement of a common goal, is expected to be high for the astronaut crew. However, there may be the possibility of strain in this aspect on missions involving both astronauts and scientists, should conflicts arise between mission goals and those of particular experiments. This possibility merits study in relation to control of conflict arousal and resolution.

On long-duration missions, major goals will be remote (5), presenting problems of motivational maintenance, which could be lessened to the extent that midcourse subgoals are meaningful. Criteria of success (6) should be reasonably clear, but the degree of uncertainty (7) of success will be lower initially than on later missions. Despite the phenomenally successful record of American manned space missions to date, they may all be characterized objectively as involving high risk. Superb planning, backup systems, careful preparation, and stepwise progress from simpler to more complex tasks have undoubtedly reduced subjective risk and increased participant confidence in the Mercury and Gemini programs. However, new programs, such as Apollo, MOL, and Mars, bring new problems of unknown and recognized hazards. Objective as well as subjective uncertainty may be expected to fluctuate as new programs and particular missions are scheduled. Uncertainty is both a source of stress and a source of motivation, and the appraisal of subjective or perceived uncertainty may be an important problem.

Value Systems

A formal study of organizational values within NASA would be rewarding, if only to clarify a number of points raised here concerning which we can only make inferences from official statements, speeches, and related sources. First, the operations of the American space program appear to fit generally into the traditions of American military aviation with respect to command structure (8), mission emphasis (9), respect for individual lives and cost-risk decisions (10). Second, our Government has, until now, given the space program a very high priority (11) and has placed extensive facilities at the disposal of the space agencies for effective support. Third, astronaut value systems have appeared to reflect the ideals and patterns of American military airmen—in character, mission motivation, attitudes toward family and personal goals, professional attitudes and identifications (12), as well as in the historic traditions of the American culture with respect to religious, moral, political, and social philosophy (13). The introduction of scientists into the astronaut ranks presents the possibility of another elite professional group with different professional attitude and identification patterns; this must be watched in relation to issues of status, competition, and possible conflict.

Personnel Composition

Crew composition for long-duration missions is determined principally by task requirements, but these are not completely rigid. Crews will be larger for landing missions involving exploration and scientific study than for flybys, but the numbers and specialties represented must be decided on the basis of all factors that may contribute to success. Astronaut selection, judged by most criteria of performance, has been rewardingly successful with reference to items 14 through 24 and for the aerospace operations that are familiar to all of us. Looking ahead to space travel, a number of questions requiring study can be raised. These are related to items in the outline.

Until now, the stereotype (18) of the astronaut has been a masculine, aggressive, technically skillful, military test pilot, a man of action, a risk taker when the odds are reasonable, a leader, decisionmaker, and self-confident individualist. This may be overdrawn, but it is necessary to make a point. The question should be raised whether the active, aggressive, take-charge characteristics are ideal for situations involving long-term confinement with a small group in a small space. This is not a simple question because it is not known how these aspects relate with the needed technical qualifications and risk-taking aspects. It is also a matter of degree; it is not necessarily either black or white. At present, my hypothesis would be that highly active, aggressive individuals would have greater difficulty than individuals adjusted to sedentary, passive conditions over the long haul in the Mars spaceship. It may be possible to condition the astronaut to the situation, however, rather than to look for pilots who do not have personality profiles commonly found among pilots.

A second personality question that appears highly important may be less troublesome because it involves characteristics that are probably distributed among the astronauts. This involves such considerations as great personal distance from others, autonomy, self-sufficiency, and reserve, at one pole, and group dependence, need to relate, and need to disclose personal feelings, at the other. I am not sure how best to conceptualize this complex variable; it seems to be related to need for privacy, need for personal-emotional support, need for personal space and possessions, and territoriality, and has implications for crew composition and organization and also cabin design. Some important beginnings in the study of these problems have been made by Gunderson and Nelson (ref. 3) of the Navy NP Research Unit at San Diego, Calif.; at Antarctic sites; and by Haythorn and Altman (ref. 4) at the Naval Medical Research Institute, in Bethesda, Md.

There are also many other questions regarding personality patterns in relation to the isolation and confinement issues. Indeed, considering the length of absence from family and other identification figures that may be required for training and the mission itself, the entire area of recruiting and selection for long-duration missions may require conscientious restudy.

Two issues must be raised on the matter of the presence of noncrew personnel (25). As discussed below, the problems of living and working harmoniously must be regarded as subject to the most serious strain in the environment of the long-duration spaceship. First, there is the question of the need for a noncrewmember whose function is primarily to provide assistance in the reduction of interpersonal difficulties. Such an individual would be a combination flight surgeon, chaplain, and recreation specialist; but he would need to be pretty well integrated himself, because there would be no specialist to look after him. I am not yet persuaded of the feasibility of this arrangement, even if it is logistically possible, but these functions will be required by some member or members of the party. It might be too limiting to assign them to the flight commander although, ideally, he would be the logical person for this role.

Second, I would like to make a further comment on the scientist-astronaut question, which has been mentioned. There is much information available on the effects of competitive subgroups in remote organizations. In my own research on air control and warning (AC&W) sites in Alaska (ref. 5), the tensions between mission (radar-operations) personnel at top camp and support (maintenance, supply, and administrative) personnel at bottom camp were a major morale problem. Even if it is formally planned that every member of the party will be an integral member of the crew and that none will go along as passengers, the terminology of astronaut, scientist, scientist-astronaut, and the status accorded various individuals on this basis, in the informal structure, may be a source of serious strain. I am not prepared to offer a solution at this time, but recommend that this problem be the subject of further study.

Although a number of respected colleagues have privately recommended that serious consideration be given to the inclusion of women (23), for a variety of reasons, in the complement of the spaceship, I do not propose to open this question inasmuch as I believe that it is probably not feasible, in the American culture, to do so, any more than to include women in the infantry.

One distinctive feature of the spacecrew, as compared with most remote military groups, including submarines, radar stations, and even aircrews, is that all members will be equivalent to officers (26), with less social distance among them than when the enlisted caste is also present. The close quarters and enforced intimacy will tend to reinforce the status leveling inherent in the structure and may have implications for the style of leadership and command best suited to this situation.

Organization

On the basis of present trends, it would undoubtedly be accurate to predict that the military organization model will be used in organizing the spacecrew. That is, the organization will be specified in detail and approved by authority when the crew is assigned (27); all positions and duties related to them will be specifically indicated (28); the commander will be the supreme and unquestioned authority on board (29 and 30); and there will be a definite, announced chain of command, which also provides for succession in the event of disability or death of the commander (31). In view of the present lack of definite knowledge concerning the incidence of conflict among crewmembers under flight conditions and problems of effective conflict resolution, a number of topflight social scientists with whom I have consulted believe that the uncritical acceptance of this model is premature, particularly with regard to the distribution of authority for decisionmaking among the crew. The traditional model puts all of the eggs in one basket, so to speak, and provides only the solution of unlawful or emergency action by subordinates in the event that the behavior of the commander should, for any reason, threaten the mission in the eyes of the crew. Whether this position is valid and whether a viable alternative is needed is a pressing question.

My personal view at this time favors centralized authority in an organization that maximizes the use of effective staffwork and participative management. Research on management styles seems to me to present overwhelming support for organizational procedures in which staff members share responsibility for planning and making important management decisions (refs. 6 and 7). These approaches have been observed to be most effective in remote military groups (ref. 5). At the same time, the dangers of divided command responsibility are great, particularly in situations requiring the intricate technical coordination characteristic of the spaceship. One of the strongest arguments in support of this position is a historical study by a member of our staff (ref. 8) of the development of authority in the British Navy during the age of the sail.

The spacecrew is, of course, only a small (although most important) part of the total mission force. It can be likened to the part of the iceberg that shows above the water surface. The extensive backup organization not only feeds information of technical, as well as personal, importance to crewmembers, but also plays an important role in decisionmaking and government of the crew activities. The implications of this superstructure (32) are profound for the professional men who are part of the larger organization and are reflected in the status system that exists, the low autonomy of the captain with regard to approved goals (33), disciplinary methods (35), and the value system that permeates the organization.

As shown in table I, the crew size expected is between 8 and 12 (34), and it is expected that status in the crew will be assigned so that it is congruent with rank in the astronaut system.

TABLE I.—*Comparison of Social System Profiles of 11 System Patterns With That of the Extended-Duration Spaceship*

[Ref. 1]

System characteristics	Comparison system										
	1	2	3	4	5	6	7	8	9	10	11
I. Objectives and goals:											
1. Formally prescribed	1	2	2	2	2	2	2	0	1	1	1
2. Mandatory	1	2	2	2	2	1	1	0	1	1	1
3. Formal authority	1	2	2	2	2	1	1	0	1	1	1
4. Polarization	2	1	1	2	1	2	1	0	0	0	0
5. Remoteness of goals	1	2	2	0	2	1	1	0	2	0	0
6. Success criteria	2	2	1	2	0	2	1	0	2	1	1
7. Success uncertainty	2	2	2	2	1	2	1	2	2	0	0
II. Value systems:											
8. Obedience to command	1	2	2	2	2	1	1	0	1	0	0
9. Mission emphasis	1	2	2	2	2	1	1	0	0	0	0
10. Respect for individual lives	2	2	2	2	2	0	1	0	1	0	1
11. High national priority	0	1	1	1	1	0	0	0	0	0	0
12. Military tradition in personal attitudes	0	2	2	1	1	0	0	0	2	0	0
13. Acceptance of American way of life	0	2	2	1	1	0	0	0	0	0	0
III. Personnel composition:											
14. Intellectual	1	1	0	0	0	0	0	0	0	0	0
15. Educational level	1	1	0	0	0	0	0	0	0	0	0
16. Extent of relevant training	1	1	1	0	1	1	1	0	1	0	0
17. Extent of relevant experience	2	1	1	0	0	1	1	0	0	1	0
18. Personality selectivity	1	1	0	1	0	0	0	0	0	0	0
19. Moral selectivity	1	1	0	1	1	0	0	0	0	0	0
20. Physical selectivity	1	1	1	1	1	1	0	0	1	0	0
21. Possession of requisite skills	2	1	1	1	1	2	1	0	0	0	0
22. Motivation to participate	2	1	0	0	0	1	0	0	0	0	0
23. Sex of participants	2	2	2	2	2	2	0	0	2	0	0
24. Age range	1	1	0	0	0	2	0	0	0	0	0
25. Presence of noncrew personnel	2	1	0	0	0	0	0	0	0	0	0
26. Rank distribution (all officers)	1	0	0	0	0	0	0	0	0	0	0
IV. Organization:											
27. Formal structure	1	2	2	2	2	1	1	0	1	0	0
28. Prescribed roles	2	2	2	2	2	1	1	0	1	0	0
29. Command structure	1	2	2	2	2	1	0	0	1	0	0
30. Centralized authority	1	2	2	2	2	1	0	0	0	0	0
31. Chain of command with provision for succession	1	2	2	2	2	0	0	0	1	0	0
32. Extensive backup organization	1	2	2	2	2	0	0	0	1	0	0
33. Low autonomy re goals	1	2	2	2	2	0	1	0	0	0	0
34. Group size (8–12)	0	0	0	0	0	0	0	0	0	0	0
35. Prescribed discipline	1	2	2	2	2	1	0	0	1	2	1
36. Low prescribed social distance among crew	2	0	0	0	2	0	0	0	0	0	0
37. Congruency of rank and status	2	2	1	1	1	0	0	0	0	0	0

TABLE I.—*Comparison of Social System Profiles of 11 System Patterns With That of the Extended-Duration Spaceship*—Continued

System characteristics	Comparison system										
	1	2	3	4	5	6	7	8	9	10	11
V. Technology:											
38. High technologic complexity	1	2	1	1	1	0	0	0	0	0	0
39. Relation to aviation tradition	0	1	1	1	2	0	0	0	0	0	0
40. Use of simulators and other technical training devices	0	1	1	1	1	0	0	0	0	0	0
41. Extensive preparation for missions	2	1	1	1	0	1	0	0	0	0	0
42. Use of technical language in execution	2	2	1	1	1	1	0	0	0	0	0
43. Physical preconditioning	1	1	1	1	0	1	0	0	0	0	0
44. Scientific principles involved	1	1	1	1	1	0	0	0	0	0	0
VI. Physical environment:											
45. Required physiological protection and life support	1	2	0	0	0	0	0	0	0	0	0
46. Extreme remoteness from base	1	1	1	1	1	0	0	1	2	1	1
47. Presence of unknown environmental hazards	2	1	1	1	0	0	0	2	2	0	1
48. Extreme confinement in capsule	0	1	0	0	1	0	0	0	2	2	2
49. High endurance demands	2	1	0	0	0	1	0	2	2	0	0
50. Reduced communication	1	1	1	1	1	0	0	2	2	2	2
51. Social isolation											
52. Maneuvering situation	2	1	1	1	0	1	0	0	0	0	0
53. Embedded environmental stresses	2	2	1	1	1	0	0	0	2	0	1
VIII. Temporal characteristics:											
54. Long duration of exposure	1	1	1	1	1	0	0	0	2	2	2
55. Total environmental situation	2	2	0	0	2	0	0	0	2	2	2
56. Remoteness of goals	1	1	1	1	1	1	0	0	2	2	2

Technology

The technology of the space program is new, although it follows in the aerospace tradition. Among the distinctive characteristics of the astronaut program have been intensive training in all aspects of missions and in anticipation of all conceivable emergencies as a means of insuring reliability of performance; high level of training, experience, and skill required of crewmembers; glamour associated with astronaut status, which may have diminished somewhat since the days when they were only seven, but is still exalted throughout the Nation; and high risk associated with the American astronaut role. In looking ahead to the 1980 decade, I am strongly persuaded that every effort should be made to anticipate technological changes, in communication, food preparation and preservation, life support methods, and in other significant aspects of life on the spaceship, as we plan the long-duration missions. Space technology has already created new jobs, new vocabulary, and technical jargon, and is one of the contemporary frontiers of human culture. It will be important to visualize the problems confronting astronauts 20 yr from now in terms of the culture of their times.

Physical Environment

Assuming a crew of 10, and a 500-day mission, an educated guess concerning cabin space available for work, rest, recreation, and other crew needs is between 150 ft^3 and around 900 ft^3 per man. The crew will live in an environment unprecedented in human experience, even in the aerospace era. The integrity of the life support system and provisions for nutrition, climate, rest, health, and other creature needs will be ever present. For most of their voyage they will be weightless. The more remote they become, in relation to Earth, the more insistent will be their present circumstances and the less sympathy will they have for authorities on Earth who try to govern their activities. At the same time, feelings of separation and concerns about families and other significant objects at home will mount, even if reasonably good communications are available. Frustration over grieving and unpleasant information may be a major problem if the information is given and may be, perhaps, a worse problem if it is withheld. If left up to the ship captain, the effects may depend on his actions and may not necessarily be optimally controlled.

The extreme degree of confinement is greatly feared by many who have studied the problem and has been written off by others, on the basis of available research, as, perhaps, an unfortunate exaggeration. Actually, we have no research at this time that is adequate to project to the type of social system described here, with the pattern of organization, personnel, technological setting, goals, and rewards involved. Assuming that qualified volunteers can be obtained, which I consider quite reasonable, I am inclined to take a positive view of the possibility of a successful mission under the conditions of confinement implied by the space allotments indicated. Although cramped in terms of contemporary standards, these conditions do not present insurmountable problems if other factors, related to health, recreation, information, nutrition, compatibility, privacy, authority, management, and the like, are adequately programed. What we desperately need is imaginative research for guidelines in such programing. Nevertheless, every time I have read about a mountain-climbing expedition, a voyage of exploration, a Mindszenty, a Slocum, a Chichester, a Shepard, a Glenn, a Carpenter, a White, and others who have braved new heights of human challenge of the unknown, I have been impressed with the fact that the limits of human endurance are still remote.

Temporal Characteristics

The range of the missions in which we are interested initially is between 100 and 600 days—it is assumed that the upper limit is finite. Depending on the amount of time required in preparation, however, the actual time of absence from family and society might be longer. This obviously could be the source of a serious problem and, understandably, there is much interest in the accomplishment of crew training and preparation in the briefest overall time and also in phases separated by periods away from the capsule (54).

The spaceship is a total environment, in the sense described earlier, and subject to the difficulties mentioned. Because of this, I would think that both research and training simulations should incorporate the 24-hr continuous aspect rather than avoid it for the convenience of experimenters and crewmembers. At the same time, the inconvenience implied is a reality factor and some compromises may be forced. Item 56 is identical in statement to item 5, but in the later section it is a reminder that on extremely long-duration missions the need for meaningful and realistic short-term goals may surpass other problems in importance, if not appropriately programed.

Comparison of the Spaceship System Profile With 11 Other Social Systems

Tables I and II involve a comparison of this writer's concept of the social-system profile for the long-duration spaceship with those of 11 other social systems selected as possible sources of relevant information on the basis of isolation and confinement aspects, reported similarities, or a promising literature. The tables are based on similarity ratings for each item, of 2 (high similarity), 1 (moderate similarity), and 0 (no similarity). In this exploratory study, all of the ratings were made by me on the basis of experience, literature review, and consultation with informed observers. These tables have been reviewed by a number of experts, representing different areas; and

TABLE II.—*Analysis of System Similarities by Descriptive Category*

[Ref. 1]

Comparison systems	System description category						
	Objectives and goals	Value systems	Personnel composition	Organization	Technology	Physical environment	Temporal characteristics
2. Submarines	2	2	1	2	1	1	1
1. Exploration parties	2	1	1	1	1	1	1
3. Naval ships	2	2	0	2	1	1	0
4. Bomber crews	2	2	1	2	1	1	0
5. Remote-duty stations	2	2	0	2	1	0	1
9. POW situations	1	1	0	0	0	2	2
6. Professional athletic teams	2	0	1	0	0	0	0
11. Mental hospital wards	0	0	0	0	0	1	2
10. Prison society	0	0	0	0	0	1	2
7. Industrial work groups	1	0	0	0	0	0	0
8. Shipwrecks and disasters	0	0	0	0	0	1	0

The numbers 2, 1, and 0 are used here to indicate similarity on the following basis: 2—for matching over 70 percent of items in the category; 1—for matching 31 to 70 percent; and 0—for matching less than 30 percent.

agreement with the reported data has been high. Actually, the ratings and specific scores were of less interest than the gross comparisons made.

Table II indicates that the highest similarity rating, submarines, was only 79 out of possible maximum of 112 (about 70 percent). Exploration parties are second, with a score of 68 (about 61 percent). Although these are highest in similarity to the spaceship, the matching is low, at best, which should serve as a caution in literature studies.

Table III is interesting in that it indicates areas of similarity and dissimilarity to the spaceship for each of the 11 comparison systems, by major system dimension. Prisoner-of-war situations, mental hospital wards, and prison groups are very dissimilar to the spaceship, but are higher than some of the other groups in similarity of physical environment and temporal characteristics. In terms of overall closeness of fit, it was concluded that literature studies based on submarines, exploration parties, naval ships, bomber crews, and remote-duty stations (with scores of 79 to 59) might be most profitable, while those based on industrial work groups, and shipwrecks and disaster situations, which are frequently cited, as well as laboratory situations, which were not even included, would be least valuable to the space-oriented social scientist. This is, of course, a gross conclusion subject to many restrictions, but may still be worth-

TABLE III.—*Similarity Ranks and Similarity Scores for 11 Comparison Social Systems*

[Ref. 1]

Systems	Similarity rank	Similarity score
2. Submarines	1	79
1. Exploration parties	2	68
3. Naval ships	3	61
4. Bomber crews	4	60
5. Remote-duty stations	5	59
9. POW situations	6	39
6. Professional athletic teams	7	37
11. Mental hospital wards	8	23
10. Prison society	9	20
7. Industrial work groups	10	16
8. Shipwrecks and disasters	11	11

while as a planning factor for bibliographic work and research planning.

One example of how this information has already been useful involves the study of authority in the British Royal Navy in the age of the sail. Our interpretation of the similarity results concerning naval ships was that similarity would probably be higher in relation to isolation and cramped quarters during the age of the sail, before wireless communication, air conditioning, motors, refrigeration, and modern technology. We were interested in the question of centralization of authority and tried to find an explanation of the traditional extreme power concentrated in the position of sea captain. I had earlier (ref. 9) hypothesized that this was a natural consequence of the need to compensate, when a ship sailed out of sight of land (a situation, in the days of Columbus and Drake, as isolated for them as the departure from the gravisphere of the Earth will be for the Mars mariners of 1980's), for the withdrawal of the forces of law and order on land; and Ronald Day, a naval historian, agreed. However, after completing a very fine study (ref. 8), his results indicated quite compellingly that the shore-hugging hypothesis was naive and that centralization of authority was related to the need for continual coordination and split-second control of the ship in an unfriendly environment, the sea; the disaffection of crews recruited mainly by impressment; and poor living conditions below decks, malnutrition, unreasonable work requirements, and frequently inhumane treatment by superiors. We have concluded that centralized authority is strongly supported by the first factor, need for coordination and control of highly technical operations, but the problem in the sailing navy was aggravated by the personnel policies employed by the British during that period. In fact, these policies also explained most of the causes of mutiny, which was commonplace until more humane living and working conditions were generally established and has been virtually unknown since.

This excursion into historical-psychological research has shown that beliefs, such as the shore-hugging hypothesis, that appear logical and reasonable may be 180° from the truth and that seeking verification is of paramount importance. As I said earlier, planning for the unprecedented adventure of space travel demands a supreme degree of originality and creativity in identification of critical research problems and in execution.

RESEARCH PROBLEMS

In the final section of this paper we will examine what appear to be some significant research problems and some significant problems related to the design and conduct of research on these problems. My thinking about these has been aided by the 2-day "Conference on Social-Behavioral Problems of Long-Duration Space Missions" (S. B. Sells, ed.; Sept. 1967) held on the Texas Christian University campus on December 2 and 3, 1966, with about 20 of the most significant workers in this general area. In view of time limitations, I propose to enumerate a somewhat lengthy list of topics, but not to discuss them in detail.

The Social System Model

The use of system concepts is generally regarded as valuable, but the model as presented here is static, and further development, reflecting transition from dimensions that have served the taxonomic functions of similarity analysis to concern with cyclical aspects, changing states, and covariation of elements in different phases, should be a high-priority task. It has been suggested that this should begin with formulation of genotypic principles and propositions of functioning social systems.

Research Design and Methodology

We have already mentioned the problem of selecting literature sources. Although wide-ranging bibliographic studies are appropriate in the development of genotypic propositions concerning social systems, the cautions mentioned as a result of the similarity analysis are appropriate, particularly on the matter of generalizing empirical observations uncritically. To the extent possible, the design of effective empirical studies should take into account the most realistic social system formulation that can be developed now. Particular attention must be given to simulation of critical aspects of isolation, confinement, and realistic task performance and to the use of subjects whose status and involvement in the research tasks are reasonably appropriate.

Astronaut Selection and Crew Composition

A number of important problems relating to selection have been raised. It also appears important to devote serious attention to composing crews whose possibilities for compatibility in capsule society are maximum. In this connection, issues of ethnic background, age, and other factors that may not be significant in individual selection may assume new significance. The astronaut-scientist issue has been mentioned.

Authority

The authority structure, including the authority of the commander in areas of living as well as work; the development of a set of ship's rules, for problem solving, conflict resolution, and as a backup when decision-making guides are needed; and the relation of authority on board with that on the ground require extensive study.

Stress

Despite concern with stress by many disciplines for many years, the state of knowledge does not permit an "off-the-shelf" approach to predicting and programing for the stresses expected in space travel. Current studies must be aware of physiological, social, and interpersonal sources of stress, related not only to parameters of the physical environment and potential dangers but also to separation, frustration, sensitivity to personal habits of associates, deprivation, boredom, inactivity, and health problems. Analysis of social-system functions and interviews with astronauts and other knowledgeable persons may be valuable in identifying sources of stress and suggesting strategies for mitigation. Creative concern with the design of interior space to maximize privacy; with the invention of games; with efficient storage of reading materials, movies, and other recreational devices; with the programing of work tasks and schedules; and with the provision for personal information needs must receive a high priority.

Training and Preparation

Is it necessary to "dry-run" a crew for 500 days to determine whether it can function for 500 days, and how realistic should the preparation be? There is much agreement that the preparation time can be cut, but the entire problem of how to achieve an adequate and effective simulation in preparation for a successful mission merits further critical study.

Motivation

How can motivation be sustained over the entire mission? This depends on task structure, role interdependence (mutual reward and reinforcement), and the relation of individual costs and rewards to mission goals.

Privacy, Personal Possessions, Personal Space, and Considerations of Territoriality

More information is required on human needs and, particularly, astronaut needs for personal privacy and related behavioral issues. Some research has shown that privacy and personal territory may be significant in socialized management of hostility and incompatibility, but in the spaceship the control of hostility and incompatibility is essential while the cost of the alternative would be prohibitive. It is necessary not only to investigate this hypothesis but also to ask whether privacy needs can be reduced by the composition of the crew; the reduction of sources of stress, hostility, and incompatibility; by the substitution of rewards; and by other approaches.

Conflict Arousal and Resolution

This topic overlaps with others that have been mentioned already, but deserves further systematic study in the context of the spaceship social system. In addition to the general system evaluation discussed earlier, the advisability of including a flight surgeon-chaplain as a noncrewmember with primary responsibility in this area must be evaluated.

Communication

Should crewmembers receive personal information of a stressful nature in flight or should such information be censored? The alternatives are both undesirable. How can crewmembers be prepared to receive and adjust to information concerning death of loved ones, notice of divorce, or similarly stressful events? The entire question of information in and out, in terms of logistics, psychological effects, and methods of control, is another critical issue.

These are only a few of the important research questions that must be faced, and the time advantage is rapidly shrinking. It is fortunate that the new national Academy of Sciences' committee on long-duration missions will have a major concern with the analysis of these research issues and that the weight of the National Academy will be marshaled to give further impetus to the important work in the area that I have surveyed, in preparation for further advances in the era of space travel.

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The Visual Realm in Space Flight

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Man's presence on extended space missions is dictated by his unique effectiveness for coping with unusual situations. For his size, mass, and energy requirements, it is probable that he can handle a broader range of eventualities more effectively than any automatic equipment that might be designed. Critical elements in his performance are his sensory input channels. The most important of these is probably vision. Visual problems that may be encountered in space flight are reviewed. The unique characteristics of the visual realm on space missions are discussed, from the instrument arrays and other aspects of space vehicle interiors to the extravehicular situations, from rendezvous and docking with other vehicles through landing on extraterrestrial bodies and exploration of their surfaces. The significant characteristics of the human visual system, which will be essentially the same in space as on the Earth's surface, are reviewed in relation to the problems that may be encountered.

INTRODUCTION

Man has an important role in the exploration of space. It is probable that for his size, mass, and energy requirement, he can handle a broader range of situations more effectively and with more flexibility than any automatic equipment that might be designed. He will be able to make decisions in relatively unique situations, many of which are beyond the ability of even the most elaborately programed automatic devices. He will not be operating in his own familiar terrestrial environment, however. His sensory input channels must, therefore, be evaluated in relation to the new situations that he may encounter and in relation to the environmental differences that may be anticipated. It is reasonable to suppose that limitations that exist in any sensory dimension on Earth will also exist in space. It is also possible that additional limitations may be imposed.

I will concern myself in this presentation exclusively with the visual dimension. I would like first to review some of the characteristics of the visual sensing system and comment on their significance for man on a space mission. I will then review some of the unique conditions that may be encountered in space flight, particularly those that can be expected to influence vision. Next, some of the visual functions that may be of particular importance will be discussed. Finally, some comments will be made on the nature of the visual environment in space.

THE NATURE OF THE VISUAL SYSTEM

The human eye is an amazingly sensitive device. Light rays that enter the cornea and pass through the various intraocular media excite receptors on the retina. Light must actually pass through a number of layers of nerve fibers and nerve cells as well as some vascular tissue before reaching the receptors. At the receptor layer, it has been demonstrated that only a very few, perhaps four or five, quanta of light energy are necessary for the conscious detection of light (ref. 1). The response varies with wavelength, and the nature of the spectral re-

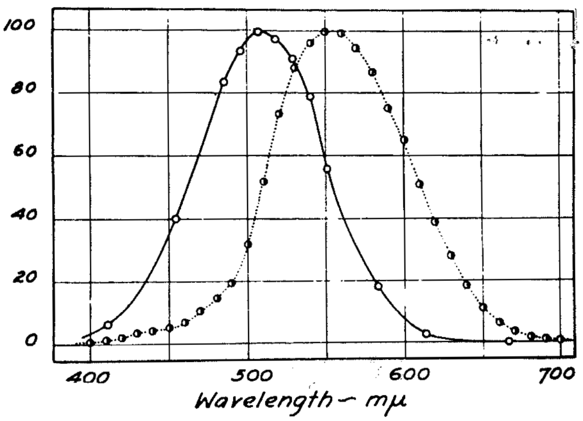

FIGURE 1.—Spectral sensitivity of the human eye at high (photopic) luminances (dotted curve) and low (scotopic) luminances (solid curve). Each curve is arbitrarily set at the same maximum amplitude value.

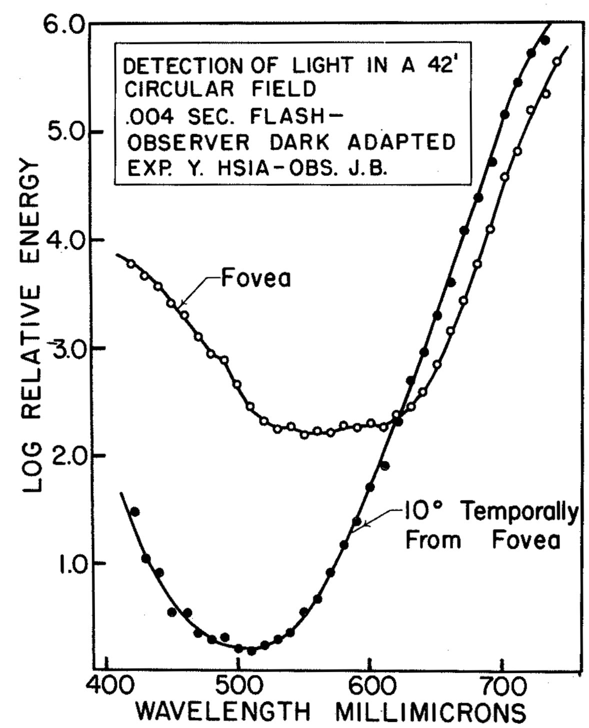

FIGURE 2.—Relative energy requirements at threshold for a stimulus presented in the foveal center of the retina (photopic) and in the periphery of the dark adapted eye (scotopic) (ref. 2).

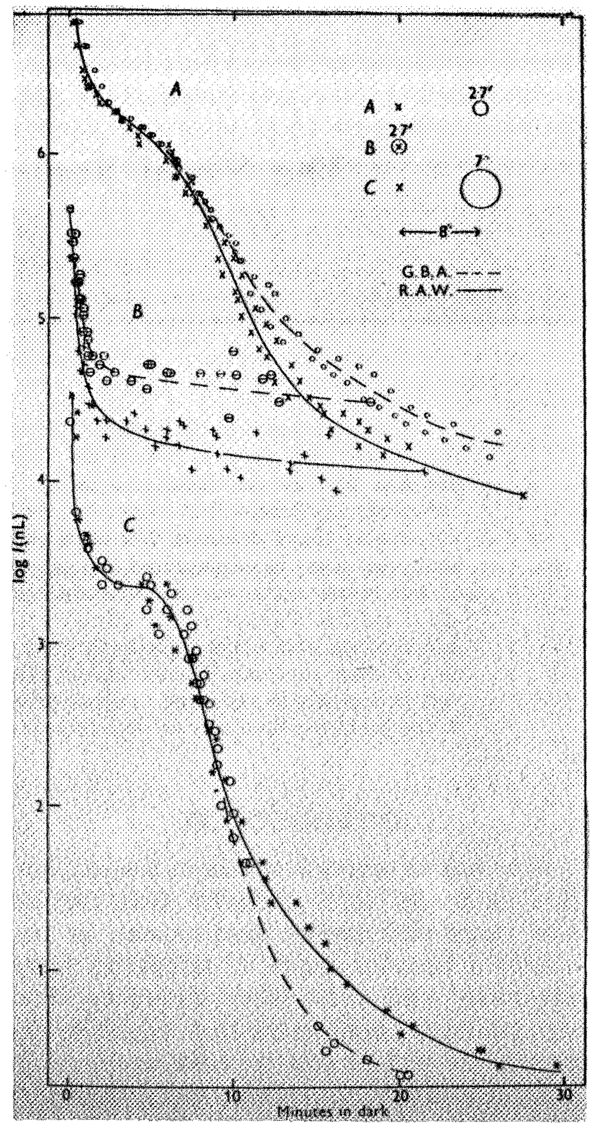

FIGURE 3.—Luminance threshold as a function of time in the dark for each of two observers (GBA and RAW) and three conditions of test. *A*: 2.7' field displaced 8° from fovea; *B*: 2.7' field centered on the fovea; *C*: 7° field displaced 8° from fovea (ref. 4).

sponse varies with the condition of adaptation of the eye (ref. 1). This is illustrated in figure 1. There will be ample illumination, at least at times, on the Moon and on Mars for visual observation. The curves presented in figure 1 are slightly misleading in that they imply equivalent maximum sensitivity for both the daylight photopic process and the low-luminance scoptopic process. Actually, the eye becomes more sensitive to light as it adapts to the lower luminance levels. There is an accompanying shift in peak sensitivity to shorter wavelength. The relation is better illustrated in figure 2 where relative energy required for stimulation is shown for both photopic and scotopic vision (ref. 2).

The transition from photopic to scotopic vision may present problems for the space traveler. Although the eye can adapt to an increase in illumination level within its functional range fairly quickly, a relatively long time is required for adaptation to very low luminance levels. Adaptation to a higher level requires no more than 3 to 5 min. Adaptation to low luminances may require 30 min or more (ref. 3). The dark adaptation process is illustrated in figure 3 (ref. 4). An important characteristic of the data presented in figure 3 is that the range of change in sensitivity shows an important relation to the area of the test spot with which sensitivity is measured. An experiment demonstrates that the tremendous gain, as much as 1 million times or more, in visual sensitivity with dark adaptation cannot be explained purely in terms of an increase in the concentration of photosensitive material during dark adaptation. The gain in sensitivity is also a result of a change in neural organization. The eye becomes able to summate energy over a larger area. This is illustrated by measurements of the receptive field of a single fiber of the optic nerve (ref. 5). In the light-adapted eye, a fairly large region of the retina, when stimulated, influences activity in a single fiber (fig. 4). The influence may be either excitation or inhibition. In a central area, light stimulation may cause increased activity in the fiber; in an annular region around this central region, light stimulation may inhibit activity in the fiber. With dark adaptation, the excitatory region is enlarged and the inhibitory region drops out. Accompanying this change there appears to be an increased ability of the retina to summate over its area the stimulating effect of light energy that reaches the retina. A corollary of the increasing sensitivity with dark adaptation is a gross reduction in spatial resolution capacity at low luminances. Increased sensitivity afforded by increased spatial summation is accompanied by decreased spatial resolution capacity (ref. 6).

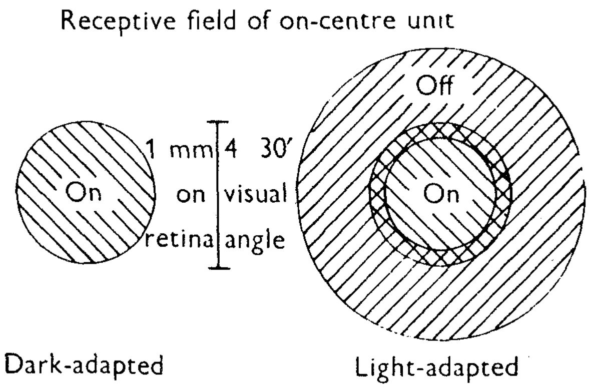

FIGURE 4.—Schematic illustration of the receptive field on the retina for a single neural unit in both the light-adapted and the dark-adapted state (ref. 5).

Spatial resolution will be an important function for the space traveler. It is important to know what the limiting resolution of the eye is and to know how this varies with changing conditions. In general, spatial resolution will increase with increasing luminance and with increasing contrast between objects to be discriminated and their backgrounds (refs. 6 and 7). The relation between visual acuity and luminance is illustrated in figure 5. Visual acuity is defined as the reciprocal of the minimum resolvable visual angle in minutes of arc. It is important to note that there are various kinds of visual acuity, however. Visual acuity for resolution of the minimum separation between two points or elements of detail in a visual array is not nearly as fine as visual acuity for the resolution of a single dark-line element against a bright field (ref. 6). It is meaningless to speak of visual acuity for a point source of light because its size is not a limiting factor. Stars are essentially point sources of light, but are detectable when their energy level is sufficient to stimulate the retina. The retinal image of a point source will always have a finite size by reason of the optical properties of the eye (ref. 8). Visual acuity for elements of

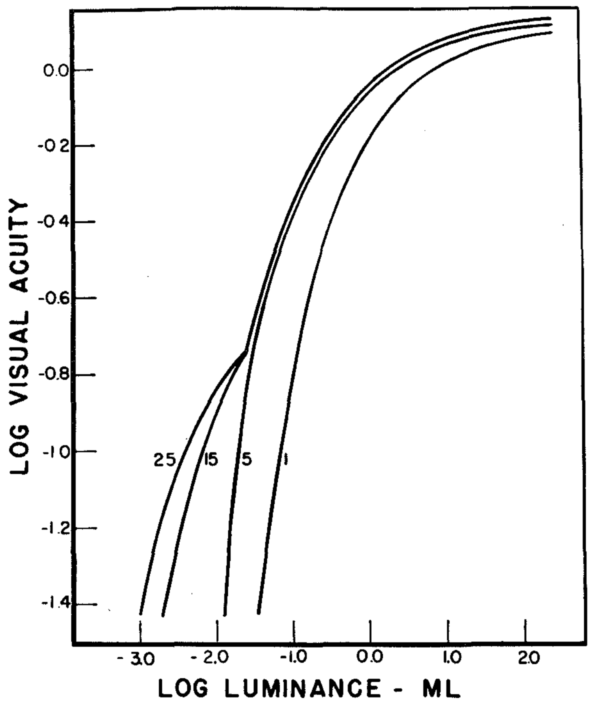

FIGURE 5.—Visual acuity as a function of luminance for each of four durations of dark adaptation. With sufficient dark adaptation, an early branch that represents the scotopic process is evident (ref. 7).

detail in a complex visual scene is of the order of 1; that is, separations between elements of detail that subtend a visual angle of 1 min of arc can be discriminated. A dark line against a bright field can be discriminated when its thickness subtends less than ½ sec of arc at the eye (ref. 6). Dark spots against a light background as small as 15 to 30 sec of arc can be detected. The length of a dimension in feet that will subtend 1 min of arc at the eye of an observer is equal to 1½ times the distance of the observer in miles (ref. 9). Thus, at an elevation of 100 miles over the surface of the Earth or the Moon, minimum resolvable elements of detail in a complex pattern must be 150 ft in length. On the other hand, a single dark line of less than 2 ft in width may be discriminated at the same distance if it is sufficiently long and affords sufficient contrast with its background. Astronauts who have participated in orbital flights have observed that tentative identification of many objects on the ground can be made on the basis of what the astronaut knows to be there or on the basis of inference (ref. 10). For example, a discontinuity along the extent of a clearly visible river may quite correctly be interpreted as a bridge, although out of context its identification would be impossible.

The character of the receptive field in the light-adapted eye is an important factor in spatial resolution. The nature of its function is illustrated in figure 6 (ref. 11). Stimulation of the center of its receptive field on the retina gives rise to much activity. Stimulation in an annular ring around its center suppresses activity. Stimulation of a larger area tends to increase activity, but the change in relation to the background level may be very slight. This combination of excitation and inhibition dependent upon spatial region stimulated provides a basis for peaking of contours in the retinal image. It is thus useful for the enhancement of visual detail. This is illustrated in figure 7. Vertical stripes of increasing darkness appear nonuniform from left to right. The edge of a given stripe near its adjacent dark stripe appears lighter than its opposite edge. The fact that this is a property of the eye may be illustrated by covering the adjacent areas on both sides of part of one of the stripes with dark paper. The apparent gradient is eliminated (ref. 12).

If our attention is transferred from single cells and fibers in the region of the retina

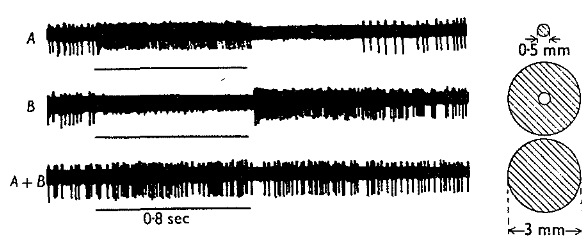

FIGURE 6.—Records of neural response for a single unit in the visual system of the cat for each of three conditions of stimulation (ref. 11).

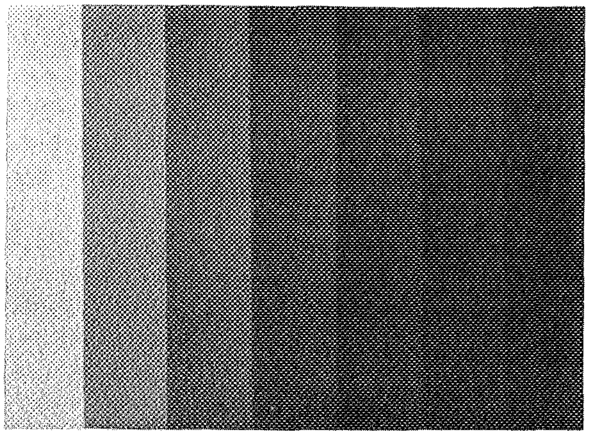

FIGURE 7.—Pattern of stripes of increasing darkness. The lightness of each individual stripe is uniform across its width.

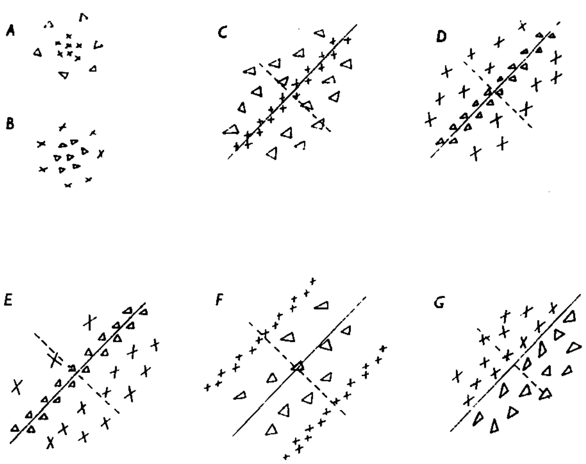

FIGURE 8.—Patterns of excitation (x) and inhibition (Δ) in the retinal receptive fields of nerve cells in the lateral geniculate body (A and B) and the visual cortex (C to G) of the cat (ref. 13).

to single cells in the visual cortex, we find a change in the nature of retinal stimulation that is optimum for excitation and inhibition of these cortical cells. Optimum retinal stimulation is found to be organized along line elements for excitation of many cortical cells. This is illustrated in figure 8 from an experiment reported by Hubel and Wiesel (ref. 13). Some cells respond to stimulation along a line of specific orientation in a certain part of the retina. Other cells appear to be sensitive to orientation of a line, but less dependent upon the specific position of the line on the retina. This is illustrated in figure 9, again from the work of Hubel and Wiesel (ref. 13). A possible effect of this kind of organization within the visual system is illustrated by figure 10. If one fixes the center of the radial line pattern for a period of approximately 10 sec and then observes a completely plain white field, an afterimage pattern of annular rings is seen. It is as if the cortical cells that mediate discrimination of the radial line pattern have been "fatigued," and stimulation by a plain field permits the accentuated response of other cells responsive to orthogonal stimulation. The result is a series of concentric circles.

The temporal resolution capacity of the eye is of concern in relation to the ability to perceive information in a rapidly changing visual field. This may be of practical impor-

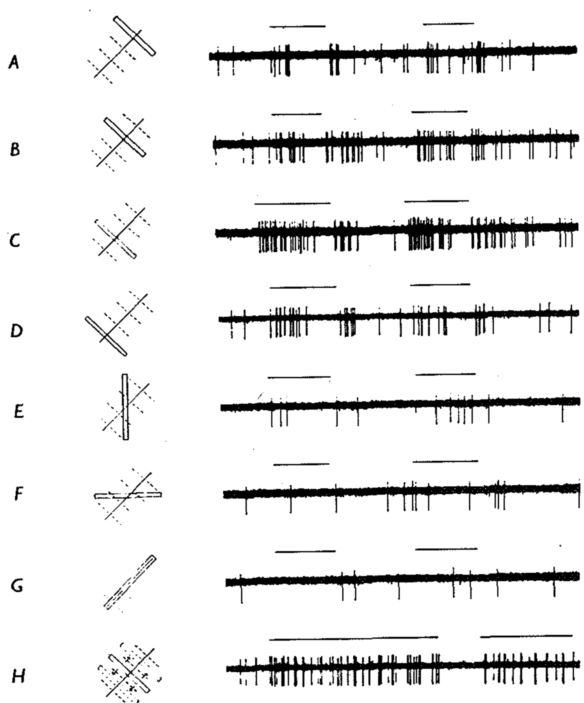

FIGURE 9.—Neural activity of cortical cells in response to stimulation of the eye with rectangular light lines. Cell response is critically dependent on line orientation but not upon precise line position (ref. 13).

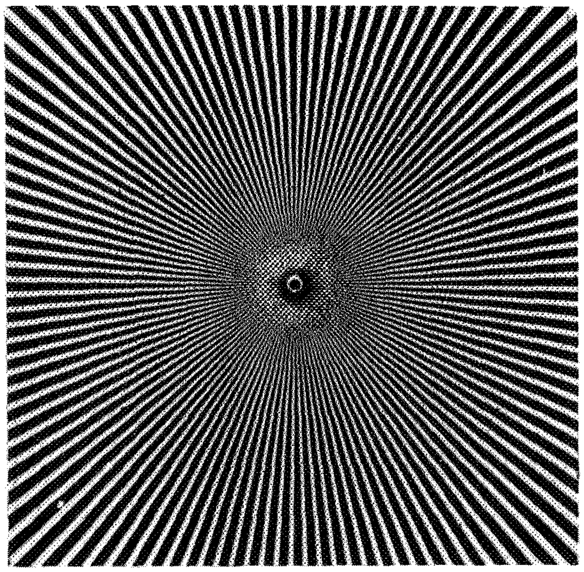

FIGURE 10.—Radial line adaptation pattern.

tance in the relatively simple case where information is transmitted via a flashing light. Temporal response characteristics of the human eye are illustrated in figure 11 (ref. 14). It is evident that the response extends to higher frequency at higher luminance levels. The ability of the retina to summate energy in time as well as over area changes with illumination and level of adaptation, although the relation is complex (ref. 15). Part of the increased sensitivity of the dark-adapted eye is attributable to increased temporal summation capacity. This is, of course, accompanied by a decrease in temporal resolution.

The ability to perceive colors depends upon the presence of three photosensitive substances within the retina having different spectral absorption characteristics (ref. 16). Color discrimination also depends on some relatively elaborate data processing within the nervous system (ref. 17). It has been demonstrated that certain cells of the retina central to the photoreceptors themselves respond differently dependent upon the wavelength of stimulation. Some wavelengths may excite these cells and others may inhibit their response. (See fig. 12 (ref. 18).) In figure 13 are shown the records of a cell that is inhibited by a green light and excited by a red light (ref. 19). There is a burst of activity from this cell when the green light is extinguished. It is as if extinction of the green light has the same effect on the cell as illumination of the red light. Response of the cell is greatest when the eye is stimulated by a red light, immediately following illumination by a green light. It can be demonstrated that the extinction of a green light may give rise to sensations similar to those that occur when the eye is stimulated by the red light. If one stares fixedly at the center of a pattern consisting of a red and a green rectangle for approximately 10 sec and then observes a completely uniform white field, the region in which the green pattern was observed will appear reddish and the region in which the red pattern was observed will appear greenish. A similar effect may be ob-

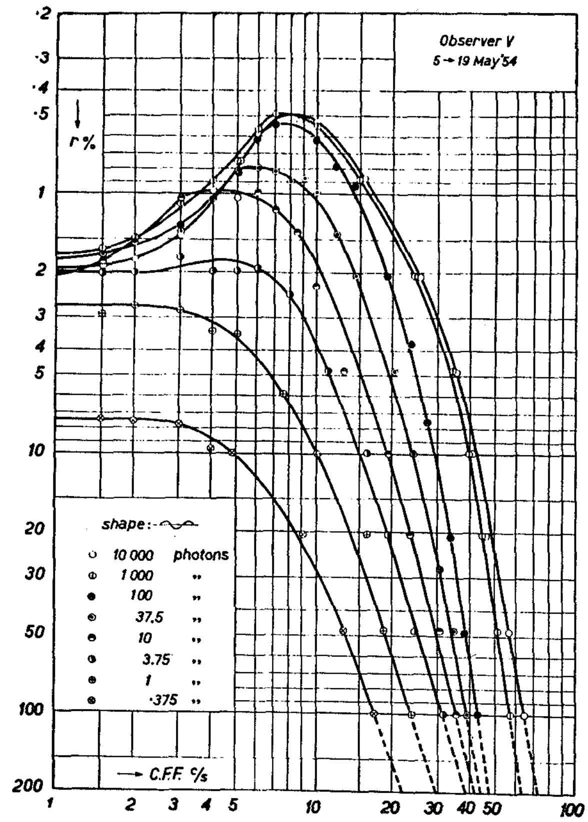

FIGURE 11.—Modulation amplitude at which a sinusoidally varying light signal appears to fuse into a steady light. Individual curves represent different average luminances (ref. 14).

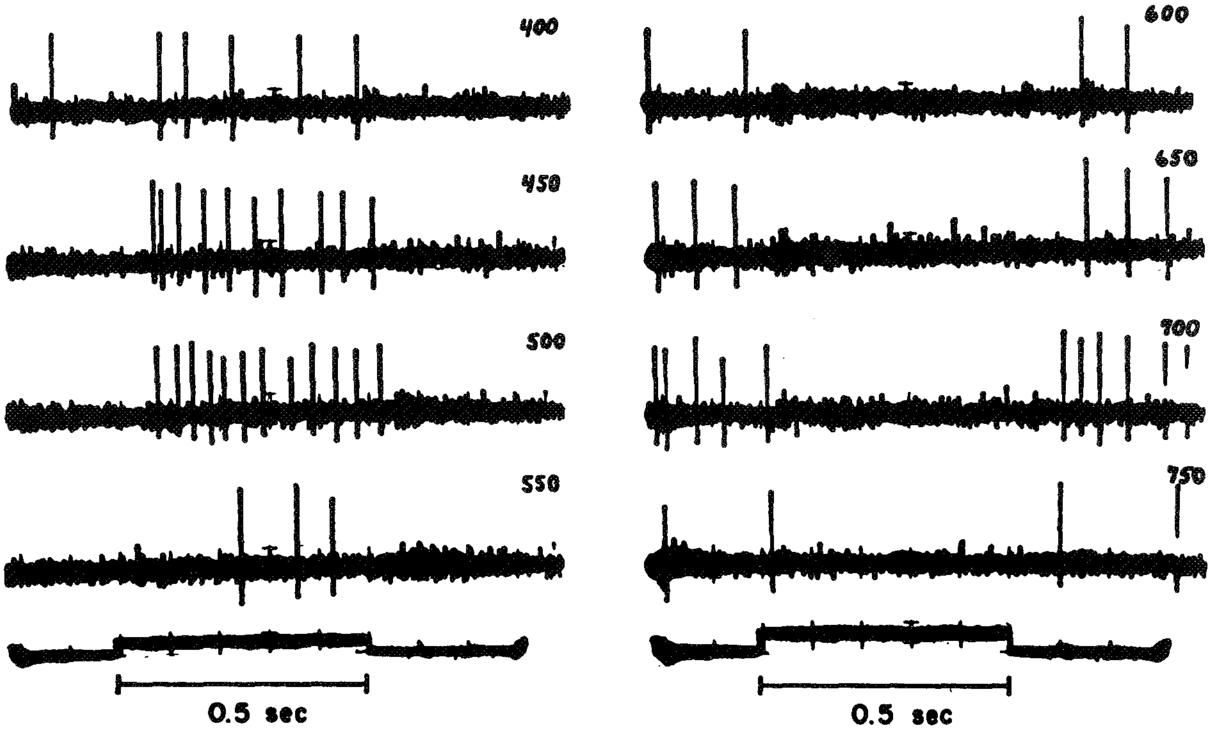

FIGURE 12.—Response of a single retinal ganglion cell to stimuli of various wavelengths in nanometers (ref. 18).

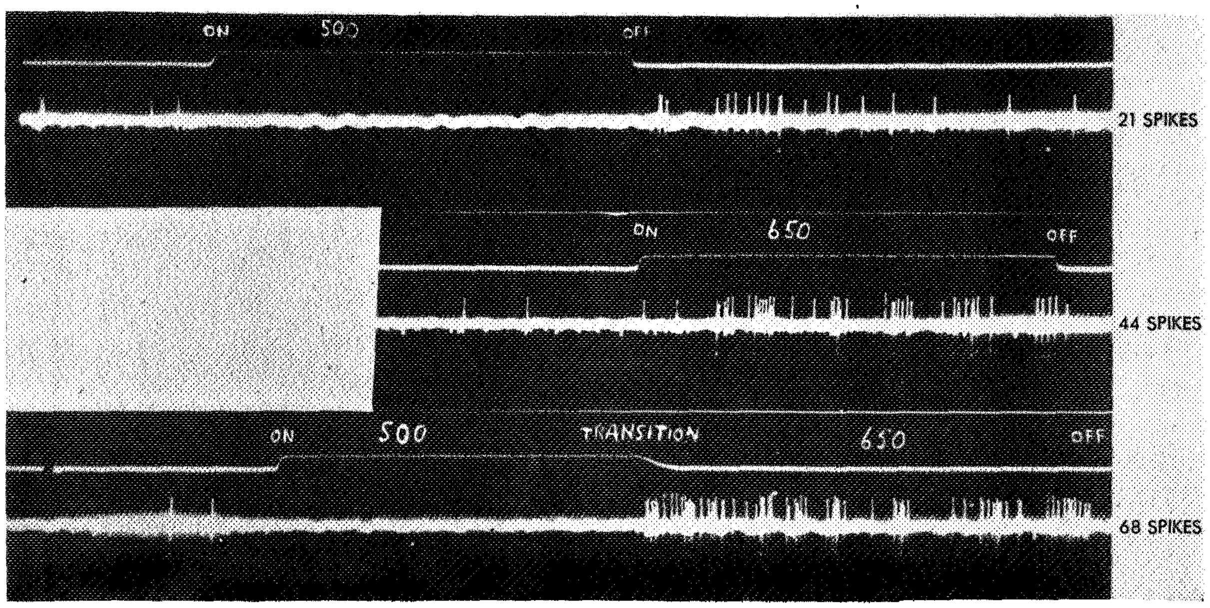

FIGURE 13.—Responses of a single cell in the lateral geniculate body of the monkey to green (500 nanometers) and to red (650 nanometers) stimulus lights (ref. 19).

served in a yellow-and-blue pattern. These successive contrast effects and other simultaneous contrast effects influence interpretations of the visual world. It has been suggested by some astronomers that the apparent coloration of the details of the Martian surface may be a result of such color contrast effects (refs. 20 to 23). It is, therefore, dangerous to interpret them as indicative of a specific surface condition if they may be artifacts of the visual process.

EFFECTS OF SPACE FLIGHT ON VISION

It has been suggested that the nature of the limitations on the visual process that are inherent in the visual system itself will be the same in space as on Earth. This notion should perhaps be qualified. Limitations that exist on Earth will undoubtedly exist in space, but additional limitations may be imposed by conditions that are unique to space flight. One element of concern is the gravity environment. In launching a space mission it is necessary to employ accelerations that impose higher gravitational forces on the occupants of a space vehicle (ref. 24). When the orientation of these forces is such as to interfere with the circulation to the eye and brain, there may be a blackout of vision and other symptoms. Studies have indicated that by so positioning a pilot that the line of action of acceleration forces is transverse to the long axis of the body, it is possible to avoid blackout. Other visual effects may occur nonetheless. These problems have been studied extensively on large centrifuges, which permit the exposure of human subjects to high acceleration forces (ref. 25). The Navy centrifuge system at the Acceleration Laboratory in Johnsville, Pa., is illustrated in figure 14. This centrifuge has been instrumented for closed-loop operations such that a pilot may perform the control operations necessary for a specific mission and the acceleration forces imposed on him will be

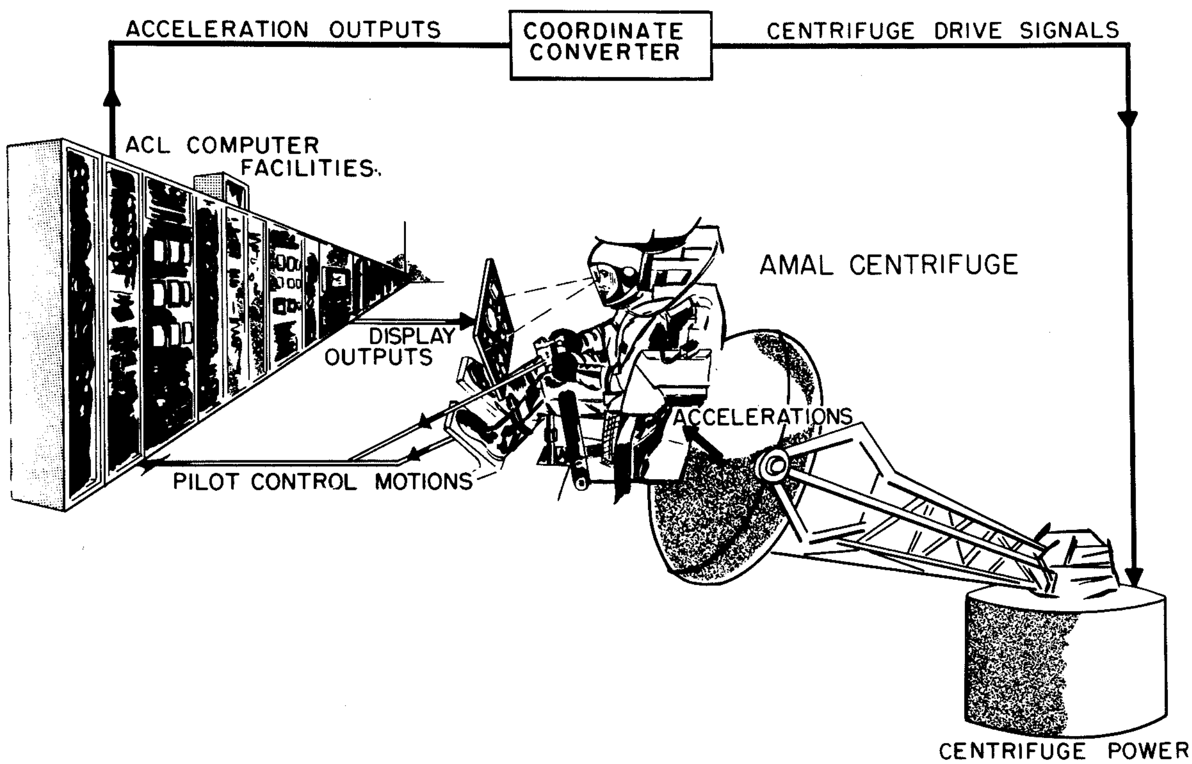

FIGURE 14.—Schematic illustration of system for closed-loop simulations with the Navy centrifuge at Johnsville, Pa. (ref. 26).

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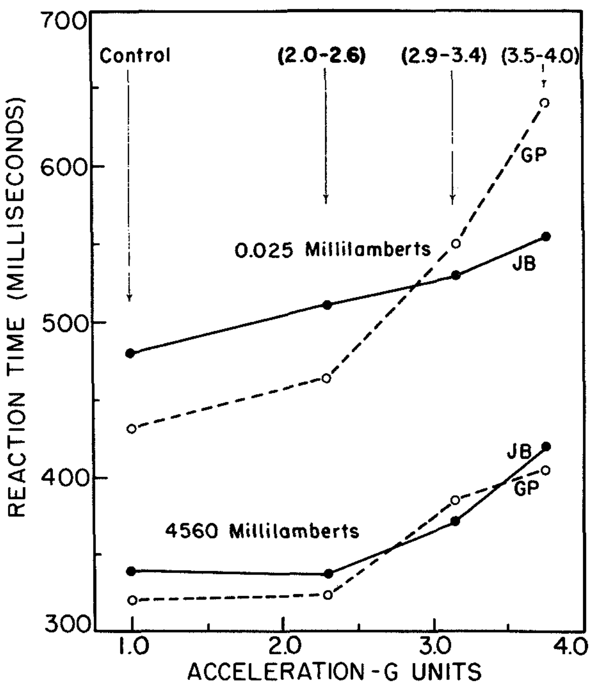

FIGURE 15.—Reaction time to visual signals as a function of level of positive acceleration for each of two subjects (JB and GP) and each of two luminance levels (ref. 27).

determined by his control manipulations. A number of experiments have been performed on this device to determine the mechanical limitations imposed on the pilot by accelera-tion forces (ref. 26). Some studies have also been performed to determine purely visual effects. One of these is illustrated in figure 15 (ref. 27). The time required for a subject to make a motor response to a visual signal is shown to increase with increased level of acceleration. It is also clear that the reaction time is influenced to an even greater extent by the luminance level of the visual signal. By using sufficiently bright illumination, relatively short reaction times can be obtained even at levels of acceleration near those that will cause blackout when acting along the long axis of the body. Dr. Joseph White and his colleagues, working at the Wright Air Development Center of the Air Force, have studied a variety of acceleration effects on vision (ref. 28). Figure 16 illustrates the

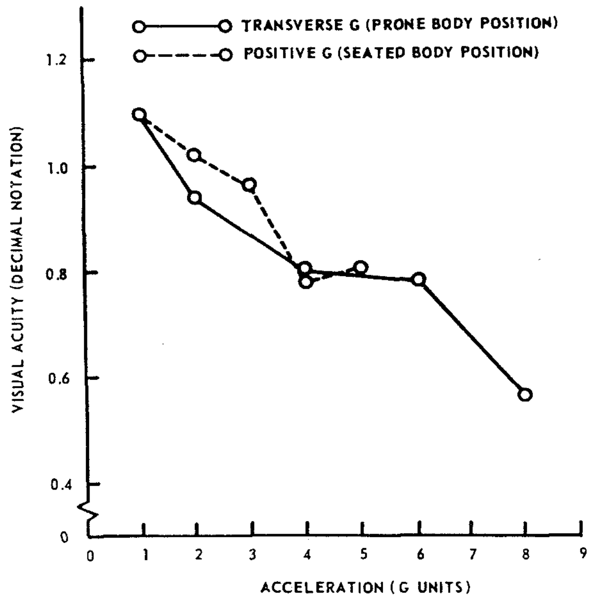

FIGURE 16.—Visual acuity as a function of level of acceleration in two body positions (ref. 29).

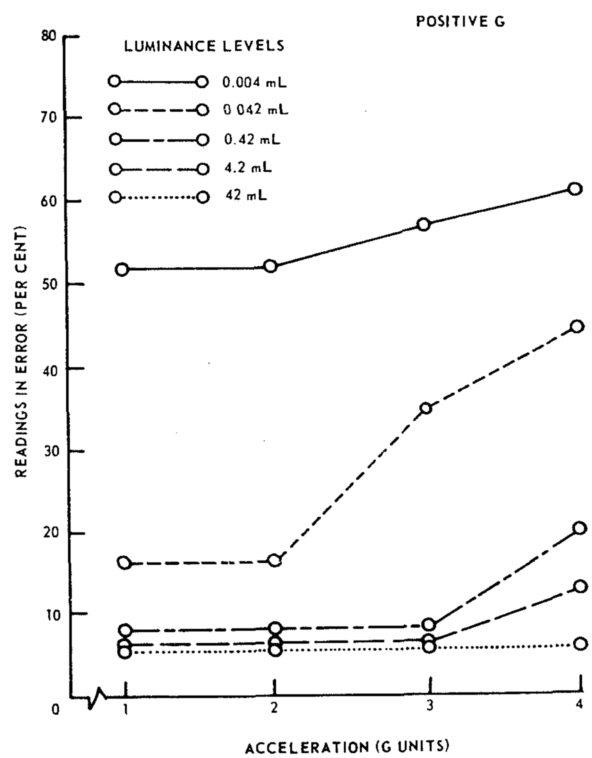

FIGURE 17.—Percent instrument readings in error as a function of acceleration for each of five luminance levels (ref. 29).

reduction in visual acuity with increased acceleration up to 8*g*. There appears to be little difference in the effect on visual acuity for transverse and positive acceleration orientations. White has suggested that the effect on visual acuity may result from deformation of the optical system rather than impairment in the circulatory system. As in the case of reaction time, it can be shown that influences of acceleration on visual acuity, measured indirectly in terms of errors in reading an instrument, may be ameliorated by increasing the luminance level. This is illustrated in figure 17, again from the work of White (ref. 29). High acceleration levels will be of relatively short duration, and barring accident, they will not be so high that they need be a major concern as an impediment to space travel.

Possibly even greater concern has been expressed over the effects that the 0*g* environment of outer space in orbit or in interplanetary flights may have on visual processes. The exact basis for concern has not been well stated in all cases, but several experiments have been performed to assess possible changes in visual acuity and other visual discriminations in the 0*g* condition. Slight changes have been measured both in the direction of decrease and increase (refs. 29 and 30). In an extensive experiment performed by astronauts in orbital flight (ref. 31), no significant difference was observed as contrasted with preflight and postflight tests made on the ground. It is doubtful that 0*g*, at least for relatively short durations, has any influence on visual acuity. There has been greater concern with the possibility that mechanisms that control eye movement might be influenced by the absence of grav-

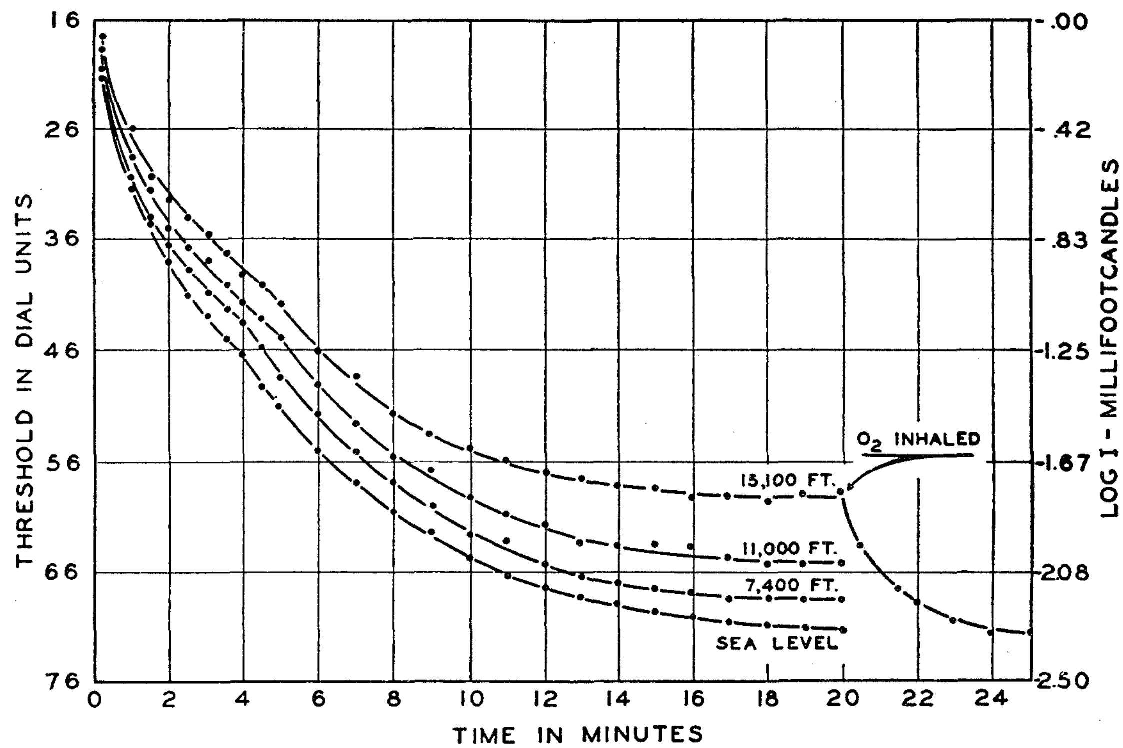

FIGURE 18.—Dark adaptation curves at each of four pressure altitudes. Inhalation of 100 percent O_2 at the highest altitude is followed by a rapid drop in threshhold to the level found at sea level (ref. 32).

ity. If coordination of eye movements is disrupted even slightly, the effect on perception and various judgments of distance or motion might be a handicap to the space traveler. Efforts to measure visual functions, such as accommodation and phorias, will be made in subsequent missions.

It is probable that motor systems adapt reasonably quickly to the absence of gravity cues. Astronauts have observed that eye-hand coordination is unimpaired under 0*g*. Even tactile approximation with the eyes closed appears to be about as good in a 0*g* condition as it is on the surface of the Earth (ref. 10). There seems to be no tendency to overshoot or underreach, which is associated with the absence of weighting of the limbs by a gravitational field.

The visual process is known to be quite sensitive to the respiratory environment. Reduction in the partial pressure of oxygen of the air breathed will cause measurable visual effects at altitudes as low as 5000 ft. An illustration is presented in figure 18 (ref. 32). Dark adaptation curves are presented for subjects breathing oxygen mixtures equivalent to the altitudes indicated. It is clear that the final threshold level in the dark-adapted eye is elevated considerably at the higher altitudes. Quick recovery from the highest altitude is demonstrated when subjects are permitted to breathe 100 percent oxygen. The astronaut will carry his atmosphere with him and he will be provided with an appropriate mixture to sustain him adequately. Any possible source of contamination, however, may cause difficulty (ref. 33). The effects of reduced oxygen pressure are compared with those of cigarette smoking in figure 19. It is shown that smoking two or three cigarettes causes an elevation in threshold equivalent to that caused by an increase in altitude of only 7500 ft (ref. 33). The effect of cigarette smoking may be explained in terms of the binding of hemoglobin by carbon monoxide inhaled with the smoke. Another possible basis of explanation is the vasoconstrictive effect of nicotine, which may influence retinal circulation.

On some space missions a 100-percent

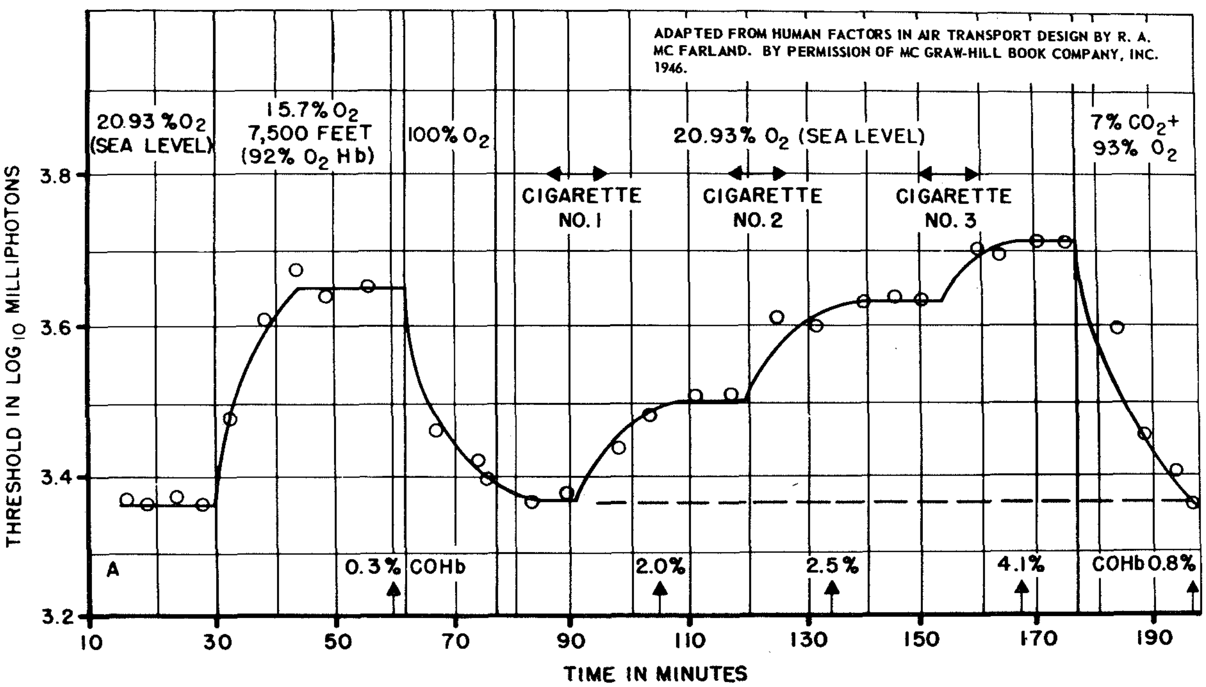

FIGURE 19.—Fluctuations in light threshold induced by changes in the respiratory environment and by cigarette smoking (ref. 33).

oxygen environment has been employed at a pressure greater than the partial pressure of oxygen at sea level. Oxygen is known to be toxic and 100 percent oxygen at sea level will probably result in death in little more than 70 hr. Lesser effects that might be reflected by changes in visual function have, therefore, been considered a possibility, with slight increases in the pressure of oxygen over the normal level. This possibility has been studied extensively with a variety of visual tests for increased partial pressures of oxygen up to that represented by 100 percent oxygen at sea-level pressure with exposures for 24 hr (ref. 34). No effects on visual processes were observed.

Ionizing radiation is probably not a serious problem in relation to vision in space travel. At high levels its effect on other than the visual system will be of most importance: at low levels it probably will not cause serious difficulty. It has been demonstrated that exposure to ionizing radiation can cause cataracts. It may also reduce visual sensitivity by direct or indirect action in bleaching the photosensitive substance of the eye (ref. 35).

An artificial restriction on the visual environment in space may be imposed by the necessity that astronauts wear a protective helmet with a transparent window. Visual field may be restricted by such a device along with the illumination, as this is restricted by the transmittance of the visor. Helmets may thus impose some limitations on vision for the space traveler, but it is reasonable to assume that with continuing development of equipment these limitations will be reduced or eliminated.

THE VISUAL ENVIRONMENT OF SPACE

With his departure from the Earth's atmosphere, the space traveler will come into an entirely new visual environment. The atmosphere of the Earth absorbs approximately 30 percent of the Sun's radiation (ref. 36). The radiant energy level from the Sun will thus be higher outside the atmosphere to this extent. Light scattering that occurs within the atmosphere will be absent and the uniform illumination provided by the daylight sky on the Earth's surface will not be seen. Stars and other objects will be seen against a darker background than that of the sky at night by reason of the absence of light scattering. Contrasts between illuminated areas and nonilluminated areas or the void of space will be much higher than those usually encountered on the surface of the Earth. This will be true on the surface of the Moon as well as in space, by reason of the absence of any significant atmosphere around the Moon (refs. 36 and 37). The hazard to be encountered by looking directly at the Sun will be increased over that which exists within the Earth's atmosphere. Whereas on the Earth's surface, injury to the retina may occur after gazing directly at the Sun for a little less than 1 min, only 10 to 15 sec outside the Earth's atmosphere is enough to cause injury (refs. 36 and 38). Stars will no longer twinkle, and the colors of the Sun and the stars will probably be more whitish in the absence of atmospheric scattering of blue rays. Solar illuminance will be nearly 14 000 foot-candles, while background-sky illumination will be an order of magnitude lower than that of the dark sky on a moonless night. Background illumination in the sky of space will be comprised of starlight, zodiacal light, and galactic light. Beyond the distance of Jupiter from the Sun, the contribution of zodiacal light will be greatly reduced (ref. 36). A substantial contribution of light in the region of the Earth will be reflected from the Earth itself, 36 percent of the solar light that falls on that body. This is substantially more than the light reflected from the Moon (albedo, 0.17 to 0.14). In the region of Venus, solar illumination will be approximately twice that in the region of the Earth and the hazards of retinal exposure will be increased commensurately. In the vicinity of Mars, solar luminance will be less than half that at the Earth. In the region of Jupiter it will be reduced to less than 1/20 of the value that prevails in the region of Earth. The ideal range of illumination, from the standpoint of human vision, may be within 10^8 km on either side of the Earth's orbital distance. Strughold has referred to this region as a euphotic belt (ref. 36). It is in this region that life as we know it is most favored; gaseous oxygen and liquid water may be present.

Even at the mean distance of Pluto from the Sun, the illuminance provided will be sufficient for reading and for photopic vision in which colors may be discriminated. Insufficient illumination for photopic vision will exist at a distance from the Sun about three times the distance of Pluto (about 1.8×10^{10} km).

The visual realm on the surface of the Moon is of particular interest at the present time (refs. 37 and 39). The illumination level will be approximately 30 percent higher than that on the surface of the Earth. The absence of atmosphere with its attendant light scattering will present a world of striking contrasts in illumination, without the veil of sky illumination to fill in shadows. Shadows will not be completely dark where surface irregularities provide scattering and back illumination. The low reflectance of the Moon's surface will limit the amount of back reflection that occurs, however. The result for an explorer on the Moon's surface may be likened to the situation where someone is searching a crowded storage room with the aid of illumination from a single open bulb. Shadows will provide a striking element of the appearance and the overall appearance will vary greatly with any change in the direction of view of an observer with respect to the location of the light source. The presence of highly reflecting surfaces needed for thermal regulation of space vehicles and Moon surface dwellings will present periodic exposures to very high luminance levels. This effect, coupled with the darkness of shadows, will render vision difficult. The problem of moving about on the surface under one's own power will be complicated both by the visual conditions and by the relatively low gravity of the Moon (0.167 Earth gravity). The surface of the Moon for the most part will be porous material. This has been inferred by the change in reflected light with angle of incidence of the Sun's illumination as measured from the surface of the Earth (ref. 40). The nature of changes of light reflected from the Moon appear to require that its surface be of some porous material. There is no evidence of any sharp selectivity in spectral reflectance, but there does appear to be a gradual increase in level of reflection with increase in wavelength of the illuminating light (ref. 39).

High illumination levels reflected from metallic surfaces as well as those seen when looking directly at the Sun will present two problems. In the first place, they will cause light adaptation of the eye, thus reducing its ability to discern detail in the darker shadows. In the second place, they present a threat of retinal injury. The nature of these problems is illustrated in figure 20 (ref. 41). As an adapting flash increases in its total energy, the time required for the eye to recover sufficiently to view visual detail illuminated at a much lower level increases. The increase occurs at increasing rate up to a point, probably representing depletion of photosensitive materials, where the curves appear to level out. Somewhere beyond this energy level there will be irreversible injury resulting from retinal burning. The eye can

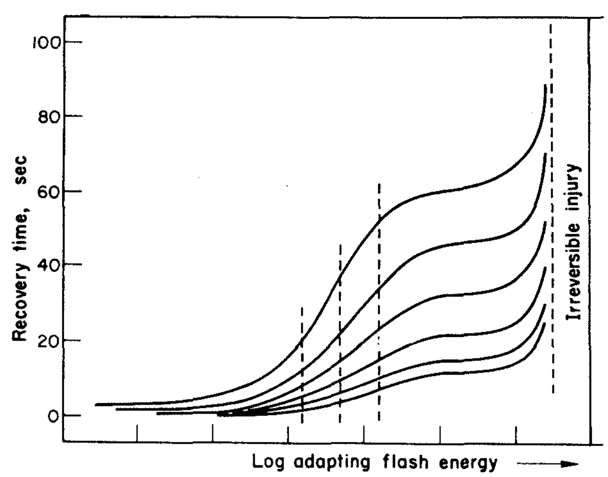

FIGURE 20.—Time required to recover from a bright adapting flash for each of six levels of illumination of the test criterion as a function of adapting flash energy (ref. 38).

recover from the adapting effect as this is represented by adapting flash energies up to the plateau of the curves. Retinal burns influence vision permanently, and if located in the fovea are extremely serious in their effect.

THE VISUAL TASKS OF THE SPACE EXPLORER

The visual requirements of an astronaut will fall in several categories (refs. 9 and 42 to 46). The first of these is related to the task of controlling his vehicle and monitoring its position and attitude in space. During many stages of space flight this will be accomplished primarily by visual reference to flight instruments. Outside visual reference through portholes or a periscope will also be of importance (ref. 47). Outside reference may be to the Earth, Moon, or another planet; a star, or another space vehicle. It has been demonstrated that rendezvous and docking with two space vehicles can be accomplished by direct visual reference when appropriate controls are provided (refs. 48 and 49). The control of a landing may also be accomplished by direct visual reference. Laboratory studies of this possibility continue to compare the efficiency of direct visual control with that of automatic procedures.

The second category of visual tasks relates to the possibility of reconnaissance of a planet's surface from a space vehicle. This function will be limited by the visual acuity of the unaided eye. Where objects on the surface may be familiar, it will be possible to make identifications with minimal visual information (refs. 46, 47, and 50). On a completely unknown planet, however, the problem will be far more difficult. The judgment of size, when the nature of the object viewed is unknown, is extremely difficult. Photographs of the surface of the Moon illustrate that different points appear very similar in terms of the distribution of visual angles that represent diameter of craters over a large range of distances—there is a range of crater sizes such that the visual pattern may look very similar from relatively near and far vantage points. Assistance in evaluating the nature of an unfamiliar surface may be obtained by the use of flares jettisoned from a space vehicle and the changing shadow patterns that result from flare illumination (ref. 43).

The detection of other space vehicles or objects in space may represent an important visual task for an astronaut. Detection of objects in space will not be limited by the resolution capacity of the eye, but only by the amount of light reflected from the object to the eye. The task will be one of light detection rather than of spatial resolution. The largest problem in detection will be in localizing the region of space to scan for an object. Some familiarity with star patterns could conceivably be of value so that an anomalous object may be detected. It has been demonstrated experimentally that such detection will be extremely difficult, nonetheless (ref. 46). Another source of concern for detection is related to the relative motion of the object to be detected with respect to that of the vehicle that carries the observer. Times during which detections may be made for two vehicles that orbit the same planet or moon may be very limited.

Astronomical observations may be made from a space vehicle. The absence of an atmosphere will be helpful, but the transmission characteristics of the window in the space vehicle may present some limitations. With the aid of a telescope, if a space vehicle carrying the instrument is sufficiently large, rather important observations can be made. Stabilization of the platform of the telescope may present a problem if human occupants of the space vehicle are moving about freely.

In general, observations outside a space vehicle will be complicated in many instances by the lack of familiarity of the observer with the actual size of objects observed or with the nature of the terrain when a surface is observed. High contrast between points of illumination and background will result in an apparent change in size and shape of the source of illumination (ref. 51).

Inside a spacecraft, other problems may

arise (ref. 43). These relate to the orientation of the astronaut with respect to his vehicle in the absence of gravity. The orbital flights that have been made to date suggest that this problem will not be a serious one. Its seriousness may increase, however, when larger vehicles are employed in which movements of much greater extent, involving the whole body, may be made. The absence of a gravitational vertical in this situation may be more serious than one in which the astronaut's position is fixed relative to his vehicle and instrument displays and controls within the vehicle. It has been suggested that it may be desirable to select arbitrarily some surface that shall be the "floor," and to construct interior spaces in the fashion similar to those with which we have become familiar on Earth (ref. 52). Such design may be less efficient than another that could conceivably cause greater confusion to an astronaut. Another suggestion has been that the vehicles be rotated to create an artificial gravity from centrifugal force. In this instance, other problems may arise. For the length of rotational axis that would be practical, angular accelerations that will produce a substantial gravitational component will be relatively high and could cause difficulty by reason of their stimulation of the labyrinthine mechanisms of the inner ear (refs. 43 and 53). It seems most probable at present that the problems associated with $0g$ are of less concern than those associated with rotation of a vehicle for creation of an artificial gravity, at least for missions of relatively short duration.

CONCLUSION

The characteristics of the human visual process have been reviewed briefly. It would appear that these characteristics will remain relatively unchanged in space flight except under abnormal and emergency conditions at excessively high acceleration or low oxygen. The problem confronting the use of the sense of vision in space for an astronaut will be primarily the lack of familiarity with the space environment. In the region of Earth there will be ample light, but there will be excessively high contrasts and large ranges of illumination with which we are relatively unfamiliar on the surface of the Earth. The lack of scattering by an atmosphere will present additional problems. It is probable, nonetheless, that an astronaut will be able to adjust to conditions that prevail in space. With increased experience and the development of equipment to assist him, it is reasonable to predict that the role of the human explorer in space will be a significant one and much of what he accomplishes will depend upon his use of vision.

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SESSION V

Man-Machine Relationships

***Chairman*: J. B. Eades, Jr.**

Operational Considerations for Extravehicular Activity as Applied to Future Space Missions

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Extravehicular excursions during the Gemini program were the free world's first attempt to determine man's capability to operate as a free body in space. The results obtained during Gemini provide a good baseline by which to plan the role that extravehicular activity (EVA) should take in defining future mission requirements. The Gemini results allow us to define, with better accuracy, the amount of useful work that an EVA crewman can perform, the propulsion and mechanical aids required, and the psychological responses to being exposed to the vast surroundings of space. The manned space-flight program is based on a "building-block approach" that allows us to explore the more complex mission objectives in a logical sequence.

With the limited knowledge we currently have, it appears reasonable to establish some basic guidelines in future mission planning:

(1) Extravehicular activity should be planned as the primary means of accomplishing a given operational or experimental task only if there is no reasonable alternative.

(2) Tasks should be carefully planned to a timeline to allow for adequate rest periods.

(3) Rigid mounting restraints should be used wherever practical.

(4) Use of umbilicals is practical when working within a fixed envelope of the spacecraft. This allows life support systems to be smaller and allows better utilization of spacecraft expendables, such as oxygen and power.

In planning the support equipment, such as suits and life support systems for long-duration missions, several aspects of system design became increasingly important. System components require longer cycle life and reliability. Individual EVA missions should be restricted to 3 to 4 hr because of physical limitations of the astronaut. On a mission of 1-yr duration, as many as 100 EVA excursions can be anticipated, thus demanding optimization of the life support systems to provide ease of maintenance and servicing and sustained reliability. Other considerations will include closed-cycle systems for life support and regeneration to minimize the weight penalty for expendables such as water, CO_2 absorbers, and batteries.

INTRODUCTION

The manned space flights of the Gemini project provided the U.S. space program its initial opportunity to study man's extravehicular capabilities while in space. The objectives for EVA, established early in the Gemini program, were basic in nature and progressed in complexity from the short and simple mission of Gemini 4 to the much longer and more complex mission of Gemini 12. These objectives were:

(1) Evaluation of man's capability to perform useful tasks in a space environment

(2) Extravehicular operations to augment the basic capability of the Gemini spacecraft

(3) Evaluation of advanced extravehicular equipment in support of manned space flight and other national space programs

The exploratory nature of the EVA program in the Gemini program provided necessary information with which to establish man's capability to perform useful tasks in the weightless environment without the necessity for major modifications to an operational spacecraft. This experience from Gemini flights has allowed review and redirection, where necessary, of many aspects of our planning for equipment design and training for the Apollo missions. Beginning with the Apollo program, EVA will be utilized as an operational tool for meeting mission objectives. This paper will attempt to delineate, in a chronological order, the role of EVA in accomplishing U.S. space-flight goals.

GEMINI

The free world's first spacewalk, as it has been coined, was performed by astronaut Edward H. White on June 3, 1965, during the Gemini 4 flight. The objectives of the EVA were to demonstrate the feasibility of EVA in space and to evaluate body attitude and position control capability using a hand-held propulsion unit and the umbilical tether line.

The equipment used for the Gemini 4 EVA can be seen in figures 1 and 2. It included the basic pressure suit garment (G–4C) with a micrometeoroid and thermal protection coverlayer and an extravehicular visor configuration to limit the infrared and ultraviolet radiation. The total visible transmittance through the extravehicular visor assembly was 10 percent. The life support system was an open-loop, gas-cooled system with total

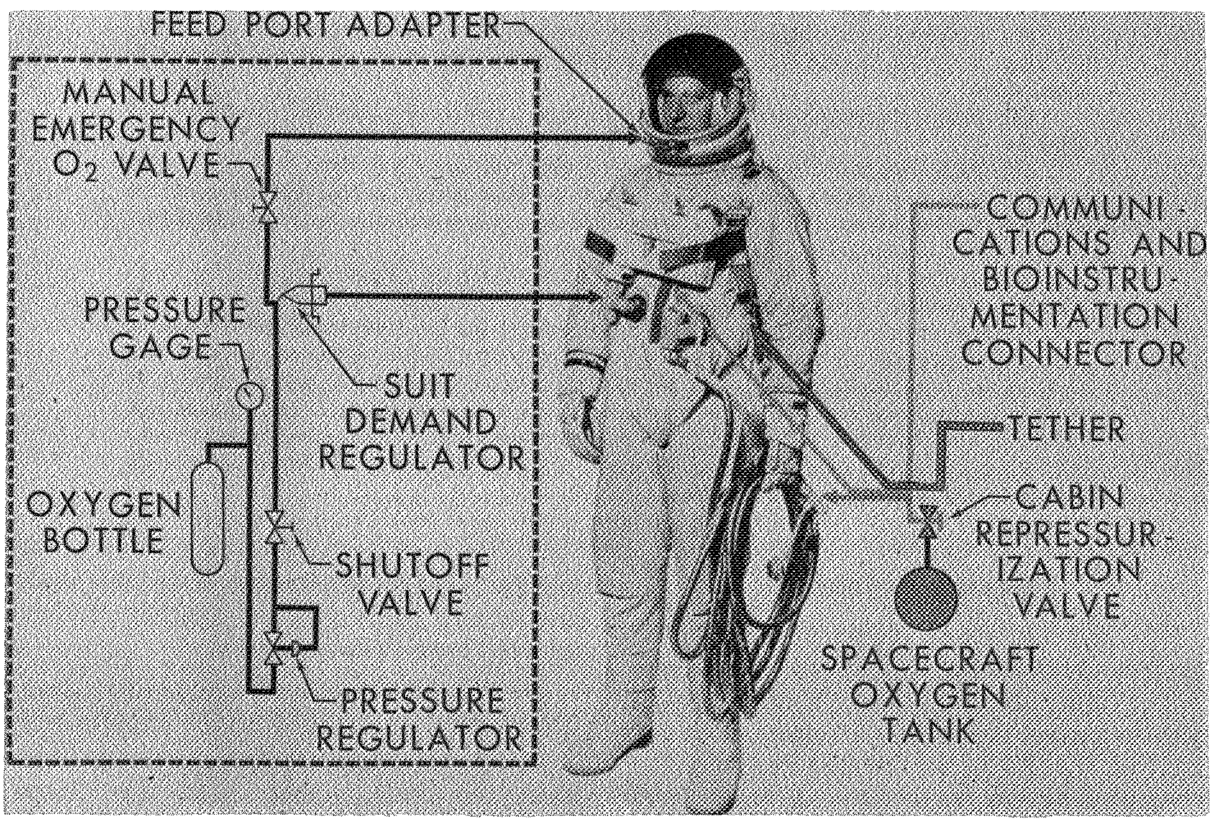


FIGURE 1.—Gemini 4 extravehicular life support system.

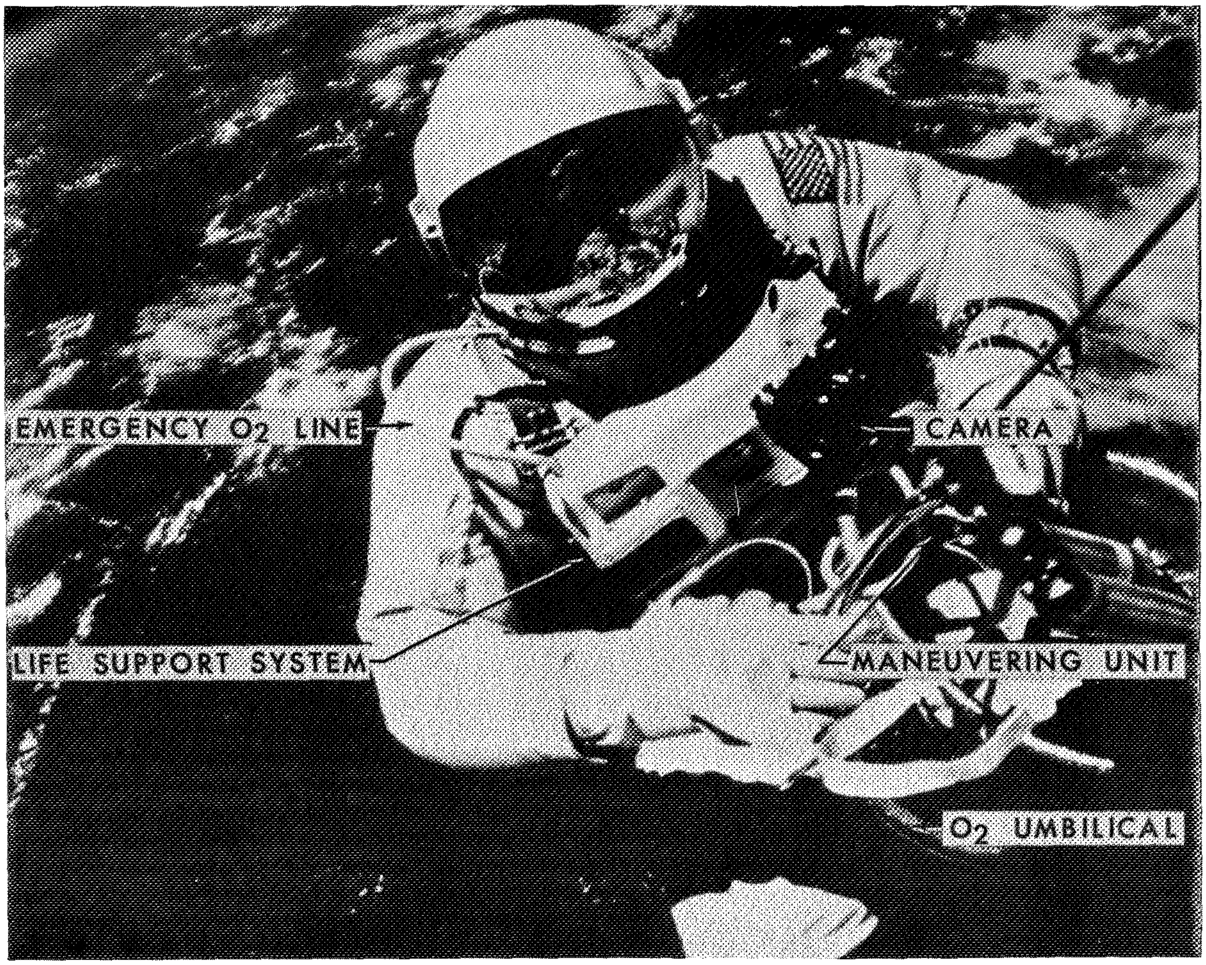


FIGURE 2.—Gemini 4 extravehicular pilot.

cooling capability of 750 to 800 Btu/hr. The oxygen was supplied, via umbilical, from the spacecraft. The hand-held propulsion unit had two self-contained oxygen bottles supplying gas to the two 1-lb thrust tractor nozzles of each and one 2-lb thrust pusher nozzle.

Prior to the flight, the training of the astronaut for the EVA was both intensive and diversified, consisting of 0*g* parabola flight in a KC–135, sea-level procedure exercises, and altitude chamber tests with the crews utilizing the flight hardware. All of these exercises were conducted by the equipment designers, training personnel, and crewman working as a team to develop coordinated and detailed flight procedures and designs that incorporated the most workable EVA techniques. This same basic testing and training philosophy was utilized on all five remaining Gemini EVA missions and was found to provide the crewman with excellent hardware and procedure familiarity and maximum confidence in the systems. The planned EVA activity on Gemini 4 was to last approximately 20 min with the EVA crewman evaluating body positioning; maneuvering, with and without propulsion aid; orientation, using the spacecraft as a reference; and photography. The actual EVA hatch-open time was 36 min. All the objectives were fulfilled.

Several conclusions were reached from the Gemini 4 EVA exercise.

(1) EVA could be accomplished without disorientation or other adverse effects.

(2) The utility of the hand-held maneuvering unit (HHMU) for self-propulsion without artificial stabilization was indicated, although the total available thrust of 20 sec was too brief for a detailed evaluation of stability control.

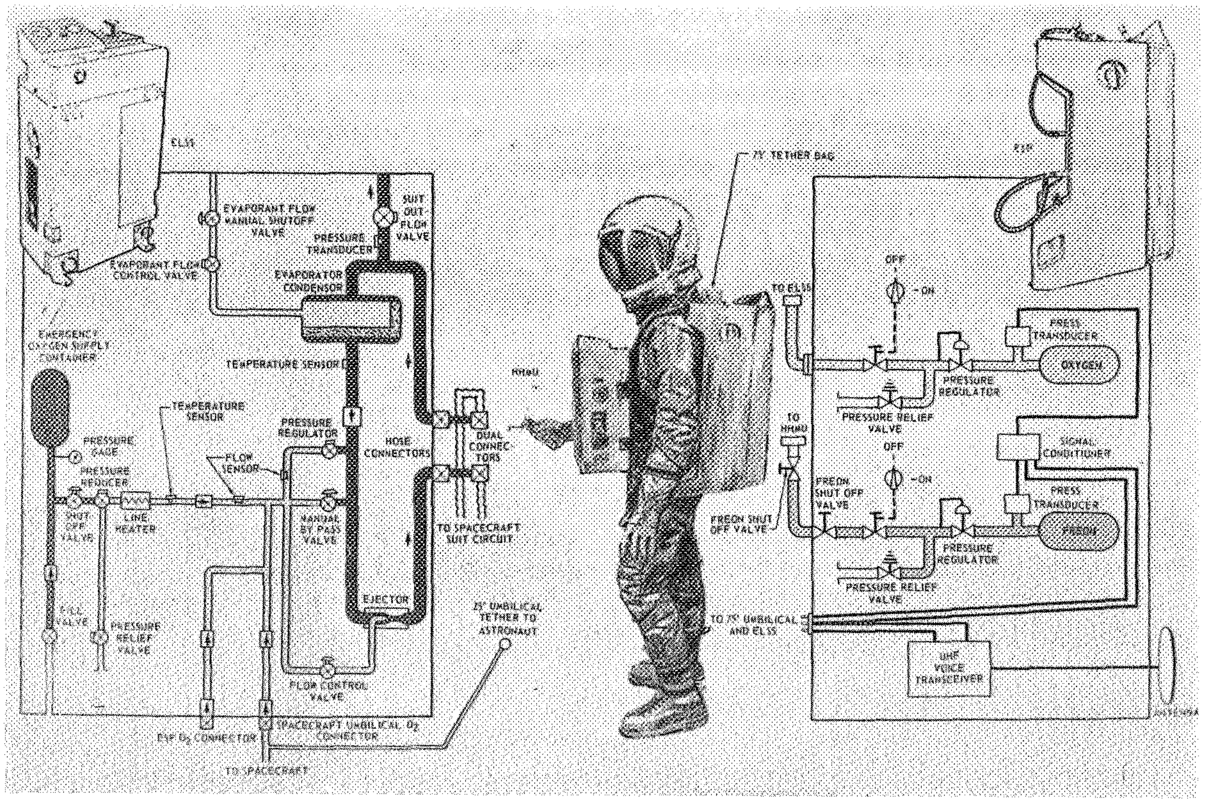


FIGURE 3.—Gemini extravehicular system.

(3) The tether did not provide a means of body-positioning control other than a distance-limiting device.

(4) Tasks that involved useful work (e.g., hatch closure) produce metabolic expenditure in excess of that provided by the life support system (750 to 800 Btu/hr).

(5) The increased hazard of EVA dictated meticulous care during preparation for the spacecraft depressurization, thus taking longer than had been anticipated.

(6) Detailed checklists were found to be useful and, in fact, necessary.

Based on the conclusions reached in Gemini 4, preparations for the next planned EVA, Gemini 8, included improved systems consisting of an improved performance emergency life support system (ELSS), a lighter thermal micrometeoroid protective layer, and a combined visor configuration with high-impact resistance. These systems were being tested and qualified even during development of the Gemini 4 EVA (figs. 3 and 4). The capability of the HHMU was extended by the use of an extravehicular support package (ESP) that contained 16 lb of Freon for propellant; 7 lb of oxygen for the ELSS, thus eliminating the need for oxygen umbilical once the ESP had been donned; and a UHF communication transceiver. The ESP was stored in the adapter and was to be donned there and then released. A 100-ft tether was to allow for maneuvering evaluations with minimum interference from an umbilical. Because of spacecraft problems early in the flight and later mission abort, the equipment was never utilized. The spacecraft was equipped with several EVA aids, such as handrails, Velcro patches, and restraint attachment points. The Gemini 8

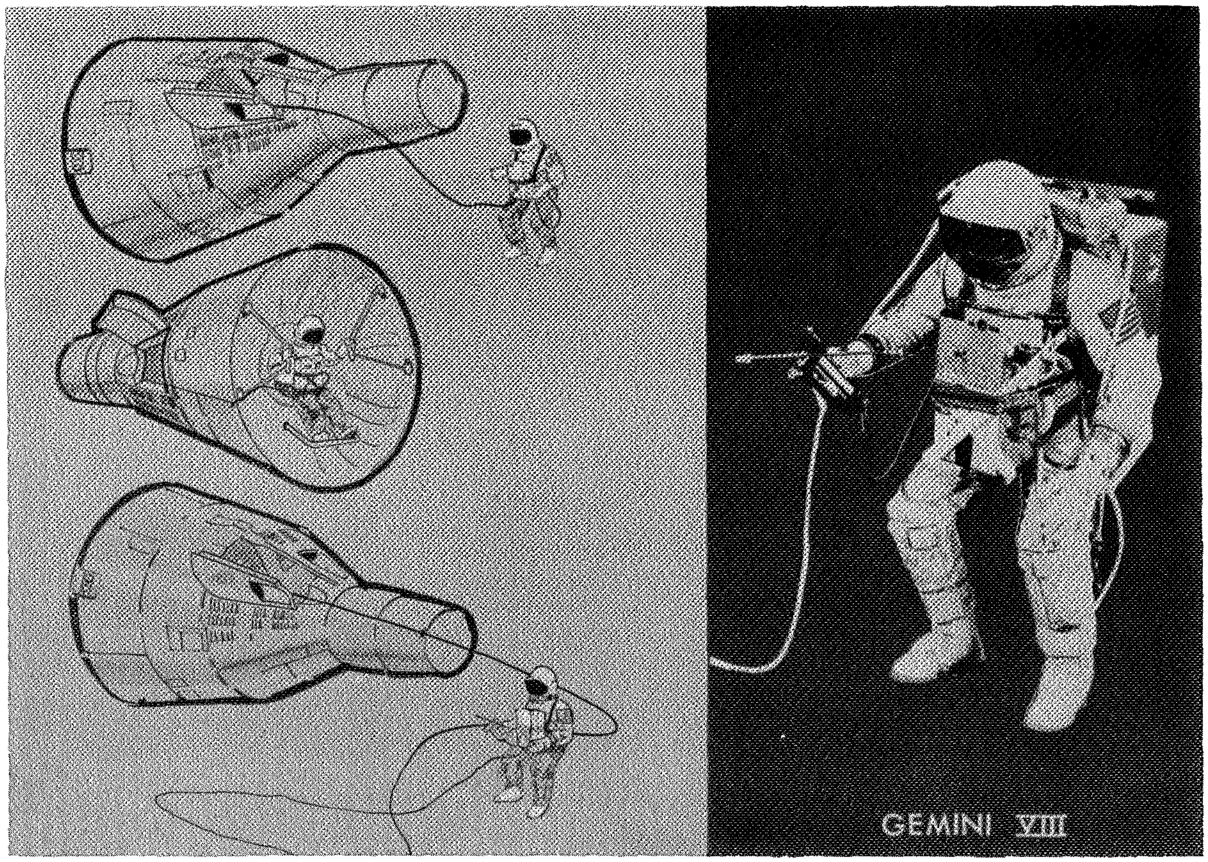


FIGURE 4.—Extravehicular life support system.

through 12 configurations differed some, but were generally as is shown in figure 5. The Gemini 9-A EVA objectives were to evaluate the ELSS and the Air Force astronaut maneuvering unit (AMU) (figs. 3 and 6).

The ELSS was semi-open-loop, gas-cooling system obtaining oxygen via the umbilical and a self-contained oxygen bottle to provide a 30-min emergency. Carbon dioxide was removed by purging with fresh oxygen. The equivalent flow was exhausted overboard. The metabolic heat rejection was nominal, 1200 Btu/hr with 10-min transients to 2000 Btu/hr. The AMU was a backpack that was similar in configuration to the ESP for Gemini 8, except it included fixed-location thrustors with automatic stabilization and utilized hydrogen peroxide for its propulsion system. Also, it contained a voice and data transceiver and oxygen supply. The ELSS display panel was configured to include systems data readout and warning lights, plus warning tones for both the suit and AMU systems in case of a malfunction.

The mission profile planned for Gemini 9-A was similar to that for Gemini 8, with the hatch being opened at sunrise of a daylight period. The first daylight period was to be devoted to familiarization with the environment and simple evaluations and experiments. The night period was to be spent in the adapter equipment section of the spacecraft, checking out and donning the AMU; the second daylight period was to be spent evaluating the AMU. Prior to sunset, the extravehicular astronaut was to return to the cockpit, discard the AMU, perform a scientific photographic experiment, and ingress.

The actual EVA proceeded essentially as

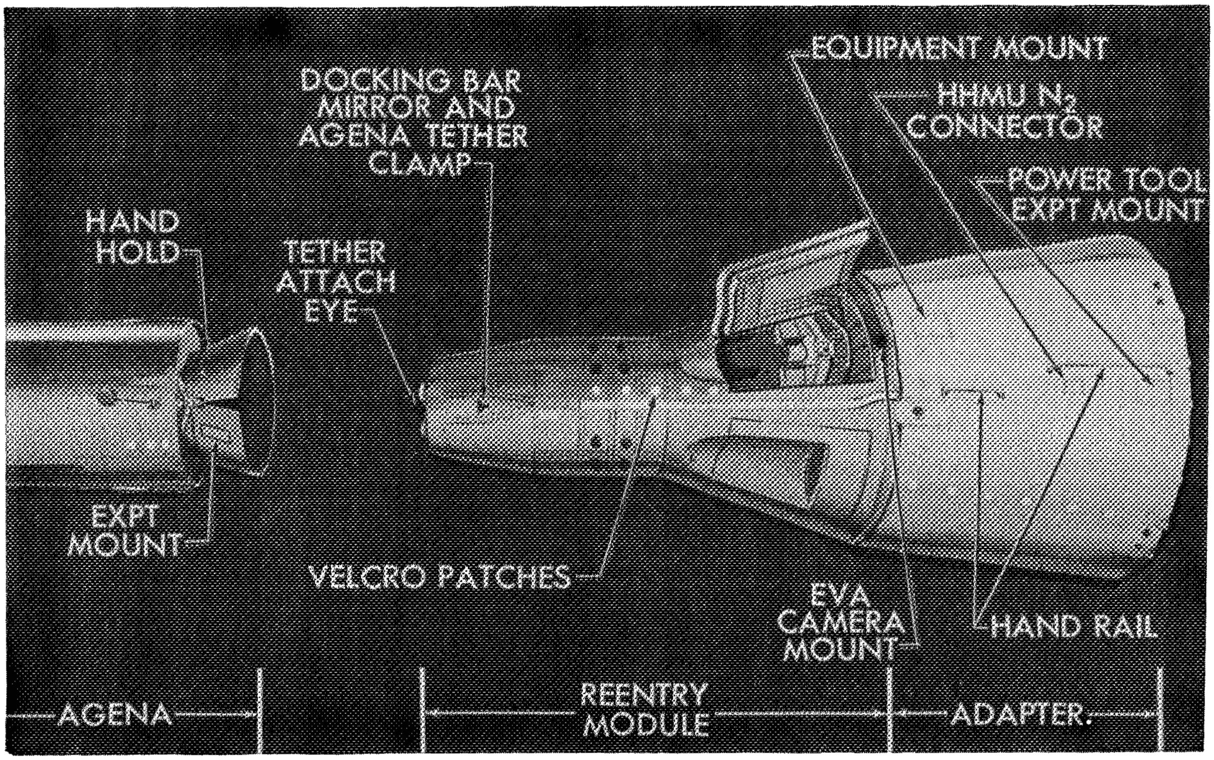


FIGURE 5.—Extravehicular equipment configuration.

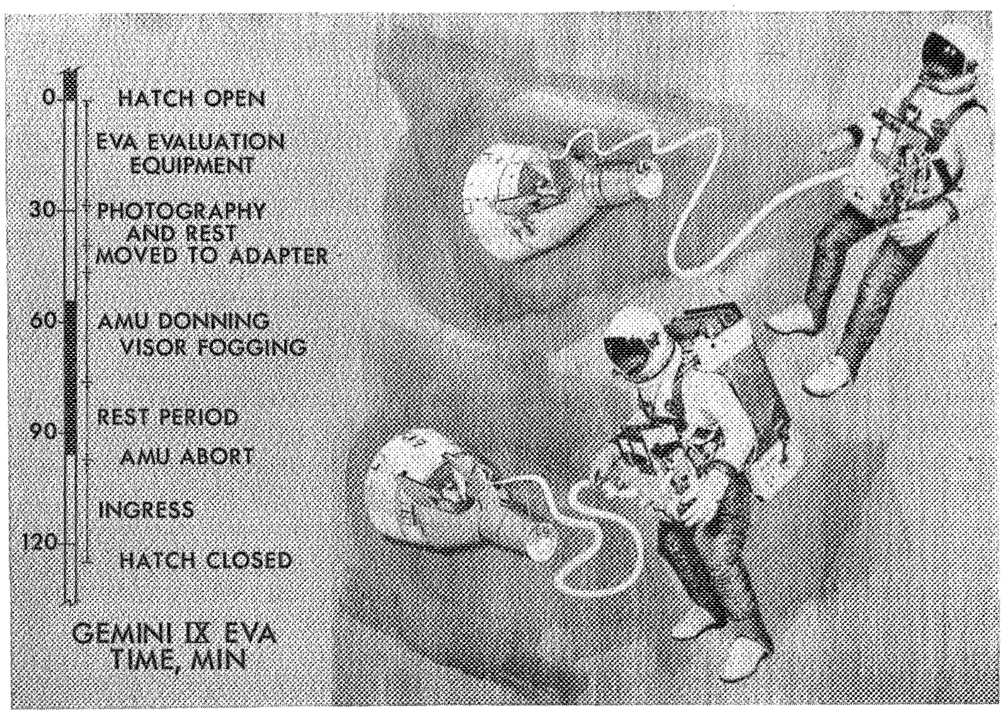


FIGURE 6.—Gemini 9 extravehicular systems configuration.

planned during the first daylight period, with the astronaut noting that the familiarization tasks and evaluations required more time and effort than during ground simulations. Minor difficulty was experienced in controlling body positions. Before the end of the first daylight period, the pilot proceeded to the equipment adapter and began preparing the AMU for donning (fig. 7); a task that required much higher workloads than had been expected. At approximately 10 min after sunset, the visor on the spacesuit helmet began to fog. This fogging increased in severity until finally the activities with the AMU were discontinued. After the second sunrise, visor fogging decreased, but increased again each time there was appreciable activity by the astronaut. The heart-rate data recorded by the bioinstrumentation indicated that the capability of the ELSS heat exchanger had been exceeded.

The flight and postflight test results indicated that the basic ELSS design capabilities of 1000 Btu/hr for 71 min, 1400 Btu/hr for 86 min, and 2000 Btu/hr for 10 min were substantially exceeded by the activity levels encountered during the Gemini 9-A EVA. For future EVA missions with the ELSS, it was apparent that the EVA workload would have to be reduced to be within the system capabilities. As a further precaution against visor fogging, provision was made for future crews to carry antifog solution to be applied immediately before EVA.

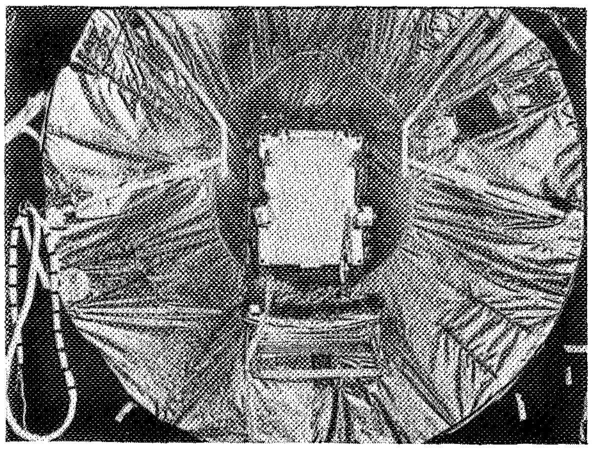


FIGURE 7.—Gemini 9 adapter work station.

The unexpected high workloads were primarily a result of difficulty in maintaining the body position relative to the work station, indicating the requirement for more positive restraints. The effort required to move the body to other than a neutral point of the suit required continuous effort and the necessity to repeatedly correct the body position. This resulted in a high degree of ineffective work.

Several corrective measures were initiated as a result of the Gemini 9-A EVA. An antifog solution would be applied to the helmet visor assembly immediately before EVA on future missions. The mission tasks were analyzed in greater detail with regard to providing positive restraints and the magnitude of the forces involved. Underwater simulation was initiated to augment the other ground-based simulations in an effort to better understand basic body dynamics and associated restraint aids, as well as detailed task versus time data, useful in more accurate prediction of actual EVA timelines.

The Gemini 10 and 11 EVA missions were very similar in nature with both standup and umbilical EVA being employed (fig. 8). The umbilical EVA was done on a dual-hose umbilical with nitrogen and oxygen being supplied to the crewman for life support and the HHMU. One of the most significant tasks was the attachment of a tether from the Agena to the docking bar of the spacecraft, as can be seen in figure 9. The umbilical EVA's were both cut short because of technical difficulties.

Gemini 12 was the final flight of the program and offered the only remaining opportunity to do a comprehensive EVA task evaluation before the Apollo program. The prime objective was to evaluate the type of body restraints and the associated workloads for a series of representative tasks. Other objectives were the attachment of the spacecraft-target vehicle tether and ultraviolet stellar photograph. The equipment included a work station in the spacecraft equipment-adapter section and on the target-docking adapter. Several new body restraints were provided including waist tethers and the

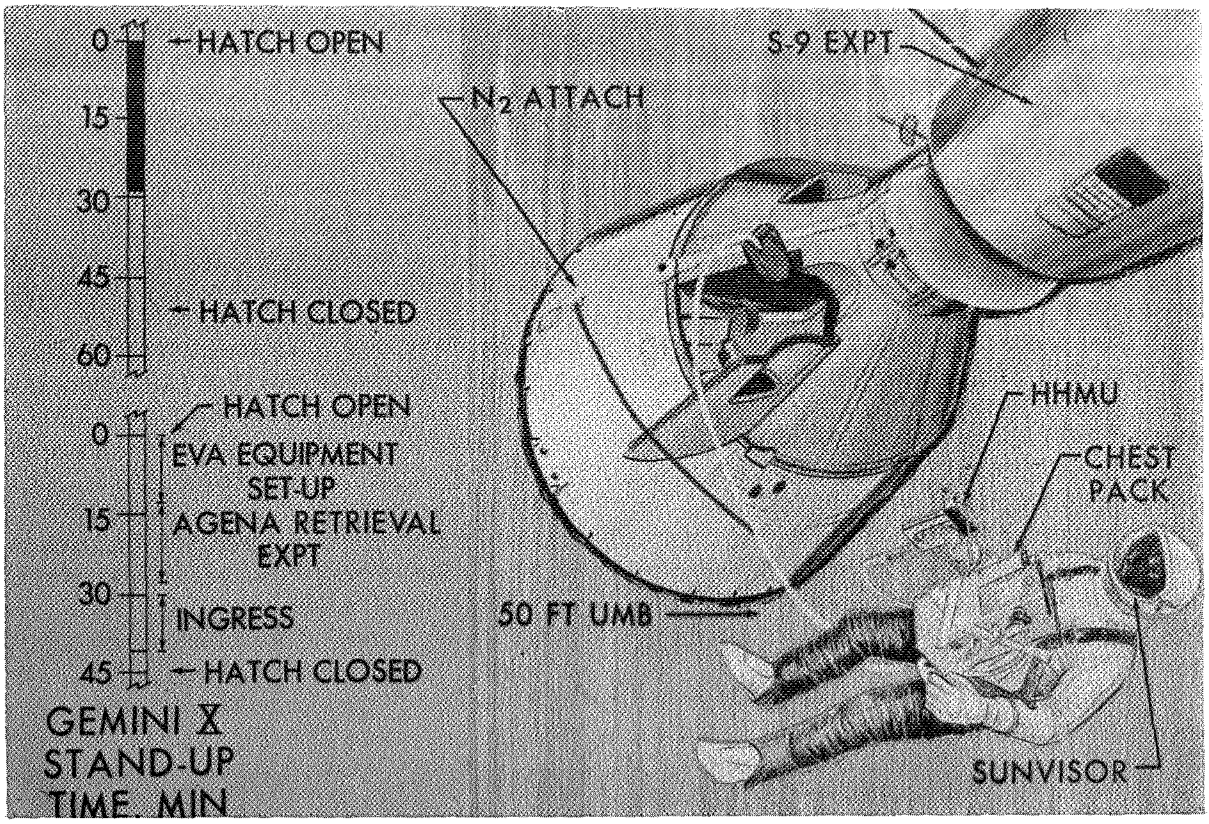


FIGURE 8.—Gemini 10 extravehicular systems configuration.

positive-position foot restraints, called "Dutch shoes" (shown in fig. 10).

The flightcrew training for the Gemini 12 EVA was expanded to include five sessions of intensive underwater simulation training (fig. 11). During these sessions, the pilot followed the planned flight procedures and duplicated the planned umbilical EVA on an end-to-end basis. The procedures and times for each event were established and used to schedule the final in-flight task sequence. The underwater training supplemented the extensive ground training and 0*g* aircraft simulations.

To increase the margin for success and provide a suitable period of acclimatization before the performance of any critical tasks, the standup EVA was scheduled prior to the umbilical activity. The planned EVA timeline was interspersed with 2-min rest periods. Procedures were established for monitoring the heart rate and respiration rate of the extravehicular pilot; the crewmembers were to be advised of any indications of a high rate of exertion before the condition could become serious. Finally, the pilot was trained to operate at a moderate work rate, and flight and ground personnel were instructed in the importance of workload control.

The first standup EVA was very similar to the previous two missions. The ultraviolet-stellar and the synoptic-terrain photography experiments were accomplished on a routine basis. During the standup activity, the pilot performed several tasks designed for familiarization with the environment and for comparison of the standup and umbilical EVA's. These tasks included mounting the extravehicular sequence camera and deploying a handrail from the cabin of the spacecraft to the target docking adapter (TDA) on the target vehicle (fig. 12). The pilot also retrieved the experi-

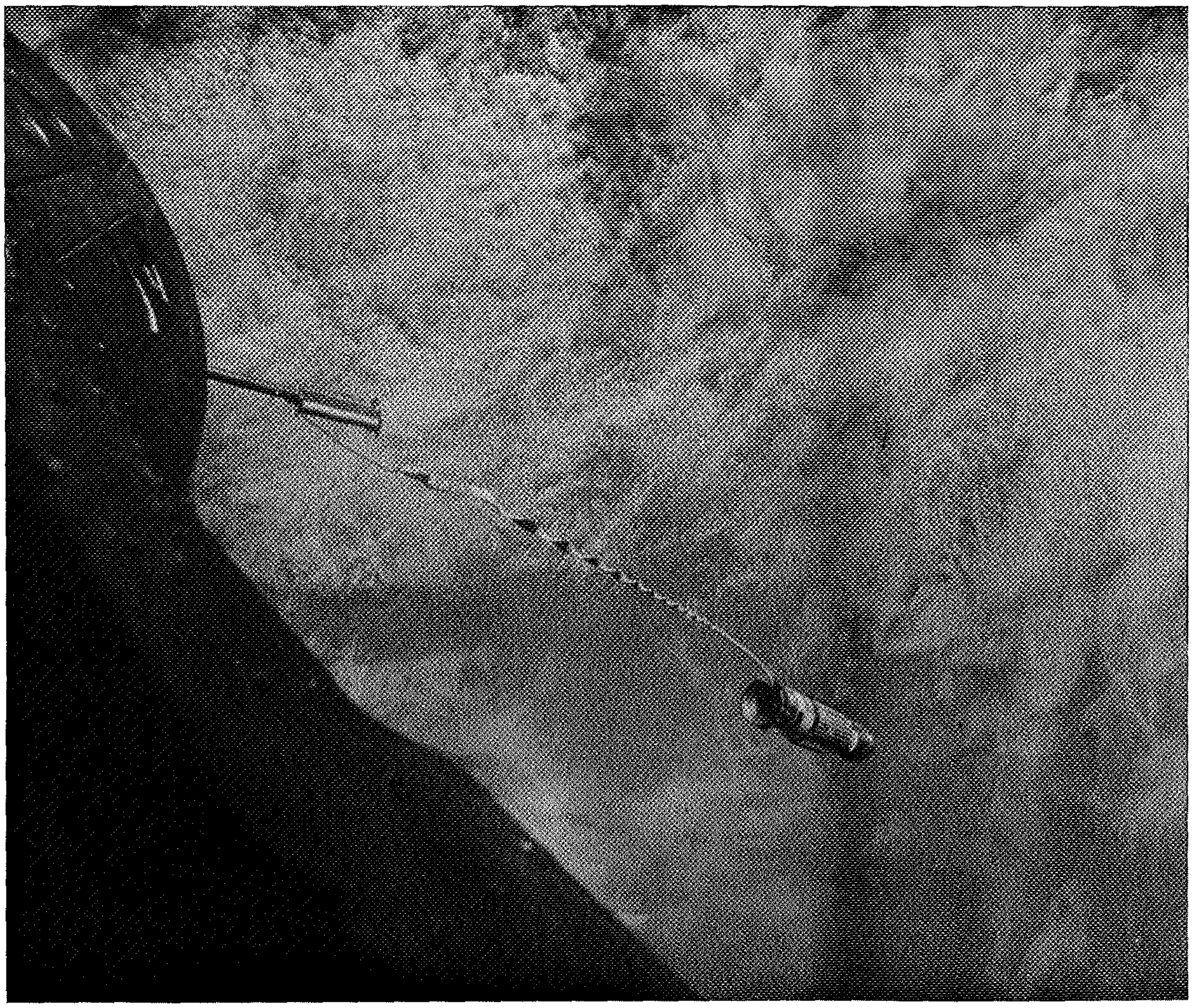


FIGURE 9.—Agena and spacecraft with tether attached.

ment S010 micrometeorite collection package and several contamination sample disks from the adapter section. The standup activity was completed without difficulty.

The umbilical EVA preparations proceeded smoothly. The hatch was opened within 2 min of the planned time. The use of waist tethers during performance of the initial tasks on the TDA enabled the pilot to rest easily, to work without great effort, and to connect the spacecraft/target vehicle tether in an expeditious manner. The pilot activated the experiment S010 Agena micrometeorite collection package on the target vehicle for possible future retrieval. Before the end of the first daylight period, the pilot moved to the spacecraft adapter section where he evaluated the work tasks of torquing bolts, making and breaking electrical and fluid connecters, cutting cables and fluid lines, hooking rings and hooks, and stripping patches of Velcro. The tasks were accomplished using either the foot restraints or the waist tethers. Both systems of restraint proved to be satisfactory.

During the second daylight period of the umbilical activity, the pilot returned to the target vehicle and performed tasks at a small work station on the outside of the docking cone. The tasks were similar to

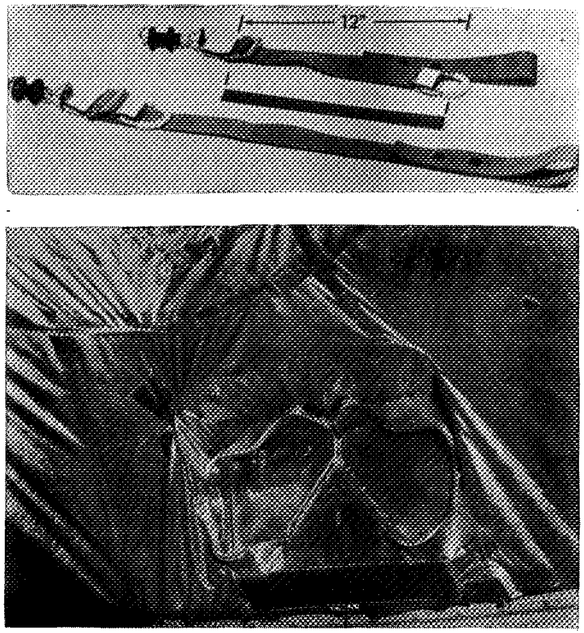


FIGURE 10.—Waist tethers (above); EVA foot restraints (below).

those in the spacecraft adapter section and, in addition, included use of an Apollo torque wrench. The pilot evaluated working with the use of one or two waist tethers and without a waist tether. At the end of the scheduled EVA, the pilot returned to the cabin and ingressed without difficulty. A second standup EVA was conducted. Again, this activity was routine. All the objectives were satisfactorily completed.

The results of the Gemini 12 EVA showed that all the tasks attempted were feasible when body restraints were used to maintain position. The results also showed that the EVA workload could be controlled within desired limits by the application of proper procedures and indoctrination. Finally, perhaps the most significant result was that the underwater simulation duplicated the actual extravehicular actions and reactions with a high degree of fidelity. It was concluded that any task that could be

FIGURE 11.—Underwater simulation tests.

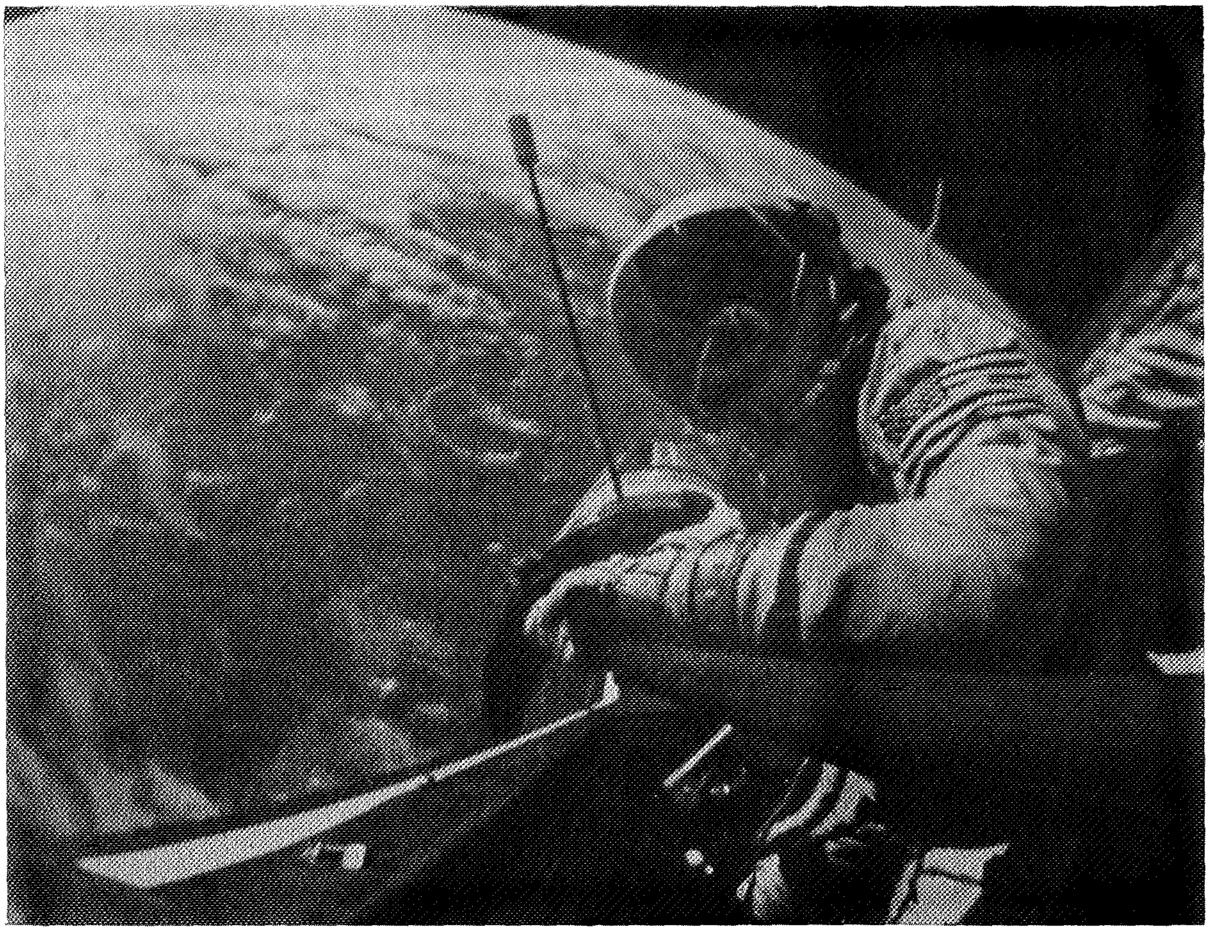


FIGURE 12.—Deployment of handrail during EVA.

accomplished readily in underwater simulation would have a high probability of success during the actual EVA.

RECOMMENDATIONS

EVA should be considered for future missions where a specific need exists, and where the activity cannot be accomplished by any other practical means. Because EVA involves some increased hazard, it should not be conducted merely for the purpose of doing EVA.

In future EVA missions, consideration should be given to body restraints, proper task sequence, workload control, realistic simulation, and proper training.

Underwater simulation should be used for EVA procedures development and crew training in conjunction with 0g aircraft simulations and ground simulations.

The HHMU should be evaluated further in orbital flight, with emphasis on stability and control capabilities. Other maneuvering systems that incorporate stabilization systems should be evaluated for comparison.

Priority efforts should be given to improving the mobility of spacesuits, with emphasis on arm, shoulder, and glove mobility.

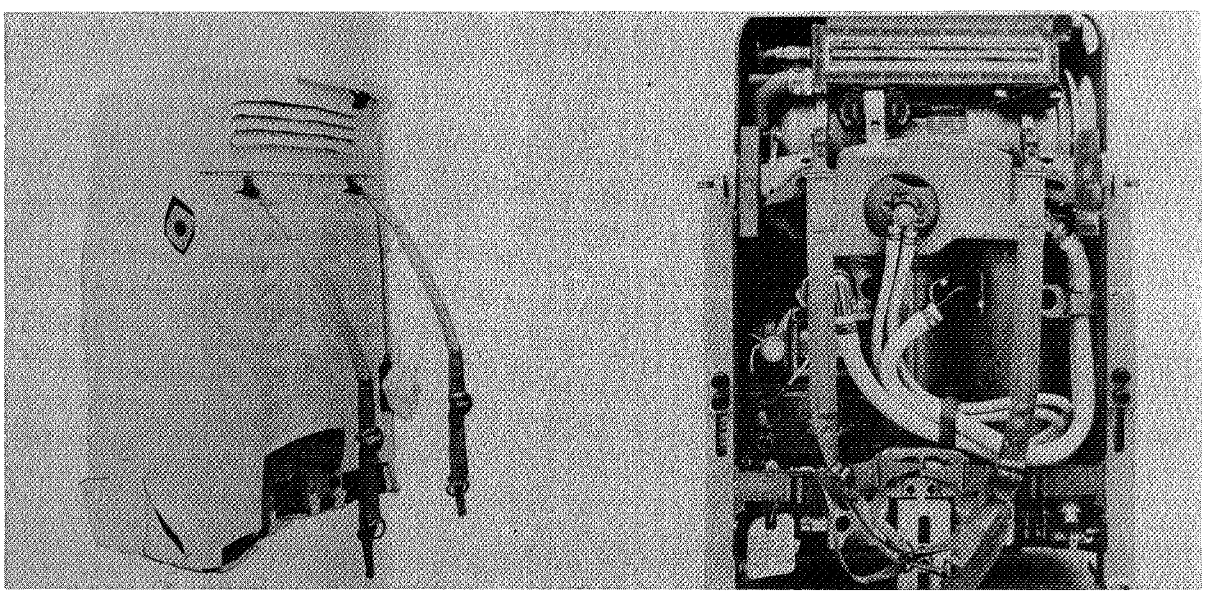
In future extravehicular life support systems, consideration should be given to cooling systems with greater heat removal capability than the gaseous cooling systems used in the Gemini program. The bulk and encumbrance of sizable chest-mounted units should be avoided. Any life support system should be capable of supporting the anticipated peak workloads.

Vacuum chamber tests should be included in the preparations for future EVA missions. Both the prime and backup crews should participate in these tests using EVA flight hardware.

Detailed EVA flight plans and crew procedures should be established as early in the hardware-development cycle as possible so that the impact of design or procedures changes can be evaluated.

CURRENT HARDWARE

The suit and life support and ancillary equipment are being developed for the Apollo program to provide the requested changes. The Apollo system is well into qualification and the suit life-support combination is called the extravehicular mobility unit (EMU) (figs. 13 and 14). The suit incorporates constant-volume joints to enhance the mobility in the pressurized condition. The portable life support system (PLSS) incorporates a water-cooled heat-transport system for metabolic heat rejection with capability of 1600- to 2000-Btu rates. The PLSS heat exchanger is capable of rejecting much higher rates; however, the 3-hr capability with 1-hr contingency will be shortened if higher rates are sustained. The heat is removed from the body by means of a liquid-cooled garment with multiple-tube passages covering the majority of the body. Carbon dioxide is removed by means of lithium hydroxide and circulating gas. The PLSS contains its own oxygen supply to support the 4-hr mission, plus emergency time.



Thermal capacity: metabolic:
- 4800 Btu's total
- 1200–1600-Btu/hr average rates
- 2000-Btu/hr peaks

External leakage:
- 250 Btu/hr in
- 350 Btu/hr out

Pressure:
- 3.8 psia nominal
- 3.2 psia minimum (emergency)

Carbon dioxide:
- 7.5 mm Hg nominal
- 15 mm Hg maximum (contingency)

Communications: telemetry:
- Redundant 2-way simultaneous voice
- 7 channels of telemetry

FIGURE 13.—Apollo extravehicular mobility unit.

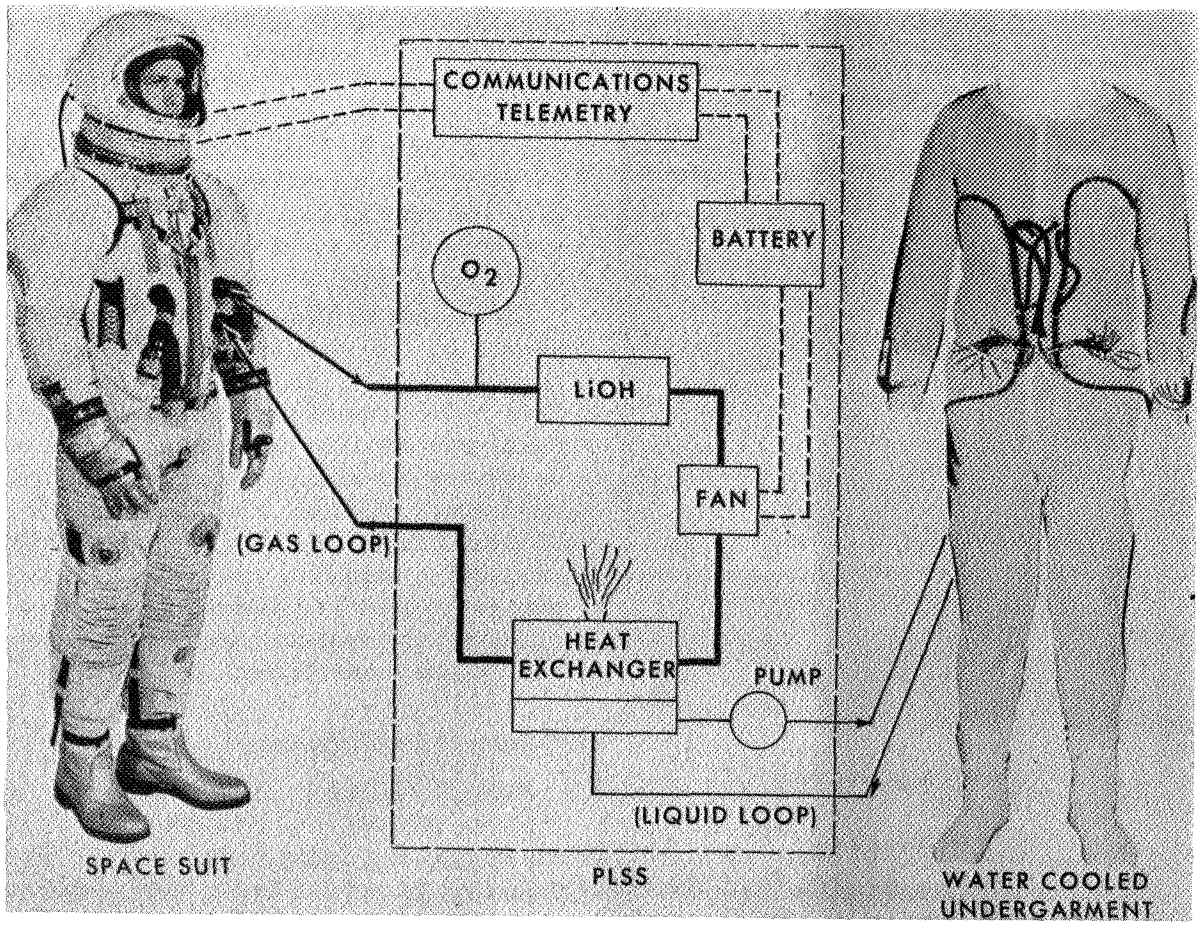


FIGURE 14.—Apollo portable life support system.

Advanced systems are currently in development to increase the suit mobility, body cooling, and life support capabilities. The "hard suit" is planned for use on extended lunar-surface missions. It is constructed of aluminum and fiber glass with rolling convolute bellows at the major points of body articulation (fig. 15). The portable environmental control system (PECS) is an advanced life support system. Its major improvements are increased performance, smaller size and volume, and a chemical oxygen source (fig. 16). Restraints and tethers are being investigated that include adhesive attachments.

The material being presented regarding advanced missions is only speculative in nature, and represents the thoughts of this writer, not necessarily those of NASA. Long-range planning for EVA is currently being formulated and might differ from some of the mission descriptions described herein.

APOLLO, APOLLO APPPLICATIONS PROGRAM, AND ADVANCED MISSION PLANNING

In support of the U.S. manned Apollo space exploration, the EVA programs can be divided into two general types of EVA missions: EVA missions occurring during Earth or lunar orbital space flights and EVA excursions occurring during a planetary surface. As presently outlined, the Apollo and the advanced Apollo programs include both orbital and lunar-surface EVA missions as a basic operational and experimental task.

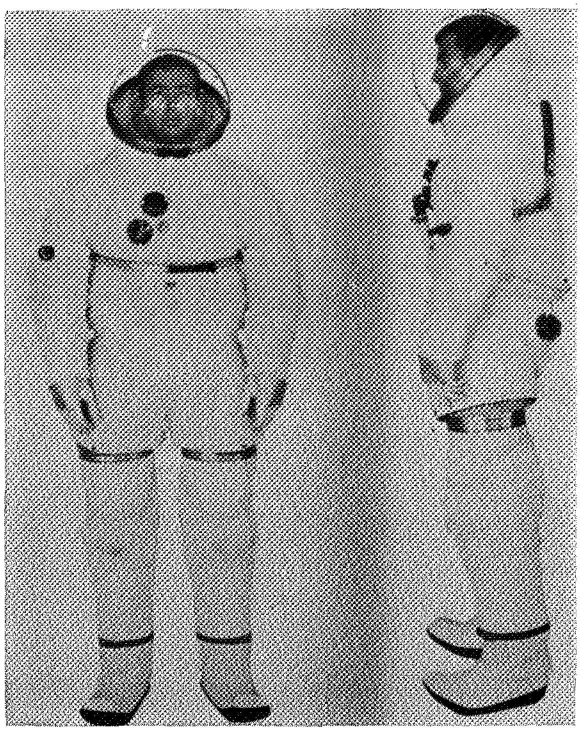


FIGURE 15.—Hard suit.

Orbital EVA

During early Apollo missions, orbital EVA will always be accomplished in the near vicinity of the spacecraft or habitable quarters. Under these conditions, the crewman will be within immediate rescue range, yet he will be able to perform a large number of EVA functions properly and efficiently. EVA tasks, some of which are described in the following discussion, include inspection of orbiting vehicles, maintenance and repair, activation and reactivation of dormant vehicles and resupply of active vehicles, materials retrieval from orbit, crew transfer, and conduct of scientific and engineering experiments.

Inspection of Orbiting Vehicles

Inspection of orbiting vehicles covers a wide range of applications, such as inspections prior to activation of dormant vehicles, inspection and photography of scientific or foreign satellites, periodic inspection of long-duration space stations, inspection or monitoring of systems deployment, and monitoring the conditions of experiment panels, such as emulsions. A planned program of periodic inspection, similar to that in aircraft applications, and inspections prior to reactivation of dormant vehicles are desirable when considering long-term usage of vehicles.

Tether attach points, "Dutch shoes," and permanent or detachable handrails are typical of the hardware required to support EVA inspections of the spacecraft. In some cases, provisions for these mobility aids can be predetermined, based on a known periodic inspection plan (fig. 17). For inspections of other orbiting vehicles, such as scientific satellites, a stabilized maneuvering system may be required. Other equipment would consist of the spacesuit assembly, life support system, tools, tethers, etc.

Maintenance and Repair

During extended orbital operation of complex systems, the probability of a failure of one or more systems increases. Complete system redundancy is one method of minimizing the impact of these failures; however, it is feasible in many cases to design a system such that component replacement is a simple process and could be performed by an extravehicular crewman. The optimum method is probably a combination of the two. One- and two-yr missions with resupply capability will tend to make replaceable modules more competitive with the redundant system designs. Typical repair tasks that could be accomplished include:

(1) Replacement of faulty sections of solar panels

(2) Replacement of thermal or radiation shields

(3) Replacement of radiator heat-transfer segments

(4) Cleaning optical surfaces

(5) Realinement of orbiting telescopes

(6) Replacement of modular components, such as power supplies and thrustors

(7) Repair of scientific satellites (in-

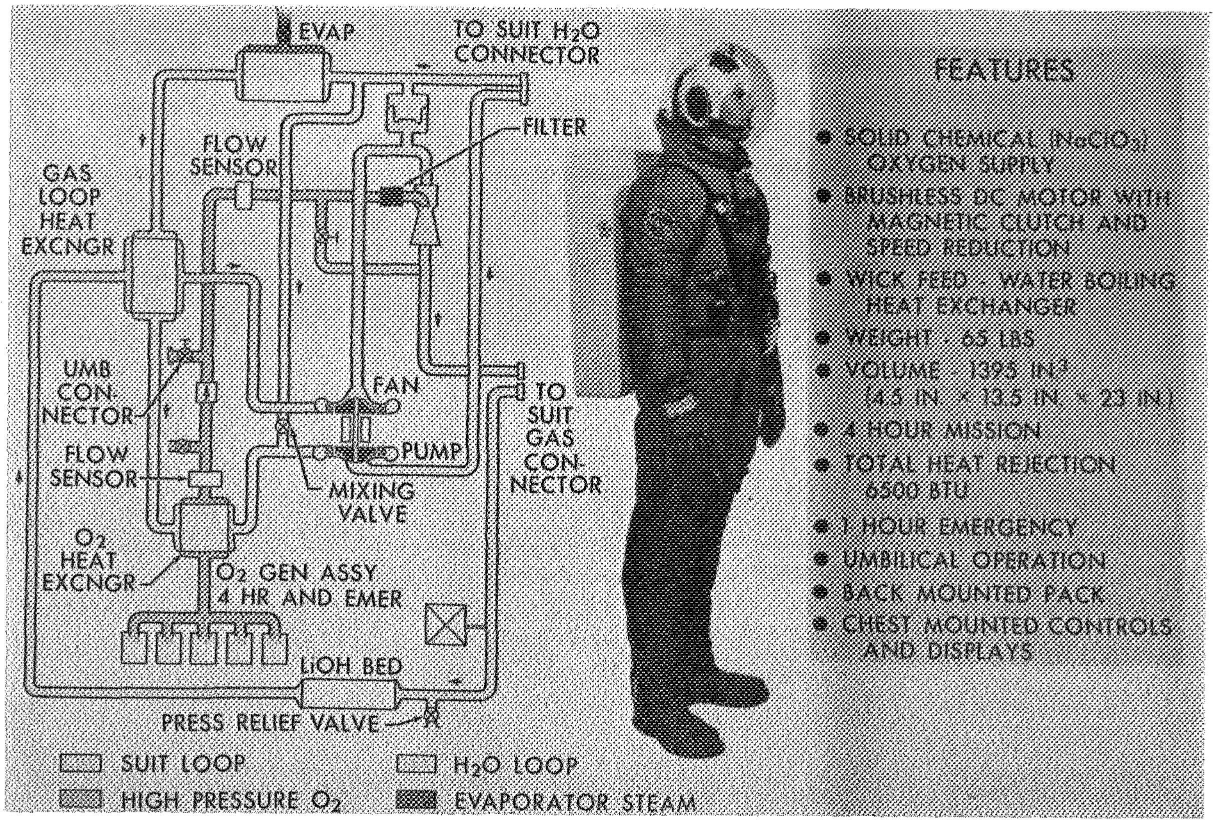


FIGURE 16.—Portable environmental control system.

cluding any of the above) after satellite capture

Simple maintenance and repair is already programed in Apollo because the PLSS required H_2O recharge, battery, and lithium hydroxide bed replacement.

The hardware required to accomplish maintenance and repair will consist of the suit, life support systems, stability augmentation equipment, and crew-transfer devices typical to those of the preceding task. In addition to these items, adequate tools will be required.

Activation and Reactivation of Dormant Vehicles and Resupply of Active Vehicles

The Apollo Applications Program (AAP) is developed around the establishment of various clusters of modules to establish orbiting laboratories (fig. 17). Activation, reactivation, and resupply each can involve the installation of external umbilicals from one module to another and can also involve the transfer of cargo from one module to another. An external umbilical installation (performed during EVA) is also included in certain concepts of the proposed Manned Orbital Solar Telescope (MOST) and the Manned Orbital Telescope (MOT). Presently, the AAP A and B mission activation, reactivation, and resupply are to be performed as intravehicular activity (IVA), except for contingencies. None of these contingencies requires extended umbilical connection or cargo transfer. However, this is based on a tentative decision to carry all O_2 and N_2 supplies on the command and service module (CSM). Should these supplies be carried on the airlock, an EVA umbilical connection would be required. Also, EVA capability may be required if the automatic solar-panel-deployment mechanism fails. Although no definite requirement for

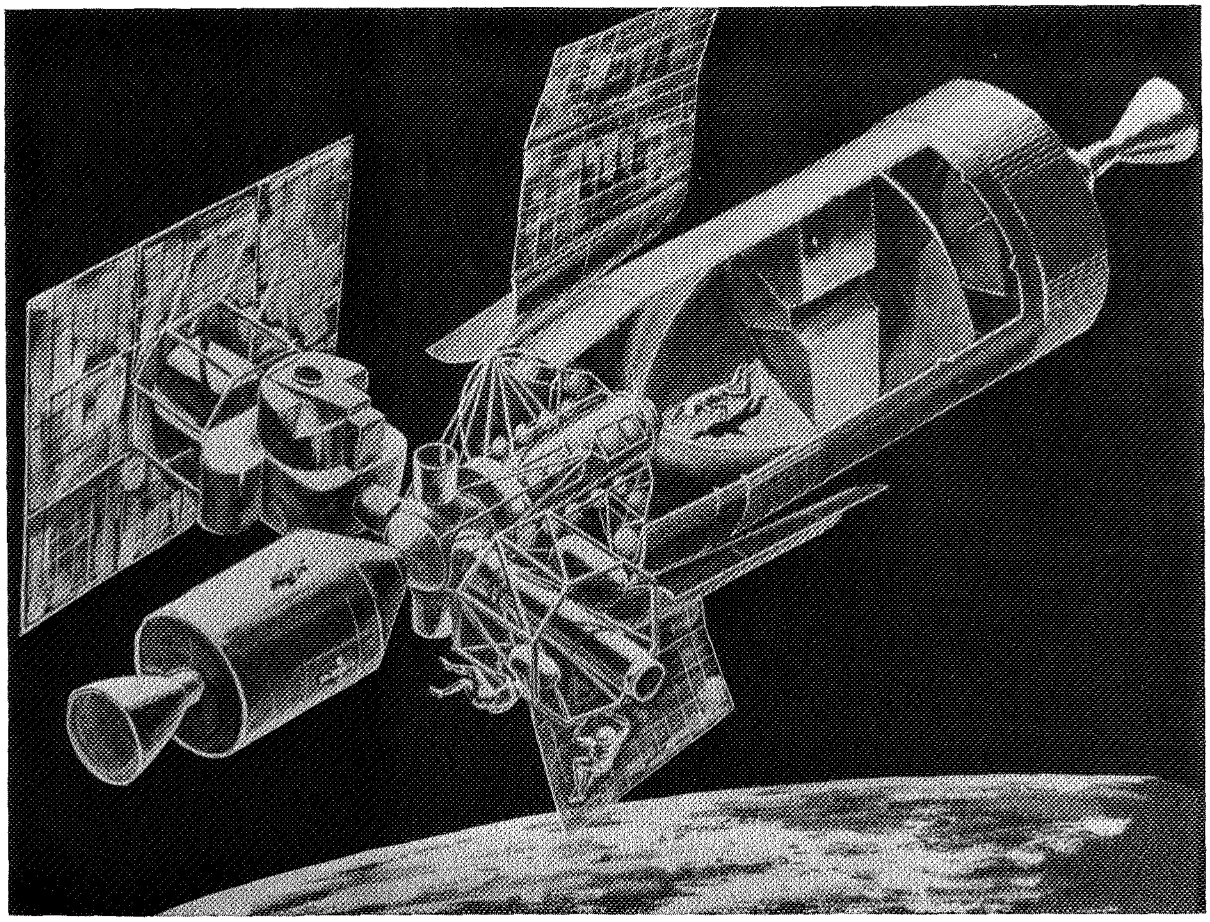


FIGURE 17.—AAP cluster.

these contingencies has been identified, it is felt that the capability should be developed in a timely manner, with the expectation that for some of the later missions the capability will be required. Development of these capabilities can evolve from the normal transfer of equipment between the CM, airlock, orbital workshop (OWS), and LM/ATM of AAP A and B and from the installation of various portable handrails and umbilicals during the normal course of the early AAP missions.

Systems required to support these activities include

(1) Spacesuit assembly, including liquid-cooled garment (LCG), thermal, and micrometeoroid protection
(2) Life support system, including umbilical
(3) Stability augmentation:
  (*a*) Station aids such as tethers and "Dutch shoes"
  (*b*) Handrails to ease cargo transfer
  (*e*) Emergency transfer devices

Apollo Program Lunar Surface EVA

During the mainline Apollo lunar-surface missions, emphasis is to be placed on astronaut exploration of the area immediately surrounding the landing site. It is planned that the major tool for this exploration should be the Apollo lunar surface experiment package (ALSEP). The ALSEP is carried to the lunar surface in the descent stage of the LM (fig. 18). The package is programed to provide experimental data

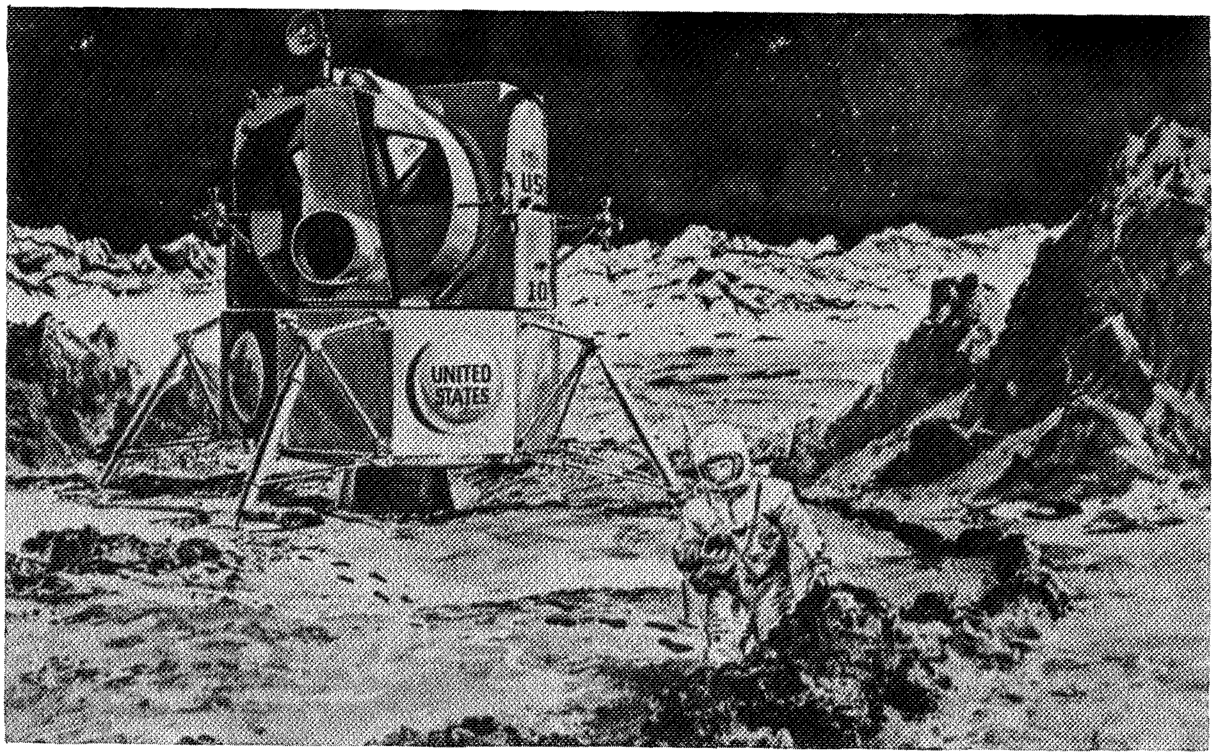


FIGURE 18.—Lunar module.

relative to solar-wind detection, passive seismometry, magnetometry, superthermal ion detection, total pressure and heat-flow measurement, and active seismic experiments.

The astronaut, after a complete checkout of the pressure suit and the extravehicular life support system, will remove the ALSEP from its stowage location on the descent stage of the LM and prepare it for the experiment. The astronaut carries the packages to a distance of approximately 320 ft from the LM boarding platform and sets them on the lunar surface. From this position the astronaut begins to position each experiment package, transmitter, sensor, etc., as required by the mission plan. Deployment is shown in figures 19 and 20.

Extended Lunar Surface EVA

Discussion herein, relative to lunar-surface EVA, will be limited to those missions and tasks that can be accomplished within the relatively short radius (15 miles) limits of the presently conceived lunar-surface mobility vehicles and the initial experimental scientific exploration of the lunar surface. Lunar-surface missions will tend to fall into one of several task categories that will be discussed.

Activation and Reactivation of Dormant Vehicles

A large portion of the lunar-surface mission (both long- and short-duration stays) requires that the astronaut participate in the establishment of the lunar base, activation of the lunar habital shelter, and in the preparation of test equipment for performing the required experiments. Typical tasks involved in such base activation would include:

(1) Securing of the habital shelter after astronaut landing; the attaching of necessary umbilicals, etc.; and preparing the quarters for the mission stay

FIGURE 19.—ALSEP deployment.

(2) Travel of the astronaut from the LM to the landing areas of the LM taxi

(3) Cargo handling at the LM taxi site to unload surface transportation vehicles, expendable stores, spare equipment, scientific test equipment, etc.

(4) Equipment assembly and checkout to complete establishment of the lunar base

Maintenance and Repair Tasks

As we begin to develop the capability for long-duration surface stays and revisit to previously occupied lunar stations, the maintenance and repair tasks will be assuming an increasingly important role. With the development of maintenance and repair technology, the astronaut will be provided with the capability to resupply vehicles with such expendables as water, oxygen, power generation fuels, etc., and will be capable of replacing worn or damaged units with new equipment with the intent of placing the facility back into operation. Frequently, it may be found that through the proper use of repair capability, loss of complex equipment and vehicle may be prevented.

Conduct of Scientific and Engineering Experiments

In the near future, one of the primary objectives for performing lunar-surface missions will be for scientific and engineering experimentation. A large portion of these experiments, accomplished in response to the scientific and industrial communities, will require that the astronaut perform duties outside the habital quarters. Many of the initial experiments are related to geological survey and data gathering during which the EVA crewman would be required to journey a specified distance from the lunar base.

During the mission, the EVA astronaut would be responsible for installing scien-

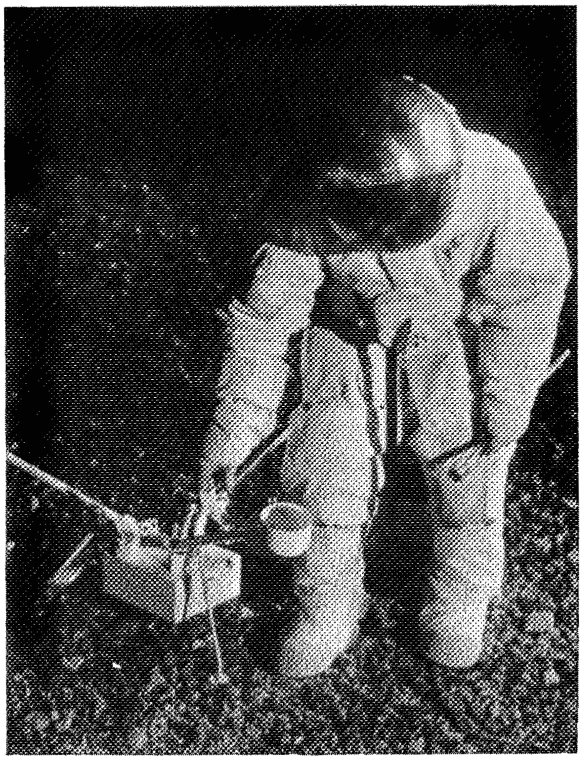


FIGURE 20.—ALSEP deployment.

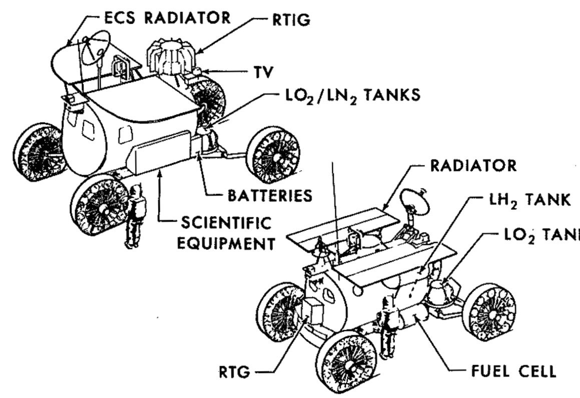


FIGURE 22.—MOBEX–MOLAB-type vehicles.

tific equipment at predetermined sites, carrying out specified photographic tasks, collecting surface and core specimens as required, and collecting data from previously established experimental stations. Lunar mobility aids are used to enhance the lunar-surface exploration capability. Two basic methods, rovers (wheeled vehicles) and flyers, and under consideration. Several types of manned roving vehicles for lunar-surface mobility have been envisioned and studied. These vehicles have ranged in size and utility from the local scientific survey module (LSSM), which is a short-range, dependent, open-type vehicle (fig. 21), to the mobile exploration (MOBEX), mobile laboratory (MOLAB) type vehicles, which are long range and self-sustaining and have environmentally controlled crew areas (fig. 22).

A review of the overall lunar program, of the study of payloads, and of the capabilities required on various missions indicates a need for a lunar flying vehicle on early lunar landings (fig. 23). Lunar flying ve-

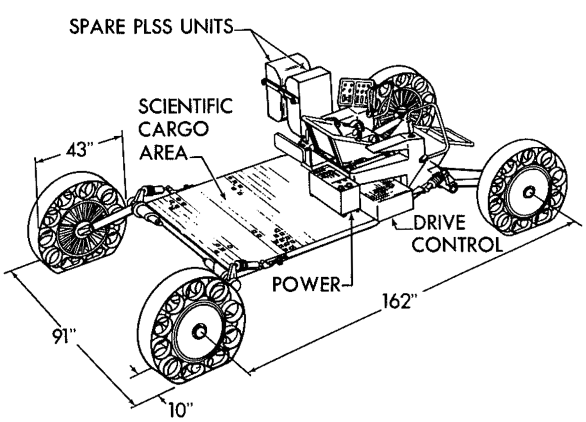


FIGURE 21.—LSSM concept.

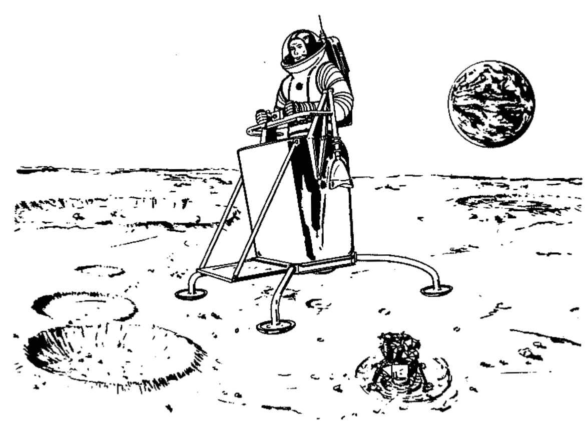


FIGURE 23.—Flying vehicle.

hicles weighing approximately 150 to 440 lb can be delivered to the lunar surface on single-launch missions, as well as on dual-launch missions. This vehicle will significantly increase the capability to investigate a number of scientifically interesting sites and to serve as a rescue vehicle. Other general capabilities include reconnaissance with or without a camera, exploration of rough terrain and craters, and traverse over inaccessible terrain in a minimum of time. The propellant for the flying vehicles would be the LM descent-stage residuals on the single launches, the LM descent-stage residuals of logistic deliveries on dual launches, and additional propellants carried as part of the lander payload.

SUMMARY

In summary, it has been the purpose of this paper to review the EVA experiences to date and to outline the type of tasks that can best be performed by EVA.

Through the centuries, construction, maintenance, and repair tasks have been performed by manual labor; likewise, in manned space missions, tasks of this nature can best be performed by man. As we progress toward exploration of the lunar surface, the capabilities of man to apply his knowledge and capacity for judgment are required to gain the best scientific data. It is considered necessary to develop an optimum EVA capability to allow our manned space-flight program to fulfill its objectives.

Man in the Operational Aspects of Space Missions

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From the outset of this era of space exploration, a main thrust of activity has been to place man in space and to utilize his unique capabilities for contributing to this endeavor. From the efforts of this country, nearly 2000 man-hours of manned space-flight experience have been accumulated in the Mercury and Gemini programs. This experience has shown that man can readily adapt to this environment, as demonstrated in flights of up to 2 weeks; but of more importance, he can make significant contributions to the success of each mission. The intent of this paper is to describe how man has been utilized in the space flights to date and to illustrate the capabilities that have been demonstrated. This information is then projected in consideration of near-term future space exploration activities in which man will be engaged, and then in consideration of what might be expected in the longer term and the influence on design approaches and operational concepts.

THE MERCURY PROGRAM

The Mercury program was the first series of experiences of this country with man in space. Prior to these initial flights, much questioning occurred concerning man's ability to adapt and function in this new environment. Particularly of concern was long-term weightlessness, but other factors, such as launch and reentry environment, confinement, and postlanding conditions, also were of concern. A listing of some of the suspected effects is presented in table I. The second column in the table shows that no major problems have as yet been experienced in this area. Because of the factors just outlined, unmanned ballistic and orbital flights were accomplished for systems demonstration and, in addition, primates were flown under these conditions as a precursor to manned flights. These early flights were accomplished successfully, but the requirement for them did influence the spacecraft design. The spacecraft incorporated features required for completely automatic flight although, in most instances, features were incorporated that allowed the astronaut to take over or back up critical functions.

A typical example of this approach is related to the system utilized for abort during powered flight. As shown in figure 1, an attempt was made to sense all critical parameters producing abort, such as attitude ex-

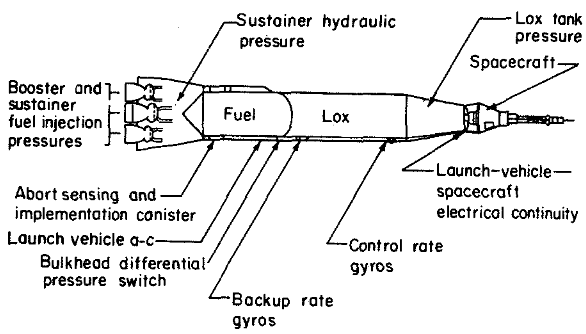

FIGURE 1.—Abort system sensors for Mercury-Atlas launch vehicle.

*Presented by John H. Disher, NASA, Washington, D.C.

TABLE I.—*Human Response to Space Flight*

Predicted	Observed
Dysbarism	None
Disruption of circadian rhythms	None
Decreased g-tolerance	None
Skin infections and breakdown	Dryness, including dandruff
Sleepiness and sleeplessness	Interference (minor)
Reduced visual acuity	None
	Eye irritation
	Nasal stuffiness and hoarseness
Disorientation and motion sickness	None
Pulmonary atelectasis	None
High heart rates	Launch, reentry, extravehicular activity
Cardiac arrhythmias	None
High blood pressure	None
Low blood pressure	None
Fainting postflight	None
Electromechanical delay in cardiac cycle	None
Reduced cardiovascular response to exercise	None
	Absolute neutrophilia
Reduced blood volume	Moderate
Reduced plasma volume	Minimal
	Decreased red-cell mass
Dehydration	Minimal
Weight loss	Variable
Bone demineralization	Minimal calcium loss
Loss of appetite	Varying caloric intake
Nausea	None
Renal stones	None
Urinary retention	None
Diuresis	None
Muscular incoordination	None
Muscular atrophy	None
	Reduced exercise capacity
Hallucinations	None
Euphoria	None
Impaired psychomotor performance	None
Sedative need	None
Stimulant need	Before reentry occasionally
Infectious disease	None
Fatigue	Minimal

cursions beyond prescribed limits and low engine thrust. These sensors were tied into a system that initiated the abort sequence automatically. The astronaut did have capability to initiate and carry out various aspects of the abort sequences as well. No special displays were provided other than an abort light.

The possibility of nuisance aborts was of great concern with this system. Although these were not experienced during the manned flights, levels of the abort parameters were adjusted during the program when it was discovered that certain conditions closely approached limits of the abort parameters but were not significant. Early in the program a nuisance abort did occur. It involved the flight of Mercury/Redstone 2. Because the engine operated at higher than expected thrust, cutoff velocity was achieved early, prior to the time the abort sequence was automatically inhibited. The spacecraft was inserted into its ballistic trajectory by firing the escape rocket—an extremely exciting event for Ham, the chimpanzee passenger. It also caused the spacecraft to land considerably uprange from the point expected. This type of problem was avoided in the Gemini spacecraft design by giving the astronaut more direct control of the abort situation.

The ability of an astronaut to circumvent a serious failure condition was well demonstrated during the Mercury/Atlas 9 flight. This flight, the longest of the Mercury program (22 orbits), proceeded quite smoothly into the last few hours when a failure was suddenly encountered in the automatic attitude-control electronics. Astronaut Cooper was able to take over manually to accomplish the critical control of spacecraft attitudes during retrofire and reentry and, in fact, performed the most accurate landing in the Mercury program.

THE GEMINI PROGRAM

The general experience with the Mercury flight program indicated that the astronaut should have more direct control of sequences of events and decision points than was possible in the Mercury design. Of considerable concern was the possibility of inadvert-

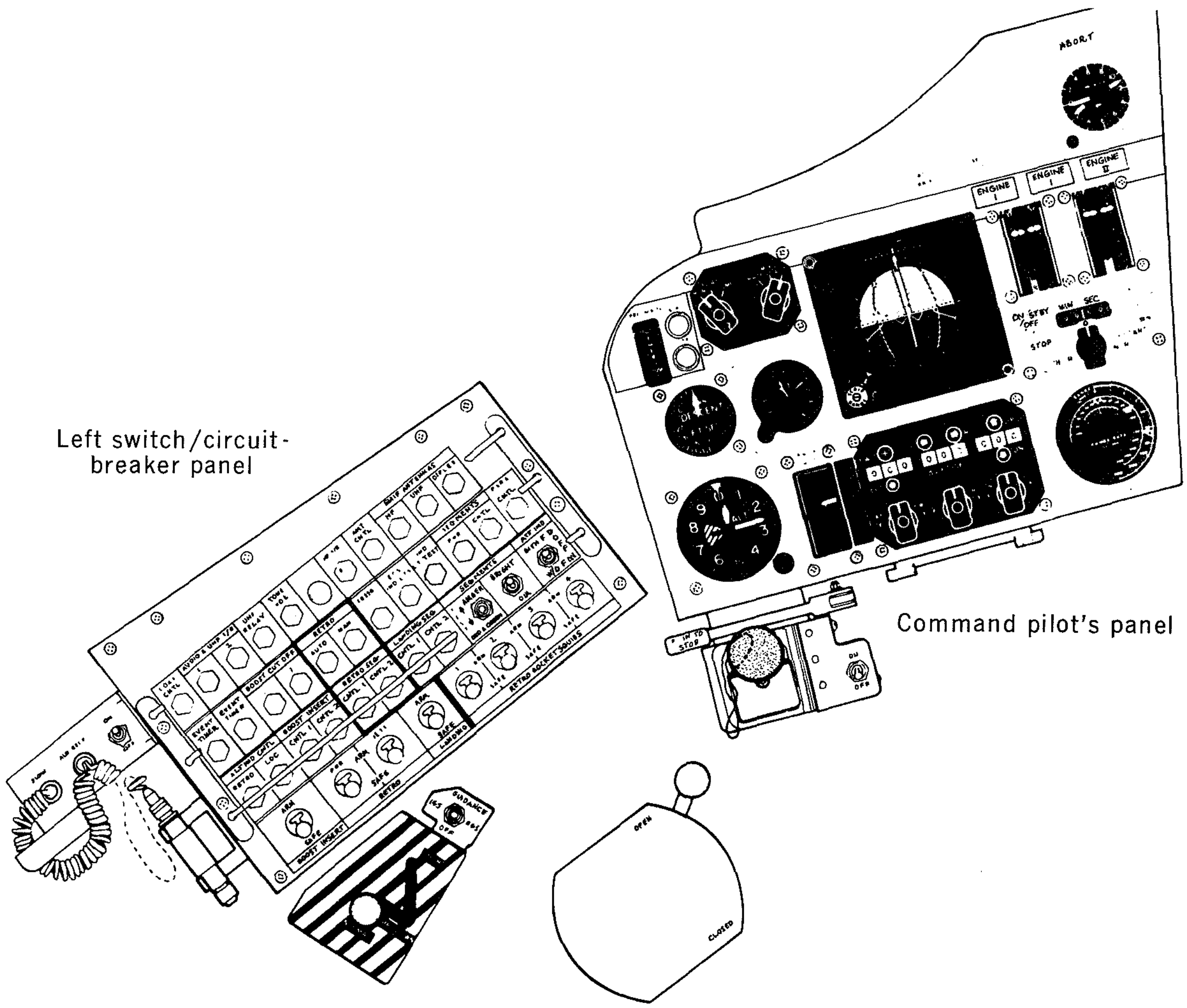

FIGURE 2.—Command pilot's displays and controls.

ent actuation of sequences under conditions that were not proper. Because automatic interlocks were used for preventing such occurrences, the alternate case, that interlock failures might prevent a critical sequence from taking place, was of equal concern. Such possibilities were largely circumvented in the Gemini design by placing the astronaut in more direct control of critical sequences, thereby assuring proper conditions for their initiation and greatly simplifying many systems as well.

A good example of this approach is the Gemini abort concept. No automatic abort capability was incorporated. Instead, the command astronaut was given a grouping of displays, as shown in figure 2. This set of displays allowed him to monitor engine performance, tank pressures, vehicle motions, and staging, and was the primary basis for manual abort initiation. For those conditions such as rapid-vehicle attitude excursions, where manual abort action would not be sufficiently rapid, a redundant flight control system was utilized in the launch vehicle and automatic switching would occur, allowing the flight to be carried on in a normal manner. This system involving manual aborts provided an extremely important capability during a Gemini 6 launch attempt. A launch-vehicle malfunction caused the engines to shut down just prior to liftoff; however, the onboard clock indicated that liftoff had occurred. Based on the

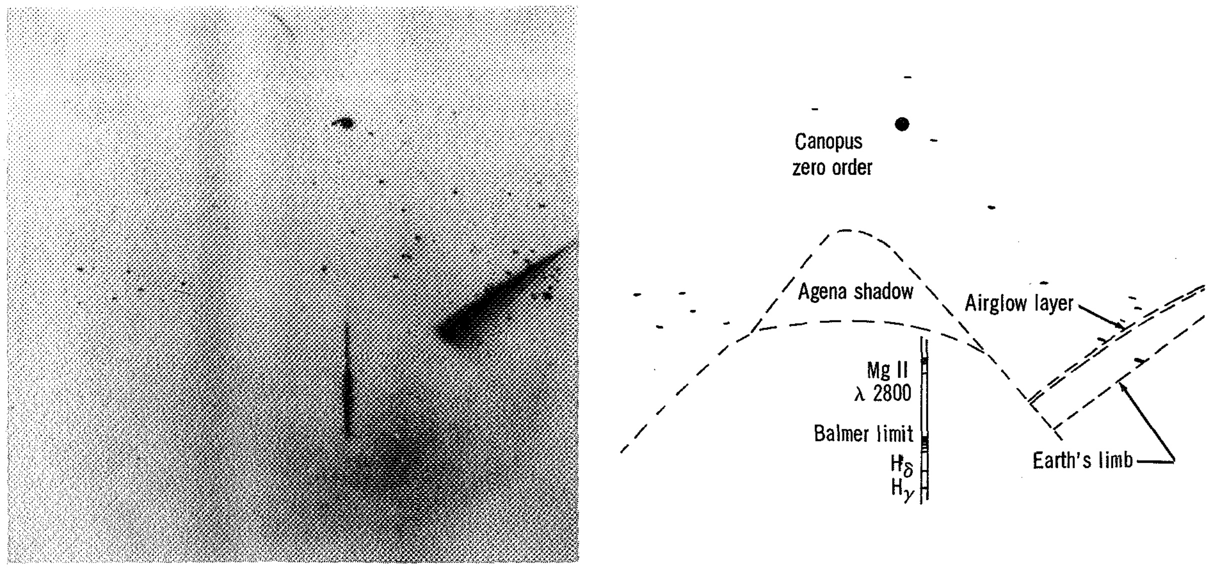

FIGURE 3.—Ultraviolet spectrum of Canopus.

off-nominal sequence of engine shutdown and clock start, and based on other cues such as sound and lack of vehicle motions, the astronauts were able to immediately determine that an abort was not necessary. Their judgment was extremely important in this case, for if an abort had been initiated it would not have been possible to recycle the operation and the Gemini 7-Gemini 6 rendezvous would not have been accomplished.

Many instances occurred during Gemini in-orbit operations where the system management capability afforded by this relationship between man and machine allowed missions to continue in the face of malfunctions. When the spacecraft electrical power system encountered difficulties on Gemini 5, the astronauts continuously altered the power requirements to allow the mission to continue and still obtain the maximum results from it. Similarly, when thrustors malfunctioned on a number of flights, the crew was able to develop alternate control techniques that allowed mission objectives to be attained.

This capability, evidenced by the crew in the systems management area, is only one instance related to the useful application of man in the system. In the experiment area, astronaut observations and photographs of unusual storm conditions, of special terrain features, and conduct of many scientific and technical tasks provided significant results. Figure 3 shows an ultraviolet photograph of a star field in the vicinity of Canopus, along with the grating spectrograms obtained. For comparison, this Gemini-acquired spectrum is accompanied by a ground-based spectrum of a similar star (fig. 4). This photograph was taken during a standup extravehicular period. With the absence of the filtering effects of the atmosphere and the spacecraft windows, much improved information was obtained. In addition, the astronauts' prior knowledge of star-field patterns enabled them to exercise discrimination in conducting their work and to obtain additional information from prism spectrograms related to a large number of stars.

Two geologic uses of manned orbital photography can be illustrated from the photograph taken over southern New Mexico during the Gemini 4 flight (fig. 5). Shown near the middle right is the Sierra Carizarilla. These mountains are a major volcanic field that, by comparison to a similar field, are thought to have been formed in the

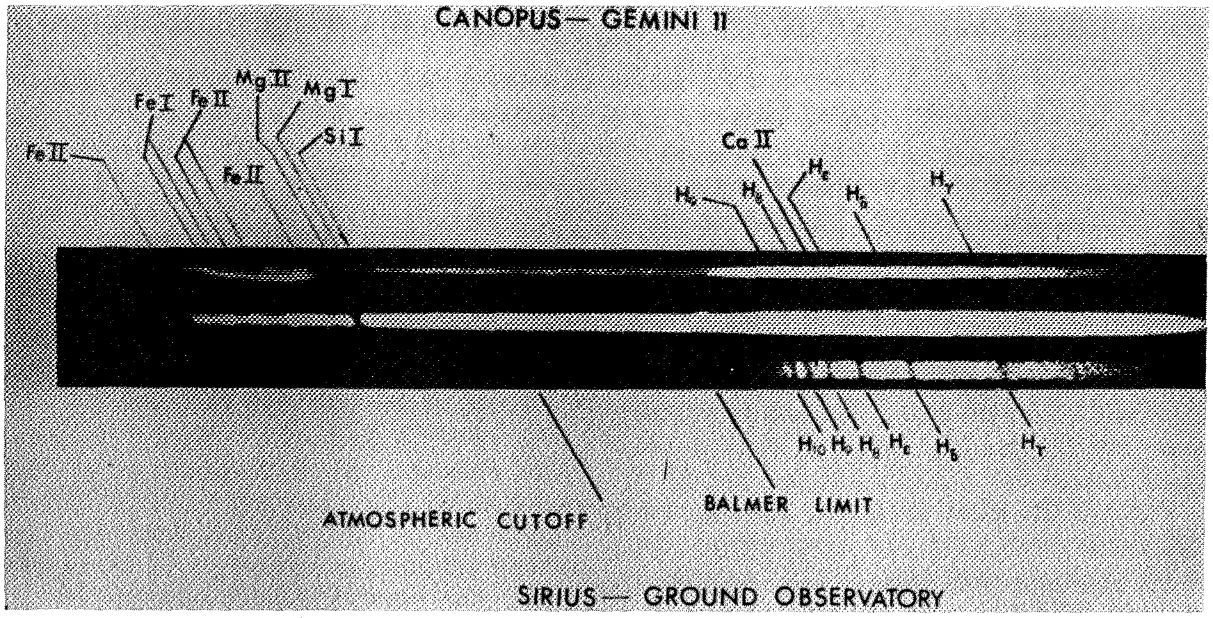

FIGURE 4.—Comparison of star spectra from orbit and Earth.

Pleistocene age, but even the most recent geologic maps show this area as much smaller in size and much older than established by Gemini. This photograph also shows at a glance the transition zone between the folded sedimentary rocks of northeastern Mexico and the faulted volcanic rocks of southwestern New Mexico and indicates considerable control of the faults by preexisting folds. Color photography of large areas without the degradation inherent in mosaics is extremely useful in studying structure, topography, and pedimentation.

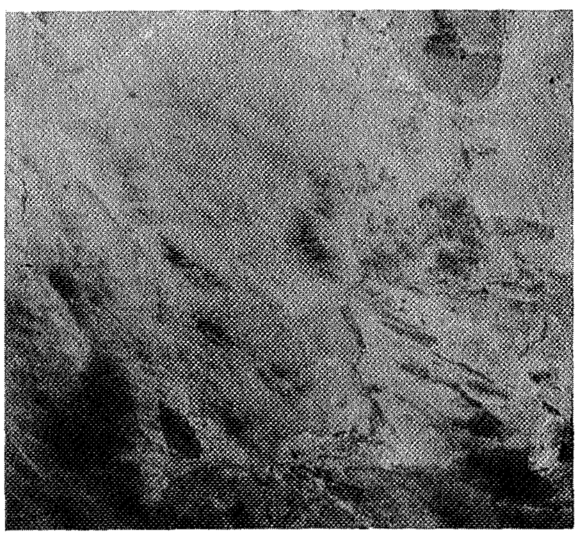

FIGURE 5.—Photograph taken over southern New Mexico from Gemini 4.

Certainly one of the more intriguing operational aspects to date of man in space has been the Gemini extravehicular activities. This subject must be highlighted as a very significant aspect of the use of man in enhancing future space operations, particularly in the area of maintenance, equipment retrieval, and observations. Much effort was spent on Gemini in developing and demonstrating a practical extravehicular capability, and this was indeed demonstrated on the last mission.

THE APOLLO PROGRAM

Turning now to Apollo, one can say that the role man played in Gemini will also exist in Apollo in terms of his ability to enhance the success of the mission by circumventing flight system difficulties and by controlling such operations as rendezvous and docking. There are, in addition, some outstanding new responsibilities that will be placed on the crew. This statement particularly applies to that phase of the flight where, for the first time, a manned landing will be made on an extraterrestrial body and the surface thereof will be explored by man himself. Although the landing approach, in a manner similar to the powered launch, will be controlled basically automatically, the discretion as to when to initiate certain sequences will be the responsibility of the crew. In particular, in the hover condition prior to touchdown, the crew will select the best place within a local area for the landing and will control the lunar module for a landing at that point.

Perhaps the most intriguing activity will be encountered when the crew leaves the lunar module to conduct scientific investigations on the surface of the Moon. The scientific community feels very strongly that the only way to achieve high return from such activity is to provide for the direct observation and control of these operations by man. A typical timeline related to the activity that might be carried out is shown in figure 6, and the configuration resulting from deployment of the initial scientific stations is shown in figure 7. The astronauts in their pressure suits, utilizing portable life support systems, will perform limited traverses on foot to gather samples of the lunar surface, to make localized geological and geophysical observations, and to activate the equipment associated with the scientific experiments to be conducted. These operations represent a truly pioneering endeavor and will depend greatly on the crew to realize maximum benefits from the Apollo investment.

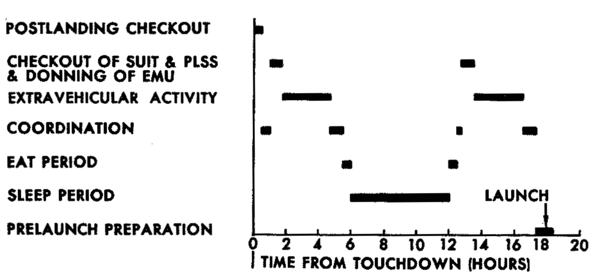

FIGURE 6.—Proposed lunar stay.

THE APOLLO APPLICATIONS PROGRAM

During the latter phases of the Apollo program and in the near-term future beyond Apollo, manned space flights will continue in Earth orbit and at lunar distances as a part of the Apollo Applications Program. The activities of this program are quite broad in scope and, therefore, it is not possible to discuss all aspects of the role that man will play; however, a few specific illustrations of the operations in near-Earth orbit will be used for this purpose.

In the early part of the Apollo Applications Program, the hydrogen tank of the upper stage of the uprated Saturn I launch vehicle will be utilized as a workshop, an experiment base, and a living area for flightcrews. The general in-orbit arrangement is shown in figure 8. Part of the modifications to the stage for this purpose are accomplished prior to launch and part are accomplished in orbit by the flightcrew. This rudimentary space station is envisioned to be inhabited for a period of 4 weeks on the first mission, but then through revisitation inhabited for still longer durations on subsequent missions. Naturally, one of the main objectives is to further establish the capabilities of man as involved in operating in a large enclosed volume, and in extending staytimes well beyond our experience to date. However, many other activities are envisioned involving 30 different medical, scientific, technological, and applications experiments. One such experiment involves a study of integrated maintenance tasks for the Department of Defense in which a molecular sieve will be periodically serviced. A typical scientific experiment to be conducted in the workshop involves a special telescope to scan the skies for X-ray sources and, in particular, to measure their basic size.

Perhaps the best example of man's participation in a major scientific effort will occur in connection with the second mission to the workshop. This mission will involve the ferrying of a large solar telescope to the workshop. After it is docked, the general arrangement of the configuration will be as

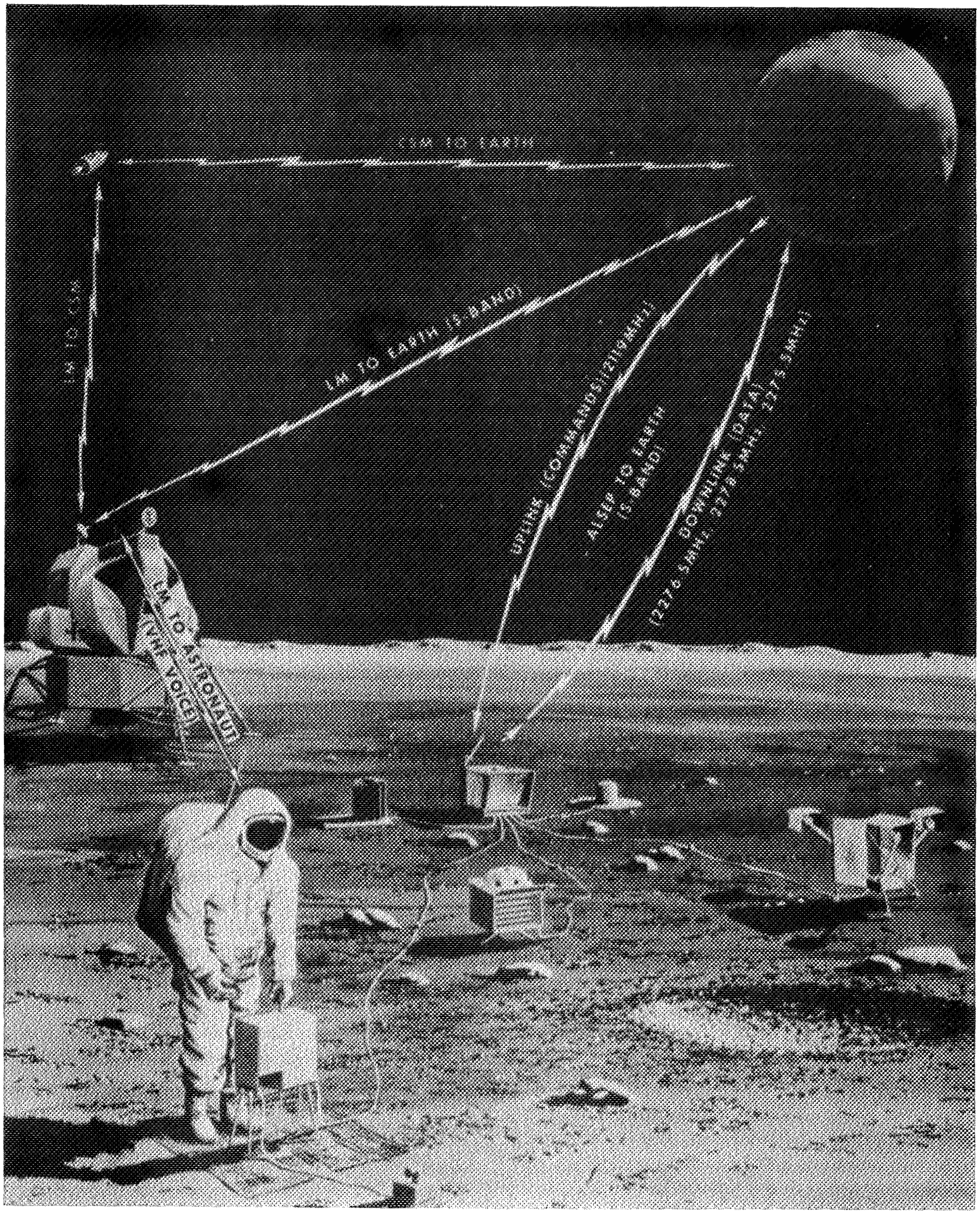

FIGURE 7.—ALSEP operations.

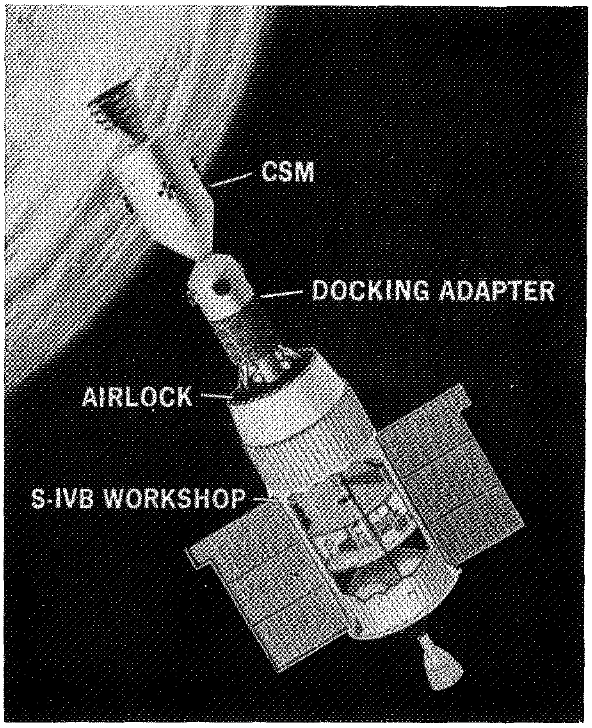

FIGURE 8.—AAP–1 and –2 orbital configuration.

illustrated in figure 9. The telescope and its supporting systems for pointing, instrumentation, thermal control, etc., are known as the Apollo Telescope Mount (ATM). This racklike structure is attached to the ascent stage of a modified lunar module, which serves as the manned control station. The telescope itself actually incorporates five different optical experiments and 13 different instruments and involves sensing in the ultraviolet, X-ray, and white-light regions of the spectrum.

The Sun's surface and its corona exhibit a very dynamic behavior, and the peak of this activity occurs in the 1969–70 time period. This equipment will enable multispectral observations to be made without the degrading influence of the Earth's atmosphere. The part that the astronauts will play is not only one of systems management but is also related to their observational vantage point associated with the dynamic behavior previously mentioned. The activities in which they will be involved are:

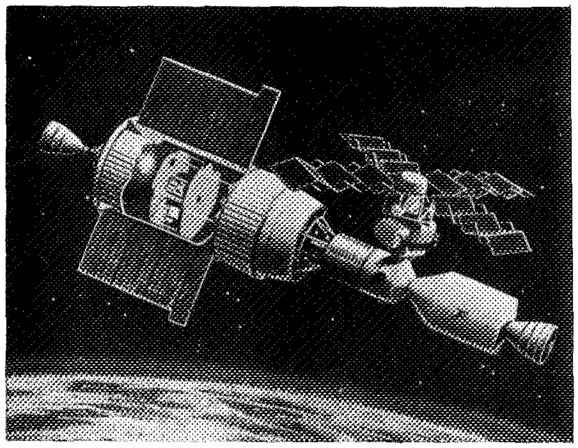

FIGURE 9.—AAP–1 through –4 orbital configuration.

(1) Sensing:
  (*a*) Initial acquisition and pointing
  (*b*) Fine alinement and trim
(2) Computing:
  (*a*) Trim for stability during "drift mode" observing periods
  (*b*) Sets and controls camera exposure sequences
(3) Maintenance:
  (*a*) Monitors experiment operation
  (*b*) Insures proper functioning of ATM
(4) Data acquisition: Recovers exposed film and magnetic tapes
(5) Scientist: Determines solar events of interest and directs system to observe

With displays projected directly from the sensing instruments, the astronauts will be able to observe continuously the development of activity areas on the Sun, such as solar flares and sunspots. Based on this information, augmented by ground observations, they will be able to very accurately point the instruments to discrete areas of interest and actually track specific features as they develop. In addition to this, they will have the discretionary capability of changing characteristics of the instrumentation such as exposure times, filters, activity of each instrument, etc. Another important activity will be the extravehicular retrieval of film packs. It has not proven practical, considering the requirements of the instruments, to develop a non-EVA mode. This operation, in conjunction with a rather large and sophisticated device, appears to be indicative of what the future may hold in many other areas.

There is reason to believe that as our space-flight capability further develops, there will be requirements for the use of more complex devices for scientific observations of the heavens, for applications related to observations of the Earth, for communications and control, for more extended journeys to and exploration of the surfaces of planets. One example of such a prospective space facility is the manned orbiting astronomical laboratory, illustrated in figure 10. In addition, all of these activities require the exploitation of long-duration operations, both for economic reasons and for operational consideration.

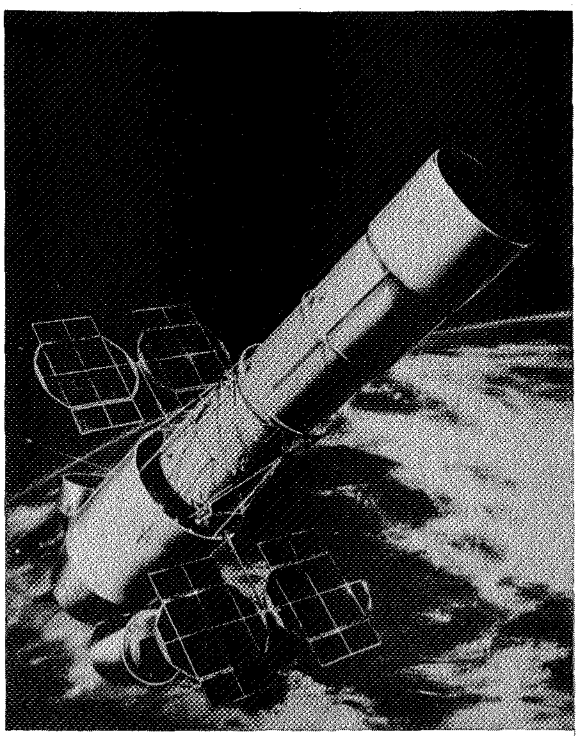

FIGURE 10.—Manned Earth orbital telescope (120-in. diameter).

The combination of complexity and long duration tends to require a mode of use that protects the large investment involved, both with respect to obtaining the utmost in flexibility of use, as well as in assuring the continued operational status of equipment. These considerations would lead one to the belief that man must be directly involved to make adjustments and changes, to evaluate new results, to maintain and repair, and in some cases to operate the equipment. These requirements can be met in several ways, such as by continuous habitation with the equipment onboard a manned space station, by man tending basically unmanned equipment operating remotely from the space station, or by ferry operations from the ground to unmanned equipment. Indeed, there is a possibility that all of these approaches will be utilized.

One of the basic prerequisites to insuring this type of capability is new approaches to equipment and systems design that allow such functions to be performed in the space environment. We are just now beginning to take steps in this direction, but it is exceedingly important that we do consider this feature in the design of future manned and unmanned systems. The Apollo Applications Program is aimed at the intent of doing primary work in this area.

SUMMARY

In summary, manned space flight has shown a continued expansion in the utilization of the capabilities of man himself. These activities have progressed from the point of simple demonstration of the ability of man to adapt to and function in the space environment to the point where his unique capabilities have been integrated and utilized in the total man-machine system. This utilization not only encompasses the capabilities for the support of spacecraft operations but also has been extended to the conduct of a variety of space experiments. Such roles will be expanded in future missions, particularly in the areas of tasks related to the flexible economic use of experimental and applications equipment. As such systems become more sophisticated, the presence of man on the spot will be an important factor in achieving maximum benefits from our investment.

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