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Summary

Focused interviews were conducted with the Apollo astronauts who landed on the Moon. The purpose of these interviews was to help define extravehicular activity (EVA) system requirements for future lunar and planetary missions. Information from the interviews was examined with particular attention to identifying areas of consensus, since some commonality of experience is necessary to aid the design of advanced systems. Results are presented under the following categories: mission approach; mission structure; suits; portable life support systems; dust control; gloves; automation; information, displays, and controls; rovers and remotes; tools; operations; training; and general comments. Research recommendations are offered, along with supporting information.

Introduction

The Apollo moon-landing missions consisted of six flights conducted between July 1969 and December 1972.[1] Of the twelve crewmembers who were deployed to the lunar surface, eleven survive today. As the only humans who have lived and worked on a solar system body other than Earth, these eleven men compose a unique experience base for use in planning future missions.

Although the Apollo astronauts have been extensively debriefed and have spoken and written widely of their experiences, we wished to determine if there were any aspects of that experience that had not yet been fully explored and that could have relevance in the design and development of future extravehicular activity (EVA) systems. The primary objective of this study was to determine if there were areas of consensus among those with operational lunar experience that could be of help in planning EVAs for future missions; a secondary objective was to explicate any other insights that could help further the planning process.

The intended primary audience for this study is mission planners and scientists and engineers responsible for EVA system design. However, we anticipate that various aspects of the report may also be of interest to a wider readership and it is written to be accessible to anyone with a general interest in EVA.

This study followed a request made by the Office of Exploration, NASA Headquarters, to the New Initiatives Office at Johnson Space Center (JSC). The study team was headed by Robert Callaway of the New Initiative Office and included members of the Crew and Thermal Systems Division at JSC and the Aerospace Human Factors Research Division and the Advanced Life Support Division at Ames Research Center (ARC). Participation of the astronauts was solicited through the Office of Exploration, with the concurrence and cooperation of the JSC Astronaut Office.

Methodology

Approach

The approach taken in this study differs in several significant ways from that of related studies. First, most astronaut reports concentrate on the responses of single individuals. Such reports frequently contain a number of direct quotes which themselves become the basis for supporting a particular avenue of development. However, it is often unclear whether the experience reported is a general finding or describes the response of one individual or the results of a particular mission sequence. In the present study, we were interested in capturing common experiences across missions and individuals.

After considering the benefits and drawbacks of various approaches, we decided to utilize a focused interview approach, with each respondent being interviewed separately. A focused interview balances structured and open-ended responses. It is an informal, conversational approach in which many topics can be discussed, but one in which a pre-determined set of topics is always covered.

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[1]The Apollo program was comprised of 17 missions. Missions 11–17 were planned as manned Moon-landing flights. Missions 11, 12, and 14–17 successfully landed on the lunar surface and returned to Earth. Apollo 13 was aborted after an explosion in an oxygen tank; the crew returned safely to Earth.

The decision to use focused interviews was influenced both by the population of potential respondents and by the nature of the information sought. Focused interviews tend to produce good results when the number of individuals is relatively small, when the number of areas to be explored is defined and limited, and when the desire is to provide maximum opportunity for new directions to be taken or for responses to be offered that were not anticipated in advance.

Another essential difference between this study and prior reports of the Apollo missions is that the astronauts were being asked not just to recollect and to recount their experiences but to project applicable aspects of their experiences to a new situation with quite different requirements. In order to help the astronauts make this transition, we needed to (1) make them aware (if they were not already aware) of current thinking about, and examples of, post-Apollo EVA system designs, and (2) provide a model or scenario representative of possible future exploration flights. To meet the first requirement, a demonstration room was set up in which a variety of EVA equipment designs, including recent designs, could be shown. To meet the second requirement, we adopted the First Lunar Outpost (FLO) mission as a representative model of future flights.[2]

Interview Content

Existing lunar surface information– The preparation of interview materials began with a thorough search of all documents and other materials related to the experiences of the Apollo astronauts on the lunar surface. Debriefing materials, special articles, memos, and all videotapes taken on the lunar surface were reviewed to gain an understanding of what the experiences had been and what information had previously been reported. Conversations were also held with several researchers who, for other reasons, had interviewed, or were in the process of interviewing, the Apollo astronauts. In reviewing previous and ongoing activities, we were attempting to understand, to the extent possible, what was already known about the lunar-surface experience and to avoid wasting time in discussing things that had previously been documented.

EVA system requirements– The second phase of preparation addressed information that was considered most important by those charged with the design and development of EVA systems. A series of interviews was held with members of the Extravehicular Systems Branch at ARC in order to understand the range of issues that should be addressed and to identify those areas where astronaut input could be helpful. Individual interviews were held with nine members of this branch. Several group meetings were also held that included these nine individuals and others. In addition to the issues raised in these sessions, all were invited to suggest questions that they would like to have addressed.

In a parallel effort at JSC, input was solicited from individuals involved in the design of suits, gloves, and other EVA systems. Six telephone interviews were conducted by the first author with various members of the JSC Crew and Thermal Systems Division, most of whom were members of the EVA Branch. Some of these individuals, in turn, solicited additional input from contractors and other personnel.

In all, input was received from a large number of people on the forefront of planning for various aspects of advanced EVA systems. This input was used only to develop the astronaut interviews and is not otherwise reflected in this report.

Content selection– With a relatively clear view of both the reported astronaut experiences and the EVA system needs, the next step was to determine the interview content. A number of suggested items were eliminated because they were already answered as fully as could be expected, they were too narrowly drawn, or they did not relate particularly to the experiences of the Apollo astronauts. The issues or questions remaining were organized into areas and assigned a value according to their design importance and the likelihood that they could be answered. This culling process resulted in twelve primary and one general topic area of inquiry, each with multiple, prioritized associated issues. These topics and the issues and questions associated with them were further reviewed by members of the EVA Systems Branch at ARC, by members of the EVA Branch at JSC, and by the Project Director in the New Initiatives Office at JSC.

Interview Plan

It was important that the interview be structured enough to ensure that predetermined issues would be addressed but unstructured enough to allow discussion to flow in unanticipated and potentially more important directions. The interview design plan is described below.

After making introductions and explaining the purpose of the interview, the respondent was given an opportunity to present any information he thought relevant or to express any opinions he wished. Written notes, rather than tape recordings, were used in order to provide a relaxed

[2]The First Lunar Outpost was an exercise conducted by the Exploration Projects Office at Johnson Space Center in the spring of 1992 to explicate design and operational requirements needed to support a crew of four for 45 days on the lunar surface.

atmosphere and to emphasize that it was the ideas that were important, not the wording used to express them. Following the preliminaries, each of the focused topics were introduced and discussed. The basic objective was simply to hear what the respondent had to say about the subject. However, for each topic, we also had a number of specific issues in mind. If answers did not flow in the general discussion, specific questions were asked. These focused-topic discussions and the questions associated with them were planned to occupy most of the interview period. Following the discussion of focused topics, questions related to the specific experiences of the particular astronaut or to his particular mission were raised, as appropriate. Finally, the respondent was asked again if there were any issues he wished to address that had not been discussed or anything else he wished to add.

Before conducting the interviews with the Apollo astronauts, the interview content and format were pre-tested under conditions similar to those of the actual interviews. The test subject for this test interview was a volunteer who had trained with the Apollo astronauts, but who, for medical reasons, had not flown during the Apollo program. This pre-testing helped us to both validate the process and to trim the length of the interview down to a manageable period.

Procedures

Of the eleven surviving Apollo astronauts who landed on the moon, eight agreed to participate in this study. Each astronaut was scheduled for a half-day, 4-hr session. The sessions were conducted over two 1-week periods during March 1993.

Approximately the first 30 min of each session were devoted to a description of the FLO mission, which served as an example of a future exploration flight. This session set the stage for what we were asking the astronaut to do, that is, to think in terms of a four-person, 45-day mission. Although basically presentational, this session provided an opportunity for the astronaut to ask questions and to discuss issues of interest to him. Some respondents offered important comments during this initial session. These comments were noted and included along with those from the interview process.

Following the briefing, the astronaut and the study team moved to the area where the flight suits, gloves, and other technology demonstrations had been set up. The astronauts viewed video clips of lunar-surface operations from Apollo showing some of the typical astronaut movements such as loping, running, and hammering, as well as some off-nominal movements such as recovery from falls and retrieving tools. The purpose was to re-evoke their Apollo experience and to help them project and think about future requirements. They then examined suits and related equipment in chronological order from Apollo to the advanced designs. The astronauts tried on several versions of pressurized gloves, and were shown new designs, for example, of portable life support systems (PLSS) and methods for suit entry, dust control, and boot testing. This hour or so of technology demonstration elicited many comments that were captured as part of the interview process.

Following the technology demonstration, the astronaut and the interview team returned to the interview room. The interview team consisted of three individuals, one of whom had primary responsibility for conducting the interview. The other two had the primary responsibility of taking notes on the responses of the interviewee and the secondary responsibility of supporting the main interviewer in conducting the interview. A fourth member of the study team from the advanced technology group was also present to answer any specific hardware questions that might arise in the course of the interview. The interview lasted about two hours.

Results

The results presented here are derived from the responses of the eight astronauts interviewed. The main purpose of this exercise was to identify those areas where the experiences of the lunar-surface astronauts led to basically similar conclusions and where, therefore, planning lessons could be learned.[3] These areas of general agreement are reported in this section and constitute the main results of this investigation.[4]

Mission Approach

A major theme arising from discussions of mission approach was the need for a mission and design philosophy that emphasizes a *total system*—one that takes into account the integration of the person and the crew as a unit with the facilities and equipment. Respondents noted that both the mission itself and the EVA facilities

[3]The various Apollo missions differed from one another in important respects. For instance, later missions were longer in duration than earlier missions; involved a rover vehicle; called for three, rather than two or one, EVA(s); etc. These differences imply different experiences. However, because the total number of astronauts who landed on the lunar surface is so small and we were asking them to project to a new, future scenario, the responses of all participants are pooled in the description of results.

[4]A number of additional comments were offered by one or by a minority of respondents. These comments are captured and recorded in appendix A of this report.

and equipment should be designed to fit the tasks to be accomplished, and not the reverse. Design strategy should be marked by *simplicity* and also *reliability*. The design should address only reasonably anticipated task requirements and should try to neither include capabilities that are not needed nor events that are unlikely to occur. In other words, design for the ordinary, not the extraordinary. A related response, voiced by several respondents, was that mission planning should not be based on a risk-free criterion. System design should, in general, address normal or expected events, with provision for emergency operations developed in parallel.

A second theme was the need for heightened autonomy and self-reliance on exploration missions. Primarily because of the length of future missions, the respondents saw a far more active role for the crewmembers in planning and executing their activities and in maintaining themselves and their equipment than has been required previously.

A third idea expressed by a number of respondents was that exploration missions such as the FLO mission need not be, and should not be, as tightly scheduled and controlled as were earlier missions. For future, longer missions, astronauts need to accomplish overall mission goals, but they also need to operate at their own pace, to appreciate the experience they are having, and simply to relax and have fun.

Mission Structure

The respondents viewed the two-man EVA team as the desired basic unit of exploration. However, most felt that a one-person, limited EVA (brief duration, close to the habitat) would be acceptable and that flexibility would be needed in determining how particular EVAs should be constituted. For instance, some activities might call for a different mix of team members, whereas others might require three or even four crew members to be out on an EVA at the same time.

Regarding the amount of time spent per EVA over a 45-day mission, the consensus was that a 7–8-hr day was generally appropriate. Most respondents felt that, overall, an EVA every other day was quite doable and, if anything, represented too little EVA. However, a number made the point that exactly when EVAs were run (e.g., one day on, one day off) should not be fixed in advance but should be adjusted to take advantage of how the individuals are feeling, to address the tasks that need to be accomplished, and to keep the EVA activity fresh and interesting over the duration of the mission.

Suits

The importance of simplicity and reliability dominated responses of the subjects to suit features.[5] For instance, respondents thought that being able to pull one's hands inside the suit to shake out the fingers or to reposition the microphone was an interesting idea but one that was not worth the complexity it would add. Respondents generally approved of changes that would reduce the required number of connections between the suit and the life-support system. Some also expressed concern that changes could increase the number of joints and bearings. These latter changes were perceived as introducing new potential points of failure. In this connection, several respondents specifically advised against introducing any more mobility into the suit than was required by the EVAs anticipated.

Regarding the requirements of habitat pressure, suit pressure, and pre-breathing, there was total agreement that the driving consideration should be adequate suit flexibility and mobility. The dominant belief was that suit flexibility demands that suit pressure be low, implying high O_2 concentration. Several respondents suggested that a high-O_2/low-total-pressure approach should be actively pursued. The argument was that the purpose of the lunar expedition is EVA; the purpose of EVA requires performing useful work; and a way to accomplish useful work is to be able to move about the surface and grasp objects easily. They felt that an O_2 suit environment approaching 100% would best accomplish this end. The issue of habitat and suit gas mixture for missions of extended duration was a recurrent theme and will be referred to again in later sections of this report.

There was less agreement on the relationship between suit pressure and habitat pressure. Some respondents felt that EVA crews will need to be able to get into their suits and exit very quickly, implying a low habitat pressure as well as a low suit pressure. Others felt that the time required for pre-breathing is not an issue of major importance. Although respondents favor operating in low-pressure suits, if a higher pressure suit is deemed

[5]Suits worn during Apollo missions served both intravehicular (IVA) and EVA requirements. They were worn during all critical IVA flight phases (liftoff, docking, landing) as well as in the pressurized EVA condition. In addition, they were to provide protection in an emergency. The combined IVA/EVA uses dictated a number of design features of the Apollo suit: It had to be capable of operating in a pressurized state for up to 5 days; for IVA comfort, it could not employ any hard elements; and life support connectors had to mate with the life-support systems of the command module, the lunar module, and the PLSS. In contrast, the suit used aboard the Space Shuttle is used only for EVAs and so is free of the design compromises required for the Apollo suit.

necessary, they generally approve the idea of a variable-pressure arrangement. This would allow one, for instance, to travel on a rover at a higher pressure and to adapt in transit to lower pressures for operating in high workload situations. However, again, this acceptance was conditioned on the assumption that the variable-pressure feature would not add significantly to the complexity of the suit.

The issue of the weight/bulk/mass/volume of EVA suits resulted in a complex of responses. To the specific issue of weight, some respondents did not see suit heaviness per se as a problem, with a couple suggesting that more weight might have been helpful during the Apollo EVAs. Other respondents (generally referring to post-Apollo suit-design concepts) felt that suit weight was indeed a problem and that limiting the weight of suits was an important consideration for future flights. Those who emphasized the need to limit suit weight also tended to emphasize the importance of reducing the volume required to transport and store the suits. Although distinctions were drawn regarding the particular question of weight, there were no differences in response to the broader question of bulk and mass. Everyone perceived bulk and mass to be an area where improvement is needed. Numerous references were made to the need to pull the suit closer to the body and to reduce the inertia involved in starting, stopping, and changing direction. It appears that from the standpoint of surface operations, the ideal lunar or planetary surface suit (and gloves) would hug the body as a second skin, fold into a small package, and weigh just enough to provide leverage and to keep the individual from lifting off the surface.

Concern was expressed that suits must last for 45 days and be maintainable with only routine care. Although there was agreement that a suit that is to be worn for 45 days must fit very well, there was only limited resistance to the idea of modularity in suits or even to shared suits. Gloves, however, were viewed as requiring customization. Modularity, properly implemented, was seen by most as an aid to suit maintenance, as an effective way of assuring the availability of spares and backups, and as a reasonable means of controlling costs.

On the question of preparation time for EVAs, the bottom-line response was that what was acceptable was whatever it took. However, there was a clear desire to keep this time relatively brief and productive and to combine several activities, including pre-breathing, attending to physical needs, donning, suit checking, and mentally preparing for EVA.

Two related suit ideas, rear entry and external docking, drew mixed responses, as did the idea of a hard suit generally. Rear entry would have the astronaut enter and exit the suit through a door in the back of the upper torso of a hard suit. External docking would mesh this aperture area to a similar opening in the airlock, allowing the crewmember to exit the suit and enter the habitat while the suit remained outside. Some viewed rear-entry as an aid to one-person donning and deployment of the suit and external docking as a significant advantage for dust control and general storage. Others felt that these design concepts, and especially external docking, introduced new concerns including sealing difficulties, changeout limitations, and problems with suit maintenance. No direct effort was made to solicit responses regarding preferences for hard or soft suits. However, since examples of both were available in the technology demonstration area, a number of comments addressed this issue. Reaction to the hard suit appeared to turn on how the respondent believed the various requirements for a 45-day mission could best be met. Clearly, all things being equal, everyone would prefer a soft, close-fitting, pliable suit. However, taking into account FLO-type conditions, conclusions varied. Opinion was almost equally divided among those who opposed the concept of a hard suit, those who were open to the idea, and those who favored a soft suit but who believed that some aspects of a hard-suit design might improve performance.

Portable Life Support Systems

The portable life support system used on the Apollo missions was given high marks for its functional capabilities in controlling atmosphere and temperature. Structurally, it did force one to assume a forward position, although most adapted readily to this shift. A few who were on earlier flights reported dehydration and difficulty with the placement of controls. These problems were corrected on later flights; in any event, they were generally judged to be minor. Of more concern was the general mass of the system.

Most would prefer a system (i.e., the suit plus the PLSS) that has less mass and is easy to move around. A possible approach to reducing the mass of the pack that must be carried is to have astronauts change out consumables. Although most respondents did not express a strong objection to doing this, some thought it was not a good idea and all were concerned that such a change-out be accomplished safely and easily. (Safety and added complexity were the major stumbling blocks, but some also expressed concern about limiting how far one could wander and about having to break one's attention away from the primary work activity in order to deal with life-support issues.) The possibility of lung-powered or pressurized breathing was viewed with even greater skepticism. For many, it did not appear workable but most were willing to consider it. In contrast to these interested-but-skeptical responses, the approach of using umbilicals while working near a rover was plainly rejected as both too dangerous, because of the possibility of tripping over cables, and too restrictive and cumbersome.

Respondents generally favored integrating the PLSS with the suit as a way of reducing failure points; of keeping donning and doffing times to a minimum; and of avoiding snagging on lines, cables, and projections.

Dust Control

Dust, a pervasive problem on the lunar surface, was viewed by the respondents primarily in terms of developing a strategy for management. Many thought the best means of control was to keep equipment that was exposed to dust separate from the living areas of the habitat. Airlocks or similar attached storage areas were seen as important in providing the space for maintenance of suits and other equipment. The role of tightly sealed connectors and covers to keep the dust out of the suit and the habitat was also stressed. This emphasis on isolating exposed materials, complemented by the elimination of dust through cleaning, vacuuming, mesh floors, etc. and strict enforcement of maintenance procedures was seen as the primary approach to dust management. A secondary line of defense emphasized avoiding disturbing the dust in the first place and preparing areas where high traffic is anticipated (e.g., around the habitat) so that a stable and non-deteriorating surface could be maintained. Some also suggested that materials might be selected with dust-avoidance or dust-control capabilities in mind, such as smooth surfaces and materials that are dust-repelling rather than dust-attracting.

The prevalence of dust was not generally thought to be a health issue. Some did believe, however, that over long periods of time it could develop into a health problem if not properly controlled.[6]

Gloves

There was consensus that gloves/hand dexterity is among the most important EVA improvements needed. There was a restrained approval of the changes that have been made in the gloves since Apollo but the general feeling was that these improvements are not nearly enough.

Virtually all respondents reported that the gloves they had worn on Apollo imposed serious limitations on movements of the fingers, hands, and forearms. These limitations ranged from lack of adequate tactility and feedback, to reduced performance and muscle fatigue, to sores and bruises. Most found that muscle fatigue disappeared overnight and thought that it probably did not pose a cumulative threat. Several suggestions were offered including customization and careful fitting to anticipate pressurization changes and exercise and training to prepare the hands for a 45-day mission.

Acceptance or rejection of the concept of end effectors to extend hand capability seemed to depend on how intractable one thinks the glove problem is. Clearly, everyone would prefer a glove that stays in place, allows gripping without significantly extra effort, and provides an acceptable level of dexterity and feedback. This goal continues to be of highest priority. However, a few of the respondents felt that end effectors could be useful for some tasks and that the idea should be further examined.

Automation

There was broad and high-level support for integrating automation into the EVA system wherever appropriate. Automation was seen as especially useful when activities are repetitive or when extended setup times are required. Automation was deemed acceptable over a wide range of activities including setup, monitoring, and control. However, there was also concern that backups, manual overrides, and selectable levels of automation be available. There was some difference of opinion about whether the use of automation should extend to intricate activities such as landing on the lunar surface, but, in general, automation was viewed as desirable, provided it did not contribute substantially to mission complexity and that it remain under the control of the crewmember. Several respondents also mentioned the extended role they saw for robotics working in conjunction with crewmembers.

Automated suit checkout generally was viewed positively, provided that proper safety controls and backups were in place. Opinion on the desirability of automated control of suit atmosphere and temperature differed, with some thinking it would be workable and others believing it to be either too complex or having too great a lag time.

Information, Displays, and Controls

The respondents wanted the information presented to be simple and limited to only what was needed. Primarily, they wanted information relevant to the current operational task. Secondarily, they were interested in having safety-related status information. Most felt this status information should be available on a call-up basis. Alarms were favored for very significant events, but the

[6]Breathing silica dust over time (as in quarry work) can result in silicosis, a chronic lung disease. It is likely that prolonged exposure to lunar dust would result in similar lung problems.

preference for normal operations was to have the ground or the habitat in an active monitoring role, calling issues to the attention of the crew only if necessary. In this way the respondents felt the EVA crew could concentrate on the task they were performing.

Visual displays were envisioned as supporting operational tasks, with aural displays used for alarms. A number of respondents expressed interest in examining how head-up displays might be incorporated into EVAs, although reservations were also expressed that they might not work well in EVA situations. Similarly, although there was a general interest in the possibility of voice-activated displays, there were also reservations about their reliability and a concern that their use could be at cross-purposes with other voice communications. A number of respondents also mentioned the importance of having good visual and aural communication links with both the ground and the habitat. The habitat was frequently mentioned as a key communication node in the EVA communication network, replacing the monitoring function that ground control had played in the Apollo missions; it was also seen as having information requirements of its own associated with laboratory activities such as information processing and data reduction.

Checklists are a common form of activity management. Electronic checklists are now being introduced in a number of areas. These systems have the advantage of being able to capture and organize information as well as display it in new ways that aid the user. The respondents in this study appreciated the need for rapid information updating and display in support of lunar and planetary operations. They also accepted, in concept, the use of electronic displays and checklists to present this information to the EVA crew.

Rovers and Remotes

The use of the rover to provide auxiliary and/or supplementary life support was generally considered to be desirable, provided the disconnections/connections could be accomplished routinely and safely and that the activity did not add substantially to the complexity of the mission. The added distances that could be traversed were mentioned by several respondents as a significant advantage of rover-supplied consumables. Potential use of a rover as a safe haven in a radiation event drew mixed responses. Those who did not support this concept felt that it introduced too much complexity at an early stage of exploration. Respondents agreed that a second rover was desirable at some early point in follow-on missions in order to extend surface operations and also as a backup to the primary vehicle.

The respondents thought that loading, storage, and access to equipment, tools, and supplies need to be improved, possibly by the use of a snap-on pallet or some other device. While there were other specific suggestions about what might be provided on the next generation of rovers, several emphasized keeping the rover simple, thereby allowing repairs (to the rover itself, as well as to facilities and equipment) to be accomplished on-site by the surface crew.

Tools

There was general agreement that it is difficult to keep equipment in place on the lunar surface, primarily because of its low weight under lunar gravity. There is also the problem of surface cables not lying flat. However, most respondents thought the difficulty of managing and using tools to be a more important concern. The light weight of the tools was mentioned as a factor but the main problem reported was in gripping—and particularly in maintaining a grip—on hand tools. The necessity of continuously exerting pressure just to hold on to a tool caused considerable difficulty, particularly when using the hammer. Some respondents related these problems primarily to limitations of the suit and glove and did not consider them tool issues per se.

Regarding what might be done to reduce the muscle fatigue associated with manipulating hand tools, a promising suggestion was to provide an attachment such as a wrist loop or other means of securing the tool. With this, the user could relax his grip without losing the tool. Some saw value in trying to achieve a better fit between glove and tool handle. However, most thought that having to snap tools on to a customized handle was more trouble than it was worth. There was also little enthusiasm for walking, sitting, or other aids, with several commenting that they had rested adequately simply by leaning on the suit.[7]

Regarding access to tools and storage of samples, several suggestions were offered. Most found the buddy system of tool access to be acceptable under most anticipated conditions. However, other arrangements would have to be made if one were operating alone. For collecting and carrying samples, something with an wide mouth, like a shopping bag, was the respondents' container of choice.

Operations

There was significant agreement among respondents about how planning and implementing for an FLO-type

[7]This raises the question of how much more tiring it might be to operate in a suit which does not support itself.

mission should proceed. A general movement toward increasingly greater crew autonomy in day-to-day planning and activity would be combined with strong ground involvement in overall planning of mission objectives and operations. In general, mission operations would be planned to a high degree in advance of the mission by all involved groups in order to meet operational and scientific objectives. This planning would serve as the basis for further planning of near-term activity, which would be developed jointly by the crew and the ground during daily discussions. However, the crew would have a high degree of flexibility in implementing the daily plan and could adapt schedules to fit events as they evolved. Several of the respondents expressed the desire to be able to spend as much time as necessary in documenting scientific findings, particularly in the event of a serendipitous discovery. It was assumed that the ground would retain a significant role in planning and monitoring during EVA. One reason given was to free the crew for scientific work by relieving them of detailed planning and monitoring tasks. With later missions, the habitat crew was seen as taking on an increasing role in planning, and especially in monitoring EVA operations.

A related issue was the reliability of equipment in general, and of experiments in particular. The respondents felt that experiments should be designed with a view toward making them less sensitive to the elements while also allowing for easy repair, if that should become necessary.

Given adequate consumables, the limiting EVA factor during nominal operations was generally assumed to be fatigue, both mental and physical. For off-nominal events, such as a suit or glove puncture, loss of PLSS, or habitat failure, respondents viewed the preferred solutions from two perspectives. First, for each projected failure, it must be determined in advance when one could and should attempt to fix the problem in situ. Second, mission rules reflecting those decisions must be put in place and strictly enforced. For instance, walking 20 km or so back to the habitat following a failure of the rover, although a stretch, was considered quite doable under favorable conditions and if required. This distance, modified by time constraints, consumables remaining, and surface conditions, could then form the basis of a mission rule involving rover failure.

During EVAs, astronauts' vision can be impaired by several factors. During Apollo, the peripheral vision of astronauts was limited by the physical structure of the helmet and movement within the suit. Other visual problems such as high contrast, shadows, and washout relate to the characteristics of the lunar surface environment itself. The general belief was that to some degree one could adapt to these differences over time. The visual area that caused the most significant surface problems involves the judgment of distance. Problems in judging distances, combined with the more general condition of not knowing where one is, indicates that range-finding, navigational, and related equipment must be available, either as part of a rover vehicle or in some other way.

Regarding operating during high noon and during lunar night, the respondents felt that neither condition should necessarily preclude EVAs, provided acceptable thermal conditions could be maintained. For the high-noon condition, most felt that taking 3 to 5 days out of the mission was an unnecessary precaution. However, they also felt that because visual conditions would be difficult, it would be advisable to plan activities closer to the habitat. For lunar night, respondents believed that operations could proceed fairly routinely with supplementary lighting as needed. Some respondents also stressed the value of using teleoperations where EVA was not practical and also as a supplement to routine activities.

Training

The astronauts' suggestions for training differed from other discussion topics in that there was wider diversity in emphasis. This diversity related both to different experiences associated with different missions and to the interests of particular individuals. The following represents a subset of suggestions where there was cross-respondent agreement. A more detailed list of training suggestions, reflecting more diverse responses, is included in appendix A.

A number of respondents mentioned the need to cross-train candidates for exploration missions. Cross-training would allow each person to have both a primary and a secondary specialty. This would provide flexibility in the overall sizing and organization of crews as well as add a safety factor to each mission.

Respondents also mentioned the need to train under realistic conditions. Specific areas included training with tools of the same weight and stiffness as would obtain on the lunar or planetary surface, maintaining one's own equipment during the training process, operating in the pressurized suit and for the extended number of hours one would have to wear it on a 45-day mission, and training for the mission as an integrated whole and not just as segmented parts.

A third area mentioned by several respondents related to continuing training on the lunar or planetary surface. Specifically, the concern was that crewmembers prepare mentally and hold rehearsals so that they will be prepared for activities later in the mission or to respond to an emergency. Conducting fire drills and reviewing procedures (for instance, for liftoff) were seen as essential to maintaining the skill and alertness needed to perform optimally under actual conditions.

General Comments

In anticipating what issues might prove most significant for an FLO-type mission, responses converged on the issue of sustained mental performance. Various respondents expressed this concern in terms of the potential for strained interpersonal relations, for boredom, for running out of mental energy, and, especially, for becoming complacent. Respondents suggested a dual approach to keeping a sound and active mental state over an extended period. The first element related to the quality and the scheduling of the work. The sustained availability of meaningful work that could be scheduled by the crew with a high degree of flexibility was seen as essential. The second, complementary element was the availability of relaxing and restorative physical and mental activity. The combination of sufficient (but not excessive) quality work, along with the time to fully take in and enjoy the experience, was the approach recommended for avoiding errors and sustaining performance over the full mission duration.

Conclusions

The results of this study revealed a level of agreement among the Apollo lunar surface astronauts that can be summarized as follows:

1. Emphasis should be given to the integration of crew, equipment, and facilities as a total system.

2. All subsystem designs should be based on fundamental principles of simplicity and reliability. Given a trade-off, simplicity and reliability are to be preferred over added functionality.

3. The EVA hardware-related items most in need of improvement are the bulkiness/inflexibility of suits and the (inadequate) manipulability/dexterity of the gloves.

4. Equipment should be designed to fit EVA task requirements and the training of crews should be on actual tasks, equipment, etc.

5. Future missions will require increased crew autonomy. Crews will need greater flexibility in operations, particularly in daily scheduling.

6. The habitat crew will play an increasingly important role in supporting EVA crew operations, replacing some of the activities previously performed by ground control.

7. High levels of maintainability and reparability must be designed into experiments as well as into equipment and facilities generally.

8. Extended missions will require ways to achieve and sustain high-level mental performance.

Research Recommendations

During the course of this investigation, certain issues came to our attention that suggested the need for follow-on research and related activities. Although outside the parameters of this study, and certainly outside the expertise of the authors, we feel that these issues are of sufficient interest and importance to be brought to the attention of those more qualified to judge them. With these caveats, we offer the following recommendations for consideration. Information supporting these recommendations is given as appendix B.

1. Conduct an analysis/investigation of the mid- and long-term physiological effects of breathing pure and high-concentration O_2 at reduced pressures. As a part of this effort, an understanding should also be acquired of human adaptability to mixed-gas, low-pressure environments, such as those experienced by mountain dwellers and climbers.

2. Conduct an analysis/investigation of the flammability issues associated with materials in low-pressure, high-oxygen environments.

3. Conduct a focused evaluation into the availability and near-term possibilities of new materials as they relate to desired suit characteristics (weight, bulk, mass, storability, serviceability, durability, comfort).

4. Conduct a detailed task analysis to determine specific performance requirements for advanced missions as related to suits, gloves, and other elements of the EVA system. Determine the priority of improvements needed in terms of mission tasks.

5. Conduct an analysis of optimal mobility requirements, specifically the relationship between the workload required to perform required tasks with a limited-mobility suit and the workload required to perform similar tasks in a high-mobility suit.

6. Incorporate, on an on-going basis, the up-to-date knowledge of orthopedic (specifically hand) researchers and practitioners into the glove design and develop and incorporate objectively determined standards of performance and measurement into the evaluations of gloves.

Appendix A

Observations of Individual Respondents

Some comments offered by the individual astronauts who participated in this study reflect particular experiences, viewpoints, interests, or areas of special expertise. These suggestions fall outside the primary focus of this report which is areas of agreement or consensus. However, these individual insights could also be of value in the planning process and are included here for further consideration.

Mission Approach and Mission Structure

A number of different comments centered on long-term effects and on concern over how missions and systems are approached. One such concern was that the EVA, and not the habitat, needs to be the expressed central focus of the mission and the driver of the design criteria. One respondent expressed a strong view that our recent EVA development efforts are overly complicated and that these efforts could set the Agency on a path from which it would be difficult to recover. A view was also offered that EVA requires unique physical and mental abilities and that we must not hesitate to select only those who possess these special skills and to train them rigorously so that they are able to perform maximally over the entire mission. Regarding the mission length, more than one respondent expressed the view that evacuation would be difficult or impossible over a 45-day mission and that illness should not be considered a condition that results in a return to Earth.

Suits

Regarding the construction and care of suits, one respondent argued against the use of metal joints, on the basis that they do not fail gracefully. Another suggestion was that suits should be equipped with dams to control pressure loss resulting from a puncture or the loss of a glove. Another respondent had a similar idea, suggesting that the suit could be sealed at the wrist and that changing gloves could be a rover-supported function. Regarding suit maintenance, one respondent suggested that all astronauts be made responsible for their own suits during training. The thrust of this suggestion is the requirement to learn the logistics of suit maintenance, a responsibility that will have to be assumed by crewmembers during a 45-day FLO-type mission.

Portable Life Support System

The issue of how to replenish life-support expendables resulted in several suggestions. One involved reducing the need for power by using passive cooling, such as Mylar protection. It was also pointed out that plugging into a rover for power would be easy, whereas making the connections for water and gases would be consider-ably more difficult, suggesting that partial replenishment might be the most useful approach. Since, as was pointed out, the critical problem would be a double failure (PLSS and rover), a condition more likely over long missions, emergency options such as cached expendables or the ability to plug into a buddy's life support system should also be considered.

Dust Control

It was noted that dust has a particularly adverse effect on fasteners, impairing zippers and destroying the connecting capability of Velcro. One suggestion was to use something very simple, like a cloth cover, to protect joints and connections. One respondent offered the opinion that cleaning had to be accomplished on an enforced, daily basis in order to keep ahead of the dust. A second dust issue concerns the structure and function of the airlock. At least one respondent felt that in addition to suit storage, the airlock should house other dirt-prone work areas, such as the geology laboratory. However, another respondent had a different idea, suggesting that rather than one airlock, the habitat should be equipped with two one-person airlocks that could provide pressurization redundancy.

The lunar habitat is generally conceived of as resting above the lunar surface. This arrangement offers some dust protection, since astronauts could scrape their boots and shake dust from their suits as they climb the ladder. However, one respondent did not think a highly perched habitat a good idea, since a 45-day mission presents multiple opportunities for someone to fall off the ladder.

Gloves

The variety of suggestions offered for glove improvement indicates both the importance and the difficulty of this suit feature. With reference to the design of the advanced series glove, one respondent expressed doubt that the metacarpal joint would ultimately be helpful since it might lead to overuse. Another respondent expressed skepticism concerning the utility of the knuckle joint, while others saw the need for a smaller wrist ring and an improved thumb. Additional suggestions included providing more than one set of gloves and incorporating an understanding of what information is transmitted through the hands into the basic glove design.

Automation

It was pointed out that time and motion analyses are needed in order to better understand the requirements for repetitive activity, the leading candidates for automation. A specific suggestion was that the process of deploying experiments, as well as other physically demanding activities, particularly those that could cause one to lose footing (e.g., digging or drilling), be automated. Other suggestions were to apply automation to the documentation process and to utilize automation to facilitate the updating as well as the operational use of checklists.

Information, Displays, and Controls

An audio communication system that allows astronauts to operate without head attachments such as a "snoopy cap," was viewed positively, with the proviso that reliability be preserved. Other information-related suggestions included a good teleconferencing capability between the habitat and the ground; a compact method of reporting PLSS status, including remaining expendables; and the use of graphics or other visuals instead of plain textual presentations.

Rovers and Remotes

Although the Lunar Rover used on the later Apollo missions was viewed favorably, suggestions for improvements were offered. It was observed that the steering on the Apollo Lunar Rover was overly sensitive and that it could climb inclines steep enough to make it feel unstable to the riders. Suggestions for improvement ranged from incremental changes to the existing vehicle to new design ideas. Among the suggestions offered for modest improvements were wider seats and seatbelts; gyrostabilized antennae; improved photographic capabilities through use of a camera on the rover (and possibly on the helmet); an installed workbench; and instrument mounts. Other suggestions were for remote control capability (to call the rover to the work site); possibly a three-wheeled vehicle; and a closer match between terrain requirements and rover capabilities. Several respondents envisioned pressurized rovers, at least for advanced lunar missions. A more radical concept was for a pressurized container that could enclose and transport two or three people, allowing them to climb in and out or to operate nearby in a remotely controlled configuration.

Tools

Several suggestions addressed the storage and availability of tools. It was noted that alternative methods need to be developed so that it is not necessary to continuously carry shovels, hammers, etc. Also, tools need to be anchored so that they are not moved inadvertently. Regarding storage arrangements, one respondent suggested that for an FLO-type mission, arranging tools to reflect the EVA schedule is probably not the right approach and that a more generic storage arrangement is needed. Another suggestion was that a system be put in place to track discarded tools, equipment, etc. for later retrieval. Other suggestions were to match tools to the handedness of the user and to include an easily accessed magnifying glass.

Operations

A suggestion for maintaining alertness was to alter the operating schedule on a continuous basis. Other specific recommendations included planning operations so that they would be in phase with circadian rhythms, conducting maintenance (as possible) in the habitat and out of the suit, and scheduling maintenance (and especially the maintenance of suits) when the crew is rested. It was also pointed out that periodic checks of the return vehicle need to be called out specifically in the operating schedule.

Training

Respondents differed in what they emphasized as training needs. For instance, one respondent thought that training should focus on the specific tasks of the mission. Another spoke of the need for generalized training, such as survival training or stress training, in order to prepare the individual to deal with unpredictable situations. Some respondents focused on the physical aspects of training, such as the need for upper body training and hand strengthening exercises. Others emphasized various aspects of mental conditioning; how it could influence physical and psychological health; and how biofeedback, virtual reality, and other techniques might be utilized to train the mind for the rigors of exploration. One respondent raised the issue of using mind-body control training as it might specifically be applied to the question of speeding up the pre-breathe process. Others suggested the possibility that pre-breathe requirements could be reduced through adaptation.

Overall, an FLO-type mission was seen as requiring lengthy and thorough training. One respondent suggested 300–400 hr as a minimum period for pressurized suit training; another thought that 5 or more years would be needed to master the engineering, scientific, physiological, and logistical skills required in order to maximize performance on a 45-day lunar or planetary surface mission. This respondent also suggested that astronauts on such missions spend a full year after the mission in processing the information they have acquired and in communicating the experience they have gained.

General Comments

As mentioned in the main body of this report, the respondents expressed concern that over a 45-day period interpersonal relations could become strained and that morale could deteriorate. Two specific suggestions were offered as means of helping to maintain crew morale. One was to equip the habitat with windows or perhaps with virtual windows. The second was to provide an opportunity, perhaps on a weekly basis, for a recreational EVA. Also related is the opinion expressed by one respondent that a mental attitude of professionalism, that is, a disciplined and consistent approach to scientific and related tasks, rather than an attitude of adventure or daring, would be a useful mechanism for maintaining productivity over long-duration missions.

Appendix B

Research Recommendations: Supporting Material

The information presented in this appendix does not reflect a thorough investigation of all relevant data. Rather, it represents a limited attempt to understand the various problem areas related to lunar or planetary operations and to make suggestions as to what needs to be done next.

1. Conduct an analysis/investigation of the mid- and long-term physiological effects of breathing pure and high-concentration O_2 at reduced pressures. As a part of this effort, an understanding should also be acquired of human adaptability to mixed-gas, low-pressure environments, such as those experienced by mountain dwellers and climbers.

Space shuttle missions are conducted with a general cabin atmospheric pressure of 14.7 psi and a normal atmospheric gas mix and with an EVA O_2 pressure of 4.3 psi. This spacecraft mix and pressure is in marked contrast to early spaceflight in which 100% O_2 was the norm. Some questions concerning the advisability of using a pure O_2 environment arose following the Gemini flights when a reduction in red cell mass was noted (ref. 1). During the Apollo program, a small amount of nitrogen was mixed with the oxygen atmosphere, although the nitrogen tended to disappear when it was replaced by oxygen as the flight progressed. For Apollo, cabin pressure for most flight phases was 6.2 psi almost pure O_2 with EVA pressure of 3.8 psi. In Skylab, the breathing gas and pressure was 74% O_2 and 26% N_2 at 4.8–5.2 psi with EVA pressure at 3.8 psi.

Questions of the optimal gas mixture and pressure continue to be raised. Operational protocols that do not require extensive pre-breathe will be especially important for lunar and planetary missions that involve significant periods of EVA. If both cabin pressure and suit pressure were to be kept low, pre-breathe could be minimized and glove mobility maximized. Since the issue of high- versus low-pressure environments is so central to EVA equipment and mission design, and since it continues to be debated, we believe the question of oxygen concentration and ambient pressure should be revisited.

Humans exposed to a one atmosphere, pure O_2 environment experience serious physiological effects known under the blanket name of oxygen toxicity. These effects can cause serious and progressive dysfunction in bodily systems, many of which are permanent and some of which can lead to death. Early research into the use of low-pressure pure O_2 suggested that oxygen toxicity may be avoided if the pressure is low enough. Work reported by Barach (ref. 2) and extended by Mullinax and Beisher (ref. 3) suggests that with O_2 inspired at a pressure between 425 mmHg and 91 mmHg, there would be neither oxygen toxicity effects nor hypoxia effects, regardless of the length of exposure (fig. 1). On the basis of these works, it would appear that use of an atmosphere of pure O_2 with a total pressure <425 mmHg may be safe from a physiological point of view. However, work by Morgan et al. (ref. 4) and Michel et al. (ref. 5) suggests that even with O_2 at low pressures, some physiological changes, though temporary, are noted. More recent reviews of the physiological effects of O_2 toxicity (see, for instance, ref. 6) suggest that the effects of high concentrations of O_2 at the molecular and cellular level are only now beginning to be understood. It is not clear whether such molecular/cellular level changes, if documented, would pose a threat to an EVA crewman or would be sufficient to decrease efficiency during extended exposure to a reduced-pressure, high-oxygen environment.

This is clearly a matter that requires more intensive, long-duration study if an environment approaching pure O_2 is to be considered for future lunar and planetary missions. These studies need to focus on oxygen toxicity in reduced-pressure, pure O_2 environments, covering the "oxygen tolerance unlimited" section shown in figure 1. Ideally, these studies should examine exposure for durations extending to several months, simulating an extended stay on the lunar surface or in an interplanetary spacecraft. There may be additional work that can be conducted in conjunction with these long-term studies that will contribute to the general scientific understanding of O_2 effects at a cellular level and may indicate either mitigating factors that can improve oxygen tolerance or therapies that might overcome or inhibit the effect of exposure to low-pressure, pure O_2.

Assuming a mixed-gas environment, there is an additional question concerning pressure requirements. Several of the respondents of this study raised questions about possible adaptation to lower-pressure gas mixtures, that is, gases that would allow greater EVA mobility. Since it appears that some level of adaptation to reduced pressure is accomplished by residents of mountainous areas, the direct hypoxia/toxicity studies suggested above should be supplemented, as possible, by analysis of any available data related to naturally occurring low-pressure effects.

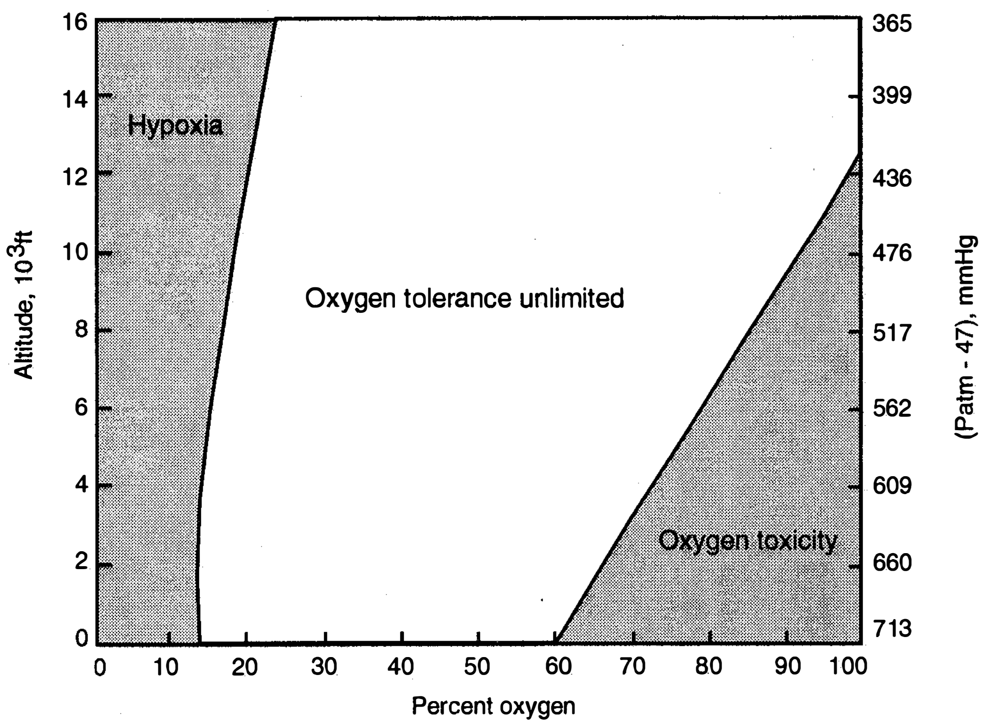

Figure 1. Oxygen tolerance (from Roth [ref. 7], based on work reported in ref. 3).

2. Conduct an analysis/investigation of the flammability issues associated with materials in low-pressure, high-oxygen environments.

3. Conduct a focused evaluation into the availability and near-term possibilities of new materials as they relate to desired suit characteristics (e.g., weight, bulk, mass, storability, serviceability, durability, comfort).

The flammability of on-board materials has been a serious and ongoing concern since the Apollo fire in January 1967. During the Apollo and Skylab programs, the solution to potential flammability problems was to limit the use of materials in the spacecraft to those passing flame-propagation tests as "nonflammable." The Space Shuttle program also adheres to strict flammability standards. However, the problem has been significantly reduced by having a mixed N_2/O_2 gas mixture at the normal atmospheric pressure of 14.7 psi. A recent overview evaluation of the flammability question is reported in a trade study conducted for the First Lunar Outpost EVA Study Team (ref. 8).

All materials used in spacecraft are subjected to flammability tests in accordance with the requirements specified in reference 9. At present, less than 5% of tested polymer-based materials can pass the NHB 8060.1 flammability tests in a 70% O_2 environment. Since flammability tests are conducted at 1 atm, this still leaves open the question of what the flammability risk would be at reduced pressures. Research in this area is needed to form a baseline understanding of probable risk.

However, the more important question is whether new materials can be identified that, while reducing the flammability danger and meeting off-gassing and related requirements, can also address the other long-duration flight requirements. Important characteristics for long-duration flight, and especially for materials for EVA suits, include light weight, low mass and bulk, storability, serviceability, durability, and comfort.

Developing crew garments and extravehicular mobility unit (EMU) thermal/micrometeorite overgarments for use in future missions will be a significant challenge. If crews are to operate in a high-O_2/low-pressure environment in future missions, a vigorous program of research and testing must be undertaken to develop these materials. This research could be pursued along two lines. The first would be to identify materials that were not previously available and to conduct a series of tests to determine which, if any, would be acceptable, including their use in a high-O_2/low-pressure environment. The second would be to identify and specify the characteristics needed, particularly for EVA suits, and to provide these as research guidelines for fabric and petrochemical industry research teams. A first step in developing new materials for both general flight and

EVA spacesuit use would appear to be to convene a workshop or a working group to identify the scope of the problem and to recommend an approach to its solution.

4. Conduct a detailed task analysis to determine specific performance requirements for advanced missions as related to suits, gloves, and other elements of the EVA system. Determine the priority of improvements needed in terms of mission tasks. (Develop tasks and show how improvements in suits, PLSS, and gloves would address those tasks.)

5. Conduct an analysis of optimal-mobility requirements, specifically the relationship between the workload required to perform required tasks with a limited-mobility suit and the workload required to perform similar tasks in a high-mobility suit.

Efforts to establish design requirements for EVA systems must begin with a thorough understanding of the tasks to be performed. At the level of fine movements, hand/glove requirements represent the most critical element. An analysis is needed to determine specific hand movements, movement durations and repetitions, and opportunities for countermovements as well as an understanding of what kinds of information are naturally transmitted through the hands.

At the macro level, the research and development effort should include an analysis of the tasks that the suit wearer would be expected to perform, including the mobility required to conduct those tasks. The tasks evaluated should include a representative range, from the more mundane, such as walking or lifting, to the more complex tasks, for example, those associated with contingencies such as bringing an incapacitated crewmember through an airlock in either zero-g or in a gravity field. Each task will then need to be deconvolved to understand the individual suit motions necessary to complete it.

Although it is generally assumed that any increase in EVA suit mobility is an improvement, there are a number of situations in which additional mobility is neither beneficial nor desired. In a gravity field, the wearer of a highly mobile suit would need to support the weight of the suit. Here it would be preferred that the suit have sufficient stiffness to support itself. In the space shuttle EVA suit, for example, the suit is stable and capable of standing on its own when the knees are locked and the weight of the suit is resting on a set of rigid legs. In this situation, the wearer is able to rest simply by relaxing against the suit. In the zero-g situation, an astronaut may brace himself against the suit while he is held by foot restraints. In this case, the rigidity of the suit becomes an anchor point to help him move a large or bulky object.

In both these cases, the rigidity of the suit allows the wearer to either perform more useful work or to avoid additional work because the stiffness of the suit becomes an aid to the wearer instead of a burden. An analysis of mobility requirements, including workload measurements, is needed to determine how much mobility is enough—how much is too much. The point of building just enough mobility was stressed by several of the Apollo crewmen. In their view, building unneeded mobility into a suit could lead not only to an increase in cost and suit complexity but also to a decrease in performance and an increase in workload.

The analyses of activities suggested here are likely to be complex. One complicating factor in applying this task-oriented approach to suit design is that it will tend to result in suits that have very specialized uses and that may not be readily modifiable for use in other applications. An obvious example would be that a zero-g suit designed with this kind of analysis in mind would have little adaptability to walking in a gravity field. What this approach does accomplish, however, is that it requires a complete understanding of the suit applications. The process of gaining this understanding should force the design team to understand and to plan during the design process for any anticipated evolution of the suit.

6. Incorporate, on an on-going basis, the up-to-date knowledge of orthopedic (specifically hand) researchers and practitioners into the glove design activity, and develop and incorporate objectively determined standards of performance and measurement into the evaluations of gloves.

In addition to understanding what hand-related tasks are required, we must also consider whether crew-members reasonably can be expected to accomplish these tasks. Previous development work has been hampered by a lack of input from those in the orthopedic community who conduct research into the biomechanics of hands. Given a particular glove design, these researchers could anticipate the level of dexterity provided and the kinds and degree of hand, arm, or other fatigue that are likely to follow. However, beyond that, it is likely that these researchers could contribute substantially to the design of improved gloves, that is, gloves that provide the least resistance to normal hand motions in a particular environment.

An additional problem with glove development has been the lack of objectively based, quantifiable standards of performance that can be used to develop and evaluate new glove designs. This problem has been pointed out previously by O'Hara et al. (ref. 10). Problems associated with objective performance measurements are in part due to the complexity of motion of a normal hand and in part due to the complexity associated with adequately representing various environmental working conditions.

To date, the evaluation of gloves designed for use in EVA has depended heavily on input from the glove users. However, this method of evaluation carries its own set of problems. Subjective inputs from glove users include individual factors such as pain tolerance, physical conditioning, the degree of hand fatigue before a particular set of activities is started, the experience an individual subject has both in doing a task and in working in gloves, and any special conditions, such as an existing hand injury or the quality of the fit of a glove. Given this complexity, it is difficult to evaluate on the basis of user reports whether changes in a glove design are adequate or if they could, in some cases, result in worse performance than that of a previously proven design.

An example of the problem of subjective glove evaluation is the flight test of the advanced series gloves. Evaluations made during preflight training in the Weightless Environment Training Facility (WETF) led glove researchers to believe that this new glove would significantly increase comfort and reduce hand fatigue relative to existing gloves. However, during flight the gloves did not work as well as in training and the hoped-for improvements in glove performance were not realized (ref. 11). Although useful in providing a qualitative assessment of overall performance, subjective assessments cannot provide the careful, multi-variate, numerical data that are needed to design improved gloves that reduce hand fatigue and increase dexterity and tactility.

Although there are no obvious solutions to the problem of adequately measuring glove performance, there are some promising leads. There are presently available in the physical medicine and rehabilitation literature examples of objective tests that give quantitative data on the degree of hand functioning under varying conditions (e.g., refs. 12–14). One example of this kind of rating protocol is the Jebsen Hand Function Test (ref. 15) which is a test that measures a range of standard hand functions commonly used in daily activities (see refs. 16 and 17). Tests such as these measure the ability of a test subject to complete a set of tasks that require coordinated uses of various muscles. These tests are designed for use with populations of varying capabilities. It is unlikely that any one of the existing tests will be directly applicable to the assessment of new gloves. However, it seems reasonable that these kinds of tests can be adapted to allow direct measurement and comparison of EVA glove designs.

The same community that conducts the kinds of measurements discussed above also conducts applied research into the development of orthotic devices that can assist an individual with significant deficits in hand functioning. These devices are designed either to enhance an individual's degraded capabilities or to provide conditions under which they can function in spite of their deficits. If one accepts the proposition that working in EVA gloves can, in a sense, be modeled as a deficit of hand function, then this community may be able to provide or design orthotic devices that will allow EVA crewmembers to conduct a wide range of tasks in spite of the limitations imposed by the EVA gloves.

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Focused interviews were conducted with the Apollo astronauts who landed on the Moon. The purpose of these interviews was to help define extravehicular activity (EVA) system requirements for future lunar and planetary missions. Information from the interviews was examined with particular attention to identifying areas of consensus, since some commonality of experience is necessary to aid the design of advanced systems. Results are presented under the following categories: mission approach; mission structure; suits; portable life support systems; dust control; gloves; automation; information, displays, and controls; rovers and remotes; tools; operations; training; and general comments. Research recommendations are offered, along with supporting information.

14. SUBJECT TERMS
EVA requirements, Apollo astronauts, Astronaut interviews, EVA suits, PLSS, Lunar/planetary missions

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