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Human Capabilities in Space

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Foreword

This paper was prepared by the NASA Life Sciences Division at the request of the Associate Administrator for Space Science and Applications. The purpose is to present an analysis of man's capability in space. Conclusions are based on past experience in manned space flight, current research, and future expectations. The subject of automation and how humans and machines can be effectively combined in future manned missions is addressed.

The role of man in space missions grows by the year. In the Space Station, he will be a critical system component. The success of this program requires that man's capabilities be employed most efficiently and productively. This paper presents the views of biomedical scientists as to what is now known concerning these capabilities and what are believed to be the key problem areas to be addressed if we are to ensure best use of man in space.

Summary

Man's ability to live and perform useful work in space has been amply demonstrated throughout the history of manned space flight. Current planning envisions a multi-functional space station that would provide a base for the conduct of scientific experiments, manufacturing, satellite maintenance, large structure assembly, and the dispatch of vehicles to high Earth orbit and deep space missions.

In deciding whether to allocate tasks to men or to machines, it is important to understand the capabilities and limitations of both. Man's unique abilities to respond to the unforeseen and to operate at a level of complexity exceeding any reasonable amount of previous planning distinguish him from present day machines. His limitations, however, include his inherent inability to survive without protection, his limited strength, and his propensity to make mistakes when performing repetitive and monotonous tasks. By contrast, an automated system can do routine and delicate tasks, exert force smoothly and precisely, store and recall large amounts of data, and perform deductive reasoning while maintaining a relative insensitivity to the environment. The establishment of a permanent presence of man in space demands that man and machines be appropriately combined in space-borne systems. To achieve this optimal combination, research is needed in such diverse fields as artifical intelligence, robotics, behavioral psychology, economics, and human factors engineering.

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Introduction

The successful completion of the verification phase of the Space Shuttle program leads inevitably to an increasing presence of man in space. The Space Shuttle will be used more in coming years for specific industrial and scientific purposes. Managers, scientists, engineers, and technicians will play larger roles. The ready availability of the Shuttle as a means for transporting humans and material into near-Earth space also gives impetus to planning for a space station. The space station is the logical next step - the permanent presence of man in space.

The incorporation of man as an integral element in space systems requires that his capabilities be used in the most efficient, productive, and economical manner possible. In order to achieve this, considerable information must be at hand concerning human capabilities as they exist within the unique environment of space. Orderly planning by NASA for the best use of humans in space systems requires answers to the following questions.

- What is the requirement for man in space in the foreseeable future? What tasks will be demanded of him in the space activities projected for the next decade?

- What classes of human capabilities appear most relevant for space activities? What do we know concerning the proficiency, limitations, reliability, and support requirements for these capabilities?

- What have we learned from past experience in manned space flight, particularly in Skylab and Spacelab, about the ability of people to live and perform useful functions in space? What has been the experience of the Soviets with their Salyut 6 and 7 space stations?

- What are the technology drivers most likely to affect the way in which humans are used in space missions? How are these technology advances likely to change the astronaut/space system interface over the next decade?

- What are the key issues to be addressed in allocating tasks to semi- or fully-automated machines versus human performance? What are the advantages and disadvantages in terms of cost, reliability, versatility, and decision making capability of automating specific tasks? How can computer-based systems best be used to support the human role?

- What NASA flight programs and plans are designed to increase our knowledge of human capability in space? How will this information be used in developing specific NASA missions for the next decade? What basic research issues remain to be addressed, either in ground-based or in-flight research programs?

Current Programs in Manned Space Flight

President Ronald Reagan, in 1982, stated four goals that would direct our nation's efforts in space during the coming decade. One of these goals was to establish a more permanent presence in space. This presence will be achieved through a number of different missions, each presenting the human with its own work requirements. The extent of the human effort in space over the next two decades can be appreciated through a brief review of the major space systems and manned missions planned for this period.

Space Shuttle

The Space Shuttle represents the key element in the American space program through the 1980's and into the 1990's. In the immediate future, nominal missions of the Space Shuttle will last for 7 days. There is some possibility of extending this to an on-oribt period of up to 30 days. Crew complement normally will vary between four and seven members. Inasmuch as four Shuttle orbiters will be in operation within a few years, the United States will have a relatively permanent presence in space through these flights alone. There also are a number of routes whereby the Shuttle can use its payload capability to provide for more extended manned missions.

Salyut

The Soviet Salyut program has contributed considerable information concerning the ability of a small number of humans to function for long periods of time in space. The Salyut 7, the latest version of a prototype space station, currently is in orbit. In 1982, Salyut 7 was the home for two cosmonauts for 211 days. Recently, three crewmen, including a physician, occupied the Salyut 7 to begin another mission.

The latest Salyut has been modified significantly. It now has two docking ports and can be resupplied as required with crew consumables. Salyut 7 also uses a new onboard computer system which relieves the crew of much routine work and which opens the way for a sharing of responsibilities. The interior has been upgraded with numerous improvements, including use of a new color scheme, to achieve a more "livable" environment for longer missions.

Soviet scientists since at least 1982 have been developing concepts for a Salyut 8 station with a multiple docking system and enhanced laboratory capabilities. The testing of the Salyut 7, Soyuz T, and Cosmos 1443 complex is a precursor to these more ambitious activities in space. Though having limited capability for EVA, the Soviets have stepped up construction and refueling in space, use of inflight repair capabilities, periodic replacement of life support systems, and deployment of new and more efficient solar panels on Salyut 7. These activities indicate Soviet space planners are looking beyond the Salyut program to the development of a modular space station.

The next Soviet station will be composed of several units, separately launched and assembled in orbit. One of the modules will be a fitted-out laboratory while others will perform purely technological duties. There will be observatory modules and facilities for manufacturing products in zero gravity. One of the features of this modular space station will be the use of technicians with new specialties and capabilities who do not go through the usual cosmonaut training. In fact, through an international cooperative program such training for non-USSR cosmonauts already has been implanted.

U.S. Space Station

A manned space station situated in low-Earth orbit is envisioned for the early 1990's in the American space program.

Initially, this station will be inhabited by a crew of less than ten. The station will provide a base for man to conduct a multiplicity of tasks including scientific experiments; materials processing; large structure assembly; satellite maintenance, upgrading, and refueling; support to high oribt and outer space missions, and a depot for payloads to be orbited or to be returned to Earth by the Shuttle. Specially trained crews will be required to construct space platforms, repair satellites, assemble telescopes, and activate other equipment that might be too cumbersome or too delicate to be assembled on Earth.

A major role of the space station's crew will be to function as engineers, scientists, and managers concerned primarily with the further development of the space station and maintaining its current operation. Much maintenance will be accomplished through EVA operations. Analyses show that the cost associated with conducting an EVA is minor compared to the alternative concept of extensive redundancy. Costs will be reduced if on-orbit servicing of the space station extends its life.

American astronauts and Soviet cosmonauts have conducted EVA's since 1965. Most of the Soviet EVA's have been performed on a contingency basis. However, the U.S. EVA program has been more frequent, ambitious, and sophisticated (retrieval of scientific payloads in Apollo and Skylab, Skylab repair, lunar surface exploration, STS satellite repair and refueling). In the future, it is foreseen that EVA will become a routine operation. A heavy schedule of satellite servicing or space construction tasks might require manned EVA on an 8 hours-a-day, 7-days-a-week basis using rotating shifts of space crews.

Potential for Man in Space

Any assessment of the purposes for which a space system would be constructed provides a compelling argument for the role for man. Man is able to handle a variety of tasks in which sensory inputs and motor outputs vary widely. He is able to store and recall large amounts of data and evaluate information to distinguish between that which is useful and that which is irrelevant. With his reasoning powers, he can evaluate a novel situation and make appropriate decisions concerning necessary actions. He can solicit additional information when necessary, estimate probabilities, and modify his performance as a function of experience. Man has a tolerance of ambiguity, uncertainty, and vagueness and can interpret an input signal accurately even when subject to distraction, high noise levels, or gaps in the flow of information. One of the greatest advantages in using man as an element within a space system is his ability to respond to the unforeseen and to operate at a level of considerable complexity. His proficiency under circumstances of unprogrammed input data and complex task requirements exceeds that of any onboard automatic control equipment.

Hall et al. (1982) reviewed a number of space missions under consideration for the future and developed a listing of potential human tasks in scheduled as well as contingency activities. Such tasks include:

- Rapid response to unforeseen emergencies
- Self-contained operations
- Vehicle control
- Enhancement of instrument flexibility
- Simplification of complex systems
- Backup reliability
- Equipment repair and improvisation
- Investigation and exploration.

The major roles to be played by humans in space systems include:

Management

As a manager, man is capable of overseeing a large and complex operation and noting aspects of this operation which seem to be moving out of tolerance. He will follow a broadly defined plan without the requirement for each minute element of the plan having been presented to him. In short, man is capable of providing that invaluable quality termed "management" or "leadership" by which a complex and dynamic system is redirected as necessary to continue toward a specified goal.

The management capabilities of man, however, can be influenced markedly by the quality of information he receives and by his general motivational state. In addition, he is essentially a single-channel signal detector and processor at a given instant. Signal detection is limited to narrow ranges, and input channel capacities can easily be saturated (Bejczy, 1982). Thus, while man can make good use of the information he receives, he cannot be considered an excellent information receiver.

The importance of information management in space operations is indicated in Table 1, which shows the rate at which information sources within a spacecraft have increased as the American space program has developed. Table 2 shows the corresponding growth in number of information items displayed both to crewmembers and ground controllers over this same time period. The role of a space crewman more and more is becoming that of a processor and manager of information.

Table 1

Crew Displays and Controls

	Panels	Work Stations	Control Display Elements	Computers Number/ Modes
Mercury	3	1	143	0
Gemini	7	2	354	1
Apollo	40	7	1374	4/50
Skylab	189	20	2980	4
Shuttle	97	9	2300	5/140
Space Station[1]	200	40	3000	8/200

[1]Assumes real-time control onboard, data base management from the ground.

Loftus, 1982

Table 2

Spacecraft System Information

Program	Total Measurements		Displayed to Crew		Displayed To Mission Control	
Mercury	100		53		85	
Gemini	225		75		202	
Apollo						
CM	475	948	280	494	336	615
LM	473		214		279	
Skylab						
CM	521	2241	289	615	365	2034
OAM	1720		326		1669	
Shuttle	7831		2170		3826	
Space Station[1]	10,000		4000		4000	

[1]Assumes real-time control onboard, data base management from the ground.

Loftus, 1982

Decision Making

An important capability of man is that of being able to make decisions, particularly when the arrival of a decision point may be unexpected. Man can easily generalize and make decisions even though he might be faced with incomplete information. Man sets goals and priorities, determines risks, recognizes targets and opportunities, and improvises under unforeseen circumstances (Bejczy, 1982).

While man is entirely capable of assessing a number of alternatives and deciding upon a course of action, his decision will not necessarily be optimal in all instances. Research dealing with human decision making processes has shown that decisions are a function of several kinds of cognitive information (Marques and Howell, 1979): (1) prior knowledge of the data source, (2) intuitive "records" or memories of past and similar concurrences, (3) simplification rules or heuristics employed by the operator, and (4) the operator's systematic biases. Some of these processing variables can be modified through training; others are remarkably resistant.

While decision making in past programs has largely been performed by ground support, it is expected that space station crews will be more self-sufficient in determining necessary actions and responses. The increased ability to be independent will result from greater use of automation and more sophisticated systems. Onboard capabilities will allow real-time modifications of planned mission overviews, accurate inventory assessments for determining resupply requirements, and first-hand assessments of the space station's "health."

Monitoring/Inspection/Repair

Reliability is a prime objective in the design and operation of any space system. The human makes a most important contribution to reliability through his ability to monitor system operation, inspect components for which a possible malfunction is suspected, and make repairs as necessary. Space systems invariably are both complex and costly. To the extent that man can sense and diagnose problems, the need for multiple redundancies in the many components is reduced with corresponding reduction in weight, complexity, and cost.

The value of an on-site repair capability was noted by an STS-9 astronaut in a debriefing report:

> We should get ingrained in the minds of the Principal Investigators and others that in a manned vehicle it is possible for the crew to take things apart and fix them. It is very fortunate that the two bottons on one particular computer were not disabled prior to flight as had been planned because we were able to reprogram the device. We can do a lot inflight if we are given half a chance.

The above position is reinforced by the Soviet Investigator Khachatur'yants (1981) who cited studies showing that the reliability of automatic planetary flight is considerably greater with a man aboard and, if the cosmonaut has the capability of repairing vehicle equipment and systems, flight reliability is greater still. Khachatur'yants concludes that, while the accuracy of these figures can be questioned, there is no doubt concerning the increase in flight reliability when there is a capability for human intervention in the operation of spacecraft systems.

The ability of the crew to monitor, inspect, and repair systems in the Space Station will be critical to its success. Logistics will render a return-to-Earth-for-repair philosophy untenable. The need for in situ and workbench maintenance has been demonstrated during every space program so far. Vehicle systems will break down, crew provisions will wear out, and experiment equipment will fail. An onboard maintenance philosophy is necessary for the Space Station and must be considered during all program phases for successful integration.

The repair of the ailing "Solar Max" satellite during mission 41-C of the Space Transportation System (STS) was a graphic demonstration of human capability in the space environment. A similar display of the value of man in space systems occurred 10 years prior when Skylab astronauts Conrad and Kerwin were able to salvage the Skylab mission by freeing an obstructed solar array wing. While the nature of these repair efforts was different, both demonstrated the advantage of having "man in the loop."

The failure of the proposed docking maneuver by astronaut George Nelson with the Solar Max satellite highlights the primary hardware consideration for future missions. In order for routine satellite servicing to occur, the spacecraft must be built for on-orbit maintenance. This includes the use of standardized docking and grapple fixtures, the use of modular electronic subsystems, and simple access to all components with a service lifetime.

In spite of the failure to achieve docking with the Solar Max satellite, important capabilities were demonstrated during the 41-C mission. These include: (1) rendezvous and inspection of a satellite by a free-flying, utethered crewman; (2) demonstration that docking is feasible with a satellite undergoing complex motion; (3) successful rotating grapple with the Remote Manipulator System (RMS); (4) repair of multiple components of the Solar Max satellite; and (5) placement of satellite in payload bay work station and deployment following repair. Missions planned for the 1980's will demonstrate the capability of on-orbit refueling of satellites. Future satellite servicing procedures will eventually be performed in a "shirt-sleeve" environment, thus eliminating most of the limitations discussed above. At that juncture any repair that could be done on Earth will also be undertaken in space, including repairs to major structural components and replacement of defective inertial upper stages.

Furthermore, during the era of the Space Shuttle, the servicing and repair of satellites will probably require the presence of crewmembers in an EVA role. This requirement for an EVA capability imposes certain mission limitations pertaining to physiologic, human factor, and hardware considerations.

The primary human factor and physiologic limitations of Extravehicular Mobility Units (EMU) are: (1) suits must be comfortable for work periods of up to 8 hours, (2) physiologic concentrations of oxygen and CO_2 must be maintained, (3) adequate provisions for waste management must be integrated into suit design including collection of urine, feces, and emesis, (4) adequate caloric/fluid intake must be available, (5) suit should be designed as an effective work station, with proper placement and design of controls, lighting, and tool storage, (6) present design of suit gloves limits fine motor movement of the hands and will preclude satellite repairs requiring delicate hand movements, (7) certain limitations on repetitive EVA and contingency EVA will be based on the need to prevent decompression sickness, (8) adequate training will be required to ensure effective crew performance, and (9) current suits do not provide adequate radiation shielding in case of active solar flare activity and would limit EVA exposure during these periods.

Telepresence

Telepresence refers to work activities in which a remote operator performs normal human functions guided by sensory feedback simulating actual presence at the work site. Telepresence will be used to perform operations which would be either too costly or unsafe for humans. For example, a telepresence system could be used to perform experiments or to service satellites in high altitude orbits. Telepresence allows the option of either ground-based operation or control from a satellite. Ground-based control, however, may be impractical in most instances because of the communication time delays in the force and tactile feedback. Therefore, most planning involves use of a space station as a control center, with a telepresence system in close proximity.

In the simplest case, a telepresence system might involve a dexterous manipulator arm coupled with a vision system which would allow an operator in a space station to perform laboratory work or maintenance activities at some external location. A free-flying telepresence system of this type might represent a more economical solution to satellite servicing tasks than using EVA with a pressure-suited human. The telepresence system can work indefinitely, is much less subject to radiation hazard, and may in fact be more proficient than a human working through the gloves of a pressure suit.

Telepresence is a promising concept that still requires considerable research and development. Much of the needed research will center on techniques for providing the required sensory feedback to the operator.

Orbital Industry

The recent Shuttle experiments conducted on the processing of pharmaceuticals provides an intriging insight into the future commercialization of space. In coming years, this commercialization of space may be expected to include communications, Earth sensing, manufacturing, nuclear waste disposal, the mining of the Moon and asteroids (Brodsky and Morais, 1982), as well as development of solar power stations and the assembly of space transport vehicles. Fluid physics and other types of experiments in materials processing also advance this prospect. A key feature of space industrialization will be the quest for materials with commercial potential which can be produced most efficiently in the space environment. Those with apparent promise, based on research being conducted today, include pharmaceuticals, infrared detector crystals, LSI circuit substrate, inertial configuration fusion targets, laser optics glass, large-particle monodisburse latexes, aligned magnets and ferromagnetic materials. Many manufacturing processes requiring a range of human skill will be necessary for successful production of these materials.

A major feature of future orbital industry in all likelihood will be the fabrication and assembly of large structures. These structures will serve as solar power collectors, operating bases to support a variety of space missions, and platforms for use by communications and surveillance systems. It has been estimated that by the year 2020, platforms as large as 10,000 square meters will be needed for these purposes (Brodsky and Morais, 1982). While automatic manufacturing techniques can be used for much of the fabrication, human operators will still be required for on-orbit management of the development and utilization of these structures.

Lessons from Manned Space Flight Experience

The successful accomplishment of manned space missions extending from the first Mercury flights of 1961 to those of the Space Shuttle through 1983 has provided a wealth of information concerning man's ability to live and to perform useful functions in space. In general, it has been found that carefully selected and well-trained astronauts adjust well to life in space and show a number of capabilities and attributes which are of great value for successful mission performance. For example, Table 3 lists some of the capabilities and actions demonstrated by Apollo crewmen during the course of the lunar exploration program (von Puttkamer, 1982). These important and frequently unscheduled actions found in Apollo typify the insight and adaptiveness of behavior shown by space crewmen throughout the program. The following sections discuss some of these abilities in more detail.

Mission Management

Until humans had actually flown in space, scientists predicted the effects of the space environment on man's sensory and motor performance and on higher-order mental functioning would produce a number of dire consequences. Therefore, man's role at the beginning of the manned space flight program was that of a semi-passive passenger whose capability had to be demonstrated but who could act as a backup system if the automated system failed. The performance of astronauts, particularly during unscheduled events, removed all doubt concerning human adaptability to the weightlessness of space. Accordingly, man's role in spacecraft operations has evolved from that of a passenger in Mercury to that of a mission manager in the Space Shuttle who supervises the highly automated systems within the craft and manually executes critical operations.

Table 3

Man's Capabilities in Space
The Apollo Experience

- Rapid Response to Emergencies
  - e.g., Lunar Touchdown, Apollo 11
    Repairs, Apollo 13

- Self-Contained Operation in Absence of Communication with Ground
  - e.g., Major maneuvers behind the Moon

- Rapid Sensing, Reaction, and Vehicle Control
  - e.g., Lunar orbit rendezvous decision

- Enhancement of Instrument Flexibility
  - e.g., Inflight EVA for film retrieval

- Reduction of Automation Complexity in Multi-Purpose Missions
  - e.g., Lunar surface sampling

- Equipment Repair and Improvisation
  - e.g., Lunar Rover repair

- Investigation and Exploration
  - e.g., 33 km in 3 days, Apollo 17 (vs. 10.25 km in 10 1/2 months, Lunokhod-1)

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von Puttkamer, 1982

As the role of the crewman has changed to one of being used as a direct system operating element, a key objective has been to assess his reliability and to establish means to maximize this reliability. In a full-scale simulation of an Apollo mission, reliability was assessed, using as test crews personnel who met criteria for astronaut selection and, in some cases, later were selected as astronauts (Loftus et al., 1975). For procedural tasks, reliability was found to vary between 0.94 and 0.98. Reliability was affected by training level and by provision of feedback concerning performance. In general, the authors conclude that the data substantiate the observation that crewmembers are very reliable with errors being detected and corrected promptly. They feel the error correction effectiveness perhaps is more noteworthy than the exceptionally low rate of error incidence. This self-correcting capability is one of the major assets of a human operating within a complex system.

The STS-9 interaction between ground and inflight scientists accentuates the benefits of man as mission controller. Essentially, each of these crews was an extension of the other: the inflight crewmen as "local sensors" and interpreters of experiment data; and the ground crewmen a central data resource for directing the science or technology effort. Scientific return can be maximized by this synergistic effect.

Vehicle Control

One of the more useful skills exhibited by astronauts, as one might expect from highly qualified test pilots, is that of vehicle control. In 1966, astronauts Armstrong and Scott successfully accomplished the first docking of one vehicle to another in space when they joined the Gemini 8 capsule with the Agena target satellite. Manual docking of space vehicles was an important phase of many American and Soviet missions after that.

During the Apollo 11 mission, the Commander was able to respond rapidly to a control emergency during the touchdown phase. The Apollo Lunar Module was about to land in a crater surrounded by large boulders. To prevent a possibly disastrous landing, it was necessary to use the manual control capability to direct the craft to another and more suitable landing location. The manual control, while practiced extensively in simulators, was being done for the first time under lunar conditions and was accomplished flawlessly.

The Shuttle program expanded the scope of vehicle control with the Remote Manipulator System (RMS) and the Manned Maneuvering Unit (MMU). The RMS has been successfully used to control payload movements for surveying orbiter and space environments with the operator remotely located on the orbiter flight deck. The RMS operator also controls in "cherry-picker" fashion an EVA crewman to facilitate extravehicular tasks, crew access, etc. Inter-crew communications has been demonstrated to be appropriate for gross placement and fine positioning. Crew control of the MMU backpack has also been demonstrated on STS-41B in free-flight EVA.

Orbiter vehicle control was demonstrated during STS-7 when the SPAS-01 payload was released from the RMS. After station keeping at 1,000 feet, rendezvous was accomplished and the payload grappled. After a second release, short-range (up to 200 ft) station keeping was demonstrated prior to regrappling and berthing the SPAS.

Maintenance and Repair

There have been dramatic examples of the capability of space crewmen to effect emergency repairs during the course of both American and Soviet missions. The Skylab program is an excellent example. Without direct intervention by an astronaut, the Skylab vehicle would have been uninhabitable because of the thermal problem caused by the loss of the micrometeoroid shield and failure of the solar array wing to deploy properly. In a difficult orbital repair job, the Skylab Commander and Scientist Pilot spent nearly 4 hours in EVA working to release the solar panel and to correct the problem to an extent that would allow the Skylab to be used. Their actions were instrumental in salvaging a $2.5 billion program.

More recently, emergency maintenance capabilities have been used to advantage in the Space Shuttle missions. Following the STS-9 flight, one of the astronauts noted that "I can think of five cases where people doing the job saved the day. Among these were the fix of the metric camera and one of the furnaces in the fluid physics module." Expensive payload items were saved through astronaut intervention.

Repair operations are dependent on the performance of the human visual and motor systems. There was initial concern over decrements which might be suffered by both of these systems in weightlessness and the length of time which might be required for adaptation. There was particular interest in the extent to which the lack of a gravity component might disrupt the skilled and precise movements required in vehicle control and in maintenance activities.

One of the first studies of perceptual-motor performance during weightlessness was conducted by Gerathewohl et al. in 1957 during vertical dives in a jet aircraft. An eye-hand coordination test was used in which subjects were required to aim at and hit the center of a test chart. During the initial trial, subjects showed a moderate disturbance from the decreased gravity. However, they made a rapid compensation and, over the six trials lasting for 10 seconds, performance improved until it was comparable to that found under normal conditions.

The first manned flight dispelled any real fears concerning the ability of an astronaut to carry out routine perceptual motor activities during weightlessness. Even though movement was rather restricted in the tight confines of the Mercury capsule, it was clear that no motor difficulties were encountered when dealing with the internal management of the spacecraft (Nicogossian and Parker, 1982).

A considerable amount of quantitative data on astronaut performance was collected during the Skylab program. A number of experiments were designed to compare astronaut performance in various tasks under one-gravity conditions prior to flight and subsequently during the zero gravity of weightlessness. Among those tasks selected for observation were fine and gross motor coordination tests done with and without the use of restraints; tasks which required visual, tactile, or auditory feedback; and routine intravehicular activities such as the donning and doffing of the extravehicular space suit. It was found that performance time for most tasks increased initially after the crew's entry into weightlessness. However, after several days of flight, performance proficiency increased as crewmen adjusted to the weightless environment and developed techniques to optimize performance. By the end of the second week in space, more than half of the experimental tasks were performed as efficiently as on the last preflight trial. There was no evidence of any performance deterioration as time spent in weightlessness increased (Kubis, et al., 1977).

Enhanced capabilities to perform extravehicular servicing were demonstrated during STS-41B in terms of the MMU and RMS/MFR (Manipulator Foot Restraint). The MMU simulated support for servicing the Solar Maximum Mission while the RMS/MFR supported an unplanned repair of a microswitch on a SPAS-01 experiment package.

The STS-9 Spacelab crew is credited with several inflight repair operations. A minor heating facility failed due to power supply problems but was restored to operation by crew action. Crew inflight maintenance was also performed on a Spacelab tape recorder. Crew brute force was used to open the airlock hatch.

Scientific Observations

Space crewmen have been required to make scientific observations in both the American and Soviet space programs since the very first flights. They have observed weather patterns, astronomical phenomena, and geologic and geographic features. Some of these observations involved viewing outside the spacecraft while others dealt with onboard scientific instrumentation.

Skylab provided many examples of man's capabilities as a scientific observer, in some instances obtaining data that would not otherwise have been recorded. The Skylab crews successfully operated the Apollo Telescope Mount, made observations of the comet Kohoutek and of the Earth, made tests of flammability in zero gravity, and conducted material processing experiments.

Inasmuch as visual acuity is important in scientific observations, this physiological capacity has been examined by both American and Soviet scientists. In the Gemini 5 program, measurements were obtained with an Inflight Vision Tester, in which astronauts judged the orientation of rectangles in an illuminated area. They also searched for large patterns displayed at ground sites in Texas and Australia. Results of both the onboard and the external vision experiments indicated that visual performance neither degraded nor improved during the 8-day mission.

In contradistinction, Soviet investigators have noted certain changes in visual parameters during space flight. Soviet investigators conclude that, during the first days of flight, the main visual functions deteriorate by 5 to 30 percent, followed by restoration of function until an approximation of preflight capability is achieved. Contrast sensitivity shows the greatest change, ranging from a 10 percent loss immediately after entry into weightlessness to a 40 percent loss after 5 days. Even so, Soviet investigators conclude from these experiments that the effect of space flight conditions on the principal visual functions under normal conditions of illumination is relatively small (Nicogossian and Parker, 1982). Similar changes were recently documented on STS missions, and investigations are underway to establish the significance and etiology of these findings.

More recently, there are reports by the Soviets of improvements in visual effectiveness during long-term space flight (Office of Technology Assessment, 1983). After an adjustment of several weeks, cosmonauts report both improved visual acuity and enhanced perception and differentiation of color, making it possible for them to identify land features and ocean phenomena, such as schools of fish, that were not calculated as being visible from low-Earth orbit. The Soviets are continuing studies of this type in the Salyut 7 spacecraft.

Tests of visual function are also continuing in Space Shuttle missions, with studies being performed by both NASA and Air Force investigators.

It is interesting to note that scientific observations have resulted not just from preplanned investigations and research. Scientific observations have also come through the serendipitous circumstances of a technically oriented astronaut in a conducive, unique, and enjoyable environment of weightlessness. For example, "Brand waves" (for Vance Brand on STS-5), giant deep-sea waves, were "discovered" by casual viewing of Earth's oceans through the orbiter windows. The scientist's penchant for off-duty activities spent in "playing in zero-g" and gazing out windows undoubtedly will increase scientific return.

Problem Areas

While it is true that the adjustment of astronauts to space operations has been remarkably successful, some problems have been identified. For instance, problems were encountered in the extravehicular tasks attempted in both the Gemini 9 and 11 missions. The workload was found to be higher than anticipated, with heat and perspiration produced at a rate exceeding the removal capability of the life support system. Shortly after the Gemini 9 mission, the pilot made use of an underwater zero gravity simulation to test the use of various restraint systems and to develop better control and distribution of the workload. Results of the Gemini 12 EVA showed that all tasks attempted were feasible, using the techniques perfected in the zero-gravity simulation. Workload was controlled within the desired limits. This episode did point out the need, however, for careful study of pilot workload during any kind of EVA mission.

The EVA program also showed that considerable care must be taken to insure that astronauts obtain satisfactory sleep. Improvement in sleep patterns was not achieved until the 14-day Gemini flight, were a flight plan was designed to allow the crew to sleep during hours corresponding to nighttime at Cape Canaveral. In addition, efforts were made to keep spacecraft noise to a minimum. In Skylab experiments, a detailed study was made of astronaut sleep. Electroencephalogram, electrooculogram, and head-motion signals were recorded during sleep periods. Results showed fewer adverse affects than those encountered in Gemini. Only during the 84-day flight did one subject experience any real difficulty. Most changes seemed to occur during sleep in the postflight period. It was concluded that readaptation to a one-gravity environment is more disruptive to sleep than the initial adaptation to zero gravity.

In both the American and Soviet space programs, the psychological adjustment of crewmen to the conditions of space flight has been observed. In both cases, this adjustment has been good. In the American program, crew irritability was noted in conjunction with a minor inflight illness. Irritability produced by fatigue also has been observed when the timeline of scheduled activities becomes too demanding.

The Soviets have made more detailed studies of psychological stresses than have their American counterparts, particularly in connection with their longer-term missions. Performance capability was evaluated against the psychological state of cosmonauts. The following five phases of task performance were observed (Space Biology and Medicine Guide, 1983):

<u>Familiarization Phase (Initial)</u>--characterized by fluctuations in productivity and the systematic development of individually effective work rhythms. Errors requiring intervention by ground controllers are committed on occasion during this phase. Emotional tension accompanies the performance of critical tasks. In all, individuals are adapting to the unusual working and living conditions of space. This phase appears to last from 5 to 7 days.

<u>Optimal Phase</u>--stable and efficient performance is noted with appropriate psychological affect. Major physiological functions are adequately adapted to zero gravity. This phase lasts from 10 to 15 dyas.

<u>Full Compensatory Period</u>--significant symptoms of fatigue are noted which are compensated by high motivation to perform. Productivity and quality of work are not affected, with

transitory fatigue disappearing after a good night's sleep. High psychological and emotional tension levels are associated with high workload periods.

Unstable Compensatory Period--increasing periods of fatigue are noted, with decreased work capability. There is evidence of emotional instability, with periodic sleep disturbance seen. Changes in sensory perception levels including visual, auditory, attention span, memory, and other mental functions are reported. These changes are highly individual and work capacity is affected only slightly, manifested by a decrease in motor reaction times, usually toward the end of the day.

Final Phase--starts 2 to 3 days prior to return and is characterized by high emotional and work performance efficiency levels.

The Soviet investigators noted that the above phases do not have clear-cut demarcations and are highly dependent upon: (1) environmental conditions of habitability such as working conditions, work ergonomics, and social motivation and (2) personal variables such as level of training and prior experience, general physical status, individual motivation level, and emotional-will power characteristics.

In the Salyut long-term flights, cosmonauts have shown some psychological stress during the final days of the mission. As a result, during the last stages of the record 211-day Salyut 7 mission, the cosmonaut working day was reduced from 16 to 12 hours as a measure to boost spirits. The Soviets also have devised a comprehensive psychological support program, including the transport of letters and news to Salyut crews and frequent two-way video communication with families and research counterparts on the ground (Office of Technology Assessment, 1983). They feel these measures are beneficial in countering the long-term isolation and the heavy workload.

Technology Drivers

Future space missions will use crewmen in a different manner and place different demands on them than was the case in Mercury, Gemini, and Apollo. In part, this will be because the missions themselves will be quite different. Another reason, however, is that astronauts will operate in a world with new and very advanced technologies. These technologies themselves will require a different kind of astronaut performance. The two of most consequence are believed to be computer systems using artificial intelligence concepts and semi-independent robotic machines.

Computers Using Artificial Intelligence

A new generation of computers is being developed which uses artificial intelligence procedures. Through a procedure known as "knowledge engineering," these computers are programmed to draw on the synthesized inputs of a number of human experts to achieve a problem-solving capability far superior to conventionally programmed computers. Already a first generation of systems that reason from rules of experience has begun to move from the laboratory into practical applications. By the late 1980's systems even further advanced, termed "deep knowledge" computers, could be ready for use (Kinnucan, 1984).

A typical knowledge-based computer system solves a particular problem by using facts about the problems supplied by the user, plus its own domain knowledge, plus general problem-solving procedures which allow it to find and apply a specific solution. A system may also include a natural-language interface for communicating with the user, a reasoning explanation subsystem, and a knowledge acquisition subsystem for expanding the current knowledge base. Later versions using "inference engines" will deal with symbols that represent objects. Use of symbolic logic rules rather than straight numeric computation will add to the power, speed, and versatility of these computers. They will be able to operate as a right-hand assistant to an astronaut as he pursues his labors in a space station. Projected computer functions include providing information on systems functions, engineering design, self-diagnostics, and repair procedures.

Robotics

The remote manipulator arm used in the Space Shuttle represents a first-general robotics system. Such systems will become increasingly important in our space program. Research in robotics is being driven by two principal goals: (1) to relieve people of tasks which are boring or dangerous and (2) to expand human capabilities, and thus increase efficiency and productivity.

Johnson et al. (1983) describes a number of mechanical classes of robots that may find application in the Space Station program. The first is the familiar robot arm used in the Space Shuttle manipulator system. These will find application in satellite repair and servicing, space manufacturing, and station laboratory tasks. Tentacle manipulators, comprised of many small links connected by joints each with multiple degrees of rotation, will have the maneuverability of an octupus arm. While such systems cannot deliver much force in a one-gravity environment, they might be of value performing relatively complex manipulative activities in the weightless environment of space.

Consideration also is being given to the development of a standardized "Versatile Space Manufacturing Manipulator." This would be a general purpose manipulator outfitted to handle a variety of end-effectors and sensors. It could be reprogrammed on-site to handle a variety of tasks and would be less costly to develop and space-qualify than a large number of specialized manipulators.

With all robotic systems, the key research issues today concern the development of effective sensors, i.e. a vision capability, and a delicate tactile sense. These sensory capabilities must be incorporated if a space station robot is to perform anything more than relatively gross manipulative activities.

Human Performance Issues in Automated Systems

All projected aerospace systems show a trend toward increased complexity and automation, with a concomitant shift in human roles toward monitoring, situation synthesis, supervision and decision making. In looking toward a future space station, increased automation should serve to reduce mission costs, diminish complexity as perceived by crewmembers, increase mission lifetime, and amplify mission versatility. To achieve this, a highly automated system must amalgamate the diverse attributes of people, machines, and computers to yield an efficient system which preserves and extends unique human capabilities (Johnson et al., 1983).

Increased automation - more reliance on computers and automatic control - has been adopted as the basis for the solution of many existing and anticipated problems. While there is no question concerning the power in automation principles, their use may be a mixed blessing. In some cases, the automation of functions can impair rather than improve human and system performance. A symbiotic relationship between man and machine must be achieved. System automation must result in an extension of critical human capabilities and an improvement of system operations. Before such a symbiosis can be achieved, however, there are many questions to be answered (Southwest Research Institute, 1982).

- <u>Man/machine function allocation</u>. Much research will be required to develop optimum human/automation function allocation strategies. In order to develop the most productive, safe, and satisfying balance between man and computer working together in a complex system, it is important to construct a systematic framework for that relationship. This relationship must be based, first, on previous experience with such systems, and second, on a careful and detailed analysis of the respective capabilities of man and computer and the manner in which these capabilities offer mutual support.

- <u>Decision making</u>. Critical decisions in a semi- or fully-automated system will remain the prerogative of the human operator. In most instances, it can be anticipated that decision making will be distributed through the system, with the computer (possibly using artificial intelligence techniques) making a number of subdecisions and presenting these results to the human operator. This being the case, we do not know the optimum manner in which computers should derive and present information for final decisions. There also is a need for research concerning the impairment of decision making under forms of stress which include physiological, divided attention, and heavy workload.

- <u>Information presentation</u>. Efficient ways of distributing and presenting both visual and auditory communications from multiple sources and channels must be developed. With the option now of using standard typewriter panel data entry techniques, voice procedures, and touch panels for communications between the human and the computer, principles must be developed to insure optimum choice.

- <u>User confidence</u>. The acceptance of automation of some or all system activities has proven to be a major problem in some manned systems. For instance, it has been quite difficult to introduce fully automated landing systems in commercial aviation even though the efficiency and reliability of these systems have been amply demonstrated. With automated systems, the main problem appears to be one of under-confidence, but over-confidence also can have severe consequences. Procedures must be developed to insure an appropriate confidence in system automation.

NASA Programs to Develop "Man in Space" Capabilities

Through observations and experiments conducted in all U.S. programs to date, a wealth of information has been accumulated concerning the capability of humans to live and to perform useful functions in space. The systematic investigations made during both the Gemini and Skylab programs were particularly productive. For the most part, however, these studies provided information concerning adaptation characteristics and performance capabilities related to the specific development and exploration objectives of these missions. Space activities a decade from now will be quite different as NASA enters a period characterized by more routine scientific and commercial programs. There is still a great deal to be learned concerning human capabilities to operate in this type of space activity with the advanced technologies that will be employed.

NASA is pursuing a vigorous program to develop a human factors technology to support manned space missions such as a space station. Notable efforts underway at this time include:

1. Human Behavior and Performance

The Life Sciences Division of Headquarters in supporting research, through the Ames Research Center, studying the determinants of high levels of human performance in unfamiliar and stressful environments. One investigation examined data for the long-term effects of isolation on a small group in a simulated Shuttle environment. During small-group isolation over a period of 105 days, subjects exhibited progressively increased levels of depression and impaired psychomotor performance. Nutritional and hormonal changes also were observed. These changes are being related to the specific conditions of isolation.

Other studies were conducted to analyze the effect of crew size and composition on hormones such as testosterone in the body. Hormonal levels changed when new members joined or departed from an established small group which produced changes in social relationships. Relationships that disrupted work routines and sleep schedules were most predictive of alterations in hormonal levels.

The effects of psychological variables such as leader selection on performance and adjustment in the space environment also have been studied. The attempt in this series of investigations is to isolate behavioral factors and develop objective measures to show the importance of variables such as motivational state, situational determinants, sex differences, the influence of mentors, and job and personal satisfaction.

2. The Human Role In Space

This is a study supported by the Marshall Space Flight Center to develop an optimum strategy for assigning functions to man and to semi- or fully-automated systems for future space missions. One objective is to use a set of representative space missions as a basis for defining anticipated activities and then to list those unique and desirable human capabilities that will match specific mission activity requirements. The program also is developing objective criteria to deal with system effectiveness, reliability, development timelines, and cost. It is evaluating use of advanced technologies such as artificial intelligence and fully programmable robotics.

3. Human Performance Issues Rising From Manned Space Station Missions

This is a program just being started by the Life Sciences Division. The purpose is to assess requirements for habitability, health maintenance and medical care, and to develop a taxonomy of human capabilities appropriate to support manned missions a decade hence.

4. Psychological Well-Being

The Life Sciences Division is supporting habitability research to develop ways to ensure the psychological well-being of space crews under the anticipated conditions of long rotational periods in a space station mission. Psychological well-being is virtually synonymous with motivation and can be a key determinant of human effectiveness. Living conditions in a space station will play a key role. At this time, it is anticipated that the volume available for a crewman's private use might be something less than 200 cubic feet, i.e., a volume smaller than 5 x 5 x 8'. Under conditions this crowded, it will be a challenge to provide living quarters that are pleasant and restful and that promote optimum crewman performance.

5. Sensory and Motor Performance

The Life Sciences Division is supporting work to develop data acquisition systems for real-time anthropometric measurements on moving subjects in order to support models showing how people work in a space situation. Efforts also are being started to develop methods for extracting cognitive and sensory information from operational tasks rather than through laboratory experimentation. Non-intrusive measures of operational performance should be most fruitful in developing procedures to describe the human operator and his response to variations in the work environment.

6. Residence in Self-Contained Environments

Since the psychological/psychiatric data base on space travelers is small, it is difficult to predict the problems that crewmembers might encounter during future missions with longer periods of unprogrammed time and social isolation. In addition, the composition of future crews is expected to be more diverse and to contain individuals who have not been as extensively screened as the pilot/astronauts of past missions. For these reasons, the Life Sciences Division is reviewing the scientific data that have been collected for confined environments such as the Antarctic, submarines, off-shore drilling rigs, and surface ships. A task force of technical experts, coordinated through the Operational and Emergency Medicine Division of the Uniformed Services University of the Health Sciences, will review the technical literature and document their own anecdotal experiences. With their first-hand knowledge of these unique confined environments, the task force members can compare the similarities and differences of these environments with long-term space flight. In addition to studying the effect of isolation on individual behavior and changes in intersocial relationships, the task force will investigate certain psychologic and toxicologic consequences of long-term exposure to a crowded self-contained environment.

7. Payloads and Requirements

The Kennedy Space Center, supported by the Headquarters Life Sciences Division, is continuously updating information concerning human requirements for life support, medical care, habitability, workload management, and health maintenance as these issues impact the design of the Space Station as well as that of potential life sciences payloads.

Research Requirements for Long Duration Manned Space Flight

The successful pursuit of "a permanent presence of man in space" requires an indepth understanding of the performance capabilities of space crewmen and the support needed to maintain best performance. The human must be studied to identify his characteristics, capabilities, and tolerance limits, and planned space systems designed with optimized interfaces. Although much already is known about the human and man/systems integration, much remains to be learned. The opportunities to discover and apply this knowledge in future space programs await us.

From the results of space missions to date and from supporting studies, it can be concluded that there are a number of broad categories of research to be addressed. The combination of diverse crew complements, longer periods of orbital residence, employment of new technologies, and demanding industrial and scientific tasks makes the resolution of these research issues of considerable importance if humans are to perform at peak effectiveness.

Architecture

A necessary first step is to develop principles and standards of the construction of a spacecraft or space station so that it accounts for the needs and characteristics of its occupants. The research must deal with a diversity of architectural topics including development of design principles to meet privacy and territoriality needs, use of restraint systems for different classes of work, anthropometric considerations for different crewmembers, tolerance for distractions such as noise and vibration, location and use of exercise facilities, and development of acceptable hygiene and waste management facilities.

Man/Machine Function Allocation

The technology for automation of many space tasks now is available. Microprocessor technology, new display systems, programmable robotics, and the advent of artificial intelligence systems lead to an entirely new working environment, but one in which a human will continue to play a critical role. However, it is imperative that the human be blended into this work environment so that best use is made of his capabilities. There currently is no widely applied methodology for allocating functions between automated systems and humans. During the early stages of design, informed decisions must be made about the allocation of functions between humans and automated systems and for the combination of both in order to maximize mission success, efficiency, safety, and economics (von Tiesenhausen, 1982).

Man/Systems Integration

There must be a proper match among the human components, the equipment components, and the operating environment in any space system. It is most important that procedures be developed to ensure the inclusion of human factors in the mainstream signoff of space station design. Timely man/systems integration review will reduce costs, improve schedules, and ensure a better finished product for crew use.

Workload

Workload problems have been encountered in essentially all manned space programs since project Gemini. The working environment in space is much different from that on Earth, particularly during EVA activities, and the physical, metabolic, and psychological workload imposed by different types and duration of activity can pose serious problems. While underwater simulation of space tasks has proven to be a valuable predictive technique for assessment of workload, much remains to be done. This is particularly true in the scheduling of multi-crew administrative, housekeeping, and management activities.

Information Management

With computer processing and new electronic displays, it is possible to present information in a number of different formats. This information also can be processed to varying levels of abstraction. The problem becomes one of presenting information so that it best supports the task demands of the crewmember and can be used by him easily and accurately. Research must be done to improve our understanding of how astronauts cognitively organize (e.g. encode) the tasks they must perform, and of how to display the needed information so that it is perceived in a manner congruent with that organization (Montemerlo, 1982). As space systems become ever more complex, problems concerning the management and utilization of information are becoming of paramount importance.

Countermeasures

There are a number of physiological changes which occur in astronauts in both short- and long-duration space missions. Some of these adaptations, such as hematology changes, appear to be self-limiting; others, such as loss of bone mineral, appear to be progressive. Numerous countermeasures have been developed and tested for moderating these physiological changes. However, the countermeasures themselves may operate to impair the effectiveness of astronaut performance. For instance, in recent years the Soviet space program has used a relatively standard program which involves three exercise periods of 2.5 hours per day for 3 days, with some optional schedule change on the fourth day. While this appears to be effective, it is very time consuming. What is the best procedure for use of the physical conditioning procedures, as well as the nutritional and pharmacological countermeasures, so as to least impact the activities conducted during long-term residence in a space station?

Artificial Gravity

Much thought has been given to the need for use of artificial gravity during space missions to alleviate physiological changes noted in major body systems. While less attention has been given to it, there remains a question of a possible need for use of artificial gravity to sustain the performance effectiveness of work crews during long space missions. Can the full class of space activities to be required on a space station and during the construction of large structures in space be accomplished as desired through the use of appropriate restraint systems or will some form of artificial gravity be necessary?

Human Sensory Extension Systems/Telepresence

Telepresence is a promising technique in which a remote operator (robot) performs normal human functions guided by sensory feedback to the human controller. A key advantage is that telepresence allows the human operator to perform dangerous EVA activities while remaining within the safety of the space station. It also is economically advantageous since there is no requirement to protect the robotic operator from such hazards as radiation or decompression. However, telepresence can only achieve its real potential if the required sensory feedback is provided to the operator within the space station. At present, this cannot be accomplished. Much research is required for the development of appropriate and efficient systems for visual and tactile sensing at the work site and for presenting this information to the human operator.

Training

Ensuring adequate crew training and on-orbit skill retention during long missions will become more important with increased mission complexity and length. A crewmember will require overall training which must be generalized to numerous vehicle areas. On-oribt provisions must include refresher materials to keep skills at specified proficiency levels. Work must continue on techniques to identify the dimensions of required training, to develop training systems for use in a spacecraft, and to devise measurement procedures with which to evaluate training effectiveness.

Life Sciences Program

The NASA Life Sciences Division either has or will be initiating in FY 1985 studies in each of the above areas of concern in support of future activities in space.

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Appendix A
The Soviet Salyut 6-7 Experience

The Soviet space station program began in April 1971 with the launch of Salyut 1, an orbiting laboratory, which soon was inhabited by a crew of three cosmonauts for a period of 23 days. Although Salyut 1 was intentionally de-orbited after 175 days, a number of scientific activities were completed ranging from astronomical and Earth photography to experiments on the effects of weightlessness on plant growth and nutrition.

The launch of Salyut 6 in 1977 inaugurated the second generation of Soviet space stations having greatly increased emphasis on "livability" and features to enhance cosmonaut performance. Improved food service and hygiene systems, as well as the inclusion of entertainment items, served to overcome problems noted with earlier Salyut vehicles. This improvement theme continued with Salyut 7, launched in 1982 and operational at this time. In both of these programs, manned missions of record length were completed and the practice of "visiting crews" was begun. As a result, a considerable body of information has been compiled concerning man's capability to work productively in a long-duration space setting.

The work schedule for a Salyut cosmonaut has been heavy and maintained during the full course of the extended missions. Cosmonaut Valentine Lebedev, who completed a record 211-day mission in 1982, commented both on the level of activity and the psychological state when he noted in his diary, "while the work is intense, it is healthy. Even if the work is difficult and one gets tired, you have mental satisfaction."

The extent of cosmonaut work requirements is reflected in the accomplishments of the Salyut 6 program. In the course of the four main missions, there was a total of 27 dockings of spacecraft with the space station, 4 redockings from one part of the station to another, 15 landings of Soyuz and Soyuz T (crew delivery) craft, as well as 12 descents of the Progress (unmanned supply) craft. One Salyut 6 crew performed 55 experiments dealing with materials technology as well as about 50 biomedical experiments (Myasnikov, 1983). The work pace did take its toll, however, and it was necessary to reduce the working day from 16 to 12 hours during the course of the 211-day mission. The establishment of optimum work schedules remains an issue in planning for long missions.

Maintenance and Repair

The capability of space crewmen to accomplish both scheduled and unscheduled maintenance and repair work has proven invaluable. For example, the Salyut 6 spacecraft has a design life of 18 months (Office of Technology Assessment, 1983). Largely as a result of cosmonauts routinely working as in-orbit repairmen, the spacecraft continued its mission for almost 5 years.

Unplanned crew repairs were instrumental recently in saving the Salyut 7 program. A solar array problem reduced electrical power and seriously affected the vehicle's environmental control system (Aviation Week and Space Technology, 1983). Without repair the Salyut 7 would have been unusable for later missions because of internal system damage resulting from excessive dampness. A specially trained repair crew was unable to reach the Salyut 7 because of a fire during the launch sequence which caused the mission to be aborted. As a result, the onboard cosmonauts, who had not been trained for station repair operations of this kind, completed the repairs successfully by following detailed instructions from ground controllers. Their mission then was completed on schedule.

Scientific Observations

The combination of direct observation of Earth by crewmen and the use of advanced photographic techniques provided information of considerable value during the Salyut program. Lebedev, in his diary, makes frequent mention of the time spent in Earth observation. During Salyut 6, some 13,000 photographs were obtained using topographical and multispectral cameras. As a result, a supply of fresh water was located in a Russian desert and large-scale geological pictures coinciding with mineral deposits and oil regions were identified (Office of Technology Assessment, 1983). It was judged that in 10 minutes, observations equivalent to several years of aerial photography could be achieved.

Appendix B
The Spacelab-1 Exercise

The European Space Agency Spacelab-1 was carried into orbit in the cargo bay of the Space Shuttle in November 1983 and represents a major advance in the use of space for scientific purposes. The Spacelab module can be outfitted with several tons of laboratory instruments for studies in astronomy, physics, chemistry, biology, medicine, and engineering. While future missions may be dedicated to a single discipline, the mission of Spacelab-1 was to demonstrate the broad versatility of the space laboratory. It was also designed to test and verify the Spacelab hardware, flight and ground systems, and crew to demonstrate capabilities for an advanced space research program. In the course of verifying Spacelab systems, a wealth of scientific data were obtained. Significant advances were made in many disciplines. Of the 38 primary investigations carried on Spacelab-1, only 3 had a real loss of scientific information due to hardware failures.

One of the successes of the Spacelab-1 mission was its demonstration of the efficiency achieved by complementary space and ground science crews working together. The synergistic relationship between the four Spacelab scientists and the larger ground crew working at the Payload Operations Control Center at the Johnson Space Center allowed continuing adjustment of experiment protocols and resulted in a better scientific return in many instances. The interchange between onboard scientists and ground-based investigators produced a greater volume of radio traffic than that between the astronauts in command of the Shuttle and their own Operations Control Center in Houston.

Maintenance and Repair

As with the U.S. Skylab program and the Soviet Salyut 6/7 missions, the Spacelab crew again proved the value of having astronauts onboard to diagnose and repair malfunctions in important items of hardware. The ability of the crew to repair major scientific instruments was a key aspect of the mission. The onboard scientists made at least four major repairs which resulted in saving experiments.

One of the most important of the Spacelab instruments, the German metric camera, suffered a malfunction which, without astronaut intervention, would have caused the loss of almost all of the scientific data it was designed to produce. The film transport in the camera jammed at the beginning of operation of the second film magazine. After 25 exposures of a 400-frame black and white film cassette, the advanced mechanism jammed. Through discussions between the Spacelab crew, the Payload Operations Control Center, the Johnson Space Center, and the Zeiss Camera Company in Germany, a set of repair procedures was devised. Repairs were successful and complete photography was achieved over numerous locations in Western Europe, Africa, South America, and the United States.

In another instance, the high data rate recorder failed on the fifth day of the mission and jeopardized data retrieval when the Space Shuttle was out of range of the Tracking and Data Relay Satellite. When the Mission Specialist opened the recorder he found that three of the rollers were stuck. By rocking them back and forth he was able to free them and thus bring this system back on-line. Again, the scientific objectives of Spacelab were achieved through an on-site repair capability.

Piloting Control

The scientific objectives of the Spacelab mission required that the Space Shuttle be placed in a number of different orientations during orbital flight. The preflight maneuvering schedule called for 182 attitude changes. During the course of the mission, 90 additional changes were requested in order to maximize the scientific return. The piloting capabilities of the two Space Shuttle astronauts were of great value in managing and accomplishing a rapidly changing maneuvering profile.

Habitability

The Spacelab is well engineered for stowage and access to crew material, location of scientific equipment, and layout of work stations. The design was developed with consideration both for ground training and flight operations. Crews have commented positively on its architectural qualities. However, such modules can only support two to three crewmembers on any given work shift without significant crowding. Larger crews will require a new layout of work stations and more habitable space. Even with smaller crews, the design of controls and placement of critical operational systems needs additional study. For example, a switch controlling the power to an experiment in Spacelab was inadvertently disabled during the mission. A careful systems engineering study will be needed to insure optimum habitability as well as safe operation in the forthcoming Space Station.

Appendix C

The Space Shuttle Mission STS 41B Experience

Two achievements of Space Shuttle Mission STS 41B were historical. For the first time, an orbiter landing was made at the Kennedy Space Center rather than at Edwards AFB or White Sands, New Mexico. Also for the first time, an astronaut flew untethered away from the spacecraft. While both of these achievements represent significant advances in the Space Shuttle program, the second is of paramount importance in determining the way in which future missions will be conducted. Astronauts now are free to leave the Shuttle to inspect it if any damage is suspected, to visit and repair other satellites in close orbit, and to conduct rescue missions should such ever be necessary. Also, when the Space Station becomes operational, space workers will be able to perform useful labors on external surfaces of the station and to participate in the construction of other space structures. The ability of astronauts to move freely and independently in space greatly increases their utility and value in the conduct of space missions. This was made possible through the development of new protocols for pre-breathing and nitrogen washout and through the establishment of optimum cabin/EVA suit pressure profiles.

The first use of the Manned Maneuvering Unit (MMU) for untethered flight successfully met all objectives, with the exception of certain tests which could not be performed due to problems with other Shuttle components. Two extravehicular activity periods totaling 12 hours were completed with the MMU system. Free flight was made to a distance of over 300 feet from the Shuttle. Handling qualities were checked and the docking capability assessed. Repair procedures to be used on disabled satellites were practiced and, in a fortuitous sequence of events, a lost Shuttle item was retrieved before it could float away into space.

Manipulative Activities

One astronaut using the MMU worked with a mockup of the Solar Max Satellite main electronics box which was mounted on a cargo bay pallet. One of the repair tasks, to be completed on the actual satellite in the next Space Shuttle mission, involved opening and disassembling the electronics box. This task was accomplished as planned, even though the space suit gloves imposed some restriction on finger and wrist movement. Then, in an actual repair task, the astronaut fixed a switch that had limited the scan capability of a mass spectrometer sensor head located also on the cargo bay pallet. These activities demonstrated a real capability of astronauts to perform repairs outside a spacecraft, even those in which small tools are used and in which delicate manipulative actions are required. This capability can be used to excellent purpose in the assembly and utilization of the Space Station.

Work Procedures

In some instances, work can be performed better in space than under one-gravity conditions. For example, during the simulated Solar Max repairs, the astronaut was seen to be hanging level from the manipulator arm over the payload bay and reaching down in a manner which would have been impossible in a gravity field. This ability to position himself as needed without fear of falling was an aid in the work performance.

In some instances, work in space can be more difficult than predicted on the basis of preflight practice. One task done easily in the neutral buoyancy water tank trials proved to be quite difficult in space. This task consisted of hanging onto a ledge with one hand while maneuvering the manipulator foot restraint platform with the other. The difference was attributed to the viscous effect of the water. In any event, it was concluded by the astronaut that a better means of restraining crewmen during EVA repair labors is definitely needed. Here is an instance where the full value of the human capability to perform external repairs is degraded through other features of the work scene.

Workload

The 41B Mission called attention once again to the problem of workload assessment and the timeline scheduling of crew activities. The Mission Commander noted that, during a period when two crewmembers were in EVA, five crewmembers could have been used efficiently within the orbiter, as opposed to the four crewmembers actually available. He stressed that it was important not to have the timelines of the two crewmen in EVA interlinked too closely. They should be timelined independently, so that one would not be delayed by the activities of the other. His comments reflect a need for continuing improvement in techniques for timeline scheduling of astronaut activities.

An ongoing problem is that of excessive workload, in this case during EVA. It was quite difficult for a crewmember to use the foot restraint system properly. It was necessary to kick one's feet into the restraints and then to react to the torque produced on the wrists. Every time the astronaut crossed the payload bay and arrived at a new work position, he encountered the foot restraint problem. As a result of dealing with the torque, his arms were exhausted by this exercise. At the end of the first EVA period, the astronaut commented that, as a result of the complete fatigue, it would be very difficult to do EVA missions on consecutive days. Research is needed to develop techniques for predicting and controlling the build-up of excessive fatigue during what should be routine space tasks.

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16. Abstract

Man's ability to live and perform useful work in space has been amply demonstrated throughout the history of manned space flight. Current planning envisions a multi-functional space station that would provide a base for the conduct of scientific experiments, manufacturing, satellite maintenance, large structure assembly, and the dispatch of vehicles to high Earth orbit and deep space missions.

In deciding whether to allocate tasks to men or to machines, it is important to understand the capabilities and limitation of both. Man's unique abilities to respond to the unforeseen and to operate at a level of complexity exceeding any reasonable amount of previous planning distinguish him from present day machines. His limitations, however, include his inherent inability to survive without protection, his limited strength, and his propensity to make mistakes when performing repetitive and monotonous tasks. By contrast, an automated system can do routine and delicate tasks, exert force smoothly and precisely, store and recall large amounts of data, and perform deductive reasoning while maintaining a relative insensitivity to the environment. The establishment of a permanent presence of man in space demands that man and machines be appropriately combined in space-borne systems. To achieve this optimal combination, research is needed in such diverse fields as artifical intelligence, robotics, behavioral psychology, economics, and human factors engineering.

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