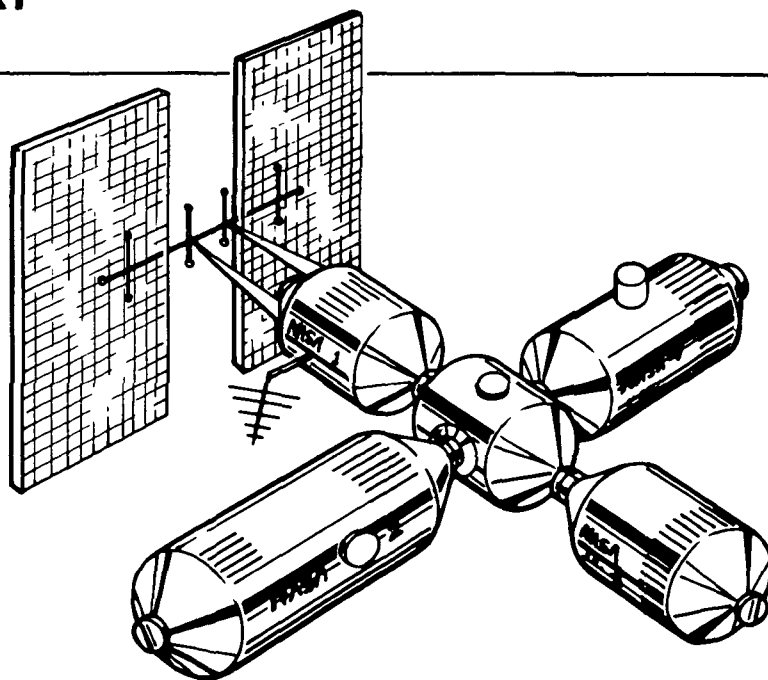


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THE ANTAEUS REPORT

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**ORBITING
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FACILITY**

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QUARANTINE
FACILITY**

THE ANTAEUS REPORT

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In Greek mythology, Antaeus was a giant encountered by Hercules. A mighty wrestler, Antaeus forced passing strangers to wrestle with him and killed them when he won. The Earth was his source of superhuman power, and as long as he could touch the ground he was invincible. If an opponent threw him down, he sprang back with renewed vigor from his contact with the Earth. Hercules was able to defeat Antaeus by holding him in the air and strangling him.

Participants in the 1978 NASA-ASEE Engineering Systems Design Summer Program studied the feasibility of establishing an orbiting quarantine facility where samples returned from Mars could be analyzed. The particular advantage in this approach is that any pathogens the samples might contain would be less likely to pose a hazard to Earth. Like Antaeus, for whom the project is named, such an organism might thrive on contact with the terrestrial biosphere. By keeping the pathogen contained and distant, the proposed orbiting quarantine facility would safeguard the Earth from possible contamination.

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Preface

On several occasions, both before and after the two unmanned Viking spacecraft successfully landed on Mars and carried out their extensive suite of experiments, NASA conducted studies aimed at defining mission requirements for the unmanned return to Earth of Martian soil samples. All aspects of such a Mars sample return (MSR) mission were considered, including mission profile, vehicle design, flight trajectories, scientific analysis of the returned samples, and planetary quarantine or planetary protection (PP) factors. During the course of these studies it became clear that PP factors could have a significant impact on mission design, cost, and complexity, depending upon how serious a concern they were judged to represent and what means were proposed to handle them during the course of the MSR mission.

Planetary protection factors of interest in this context related mainly to the issue of back contamination—that is, the possibility of contamination of the Earth's biosphere by potentially hazardous microbes which could be present in the Martian soil samples. Even after the Viking missions did not detect life in the samples analyzed, there were many scientists who felt that any samples returned from Mars should be held in strict isolation until analyses could be performed to show that the soil was free of hazardous species.

As part of these MSR mission design studies, related studies were carried out to find solutions to the potential back-contamination problem. Options studied ranged from the extreme proposal of sterilizing the sample in transit, before it reached the vicinity of the Earth, to simply housing the sample in a special Earth laboratory similar to the Lunar Receiving Laboratory. Consideration was also given to isolating the sample in a maximum containment facility like those used for highly infectious diseases or recombinant DNA research. Yet another report proposed that the best solution was to isolate and analyze the sample in an Earth-orbiting laboratory before certifying it safe for release to terrestrial laboratories.

Of all the options listed above, least was known about the latter one. Although analysis in space had been suggested several times before, very little hard information was available concerning the feasibility of this approach. No studies had been done regarding containment requirements for such a laboratory, the development of a quarantine protocol, or even sample handling and experiment conduct in the absence of

gravity. It was precisely these questions that were addressed during this engineering design study.

The purpose of the design study was to examine for the first time the feasibility of designing, constructing, and operating a unique space-based laboratory—one dedicated, at least initially, to the isolation and analysis of potentially hazardous samples returned from Mars. This report does not argue that analysis of Mars samples should be done in space. Rather, it defines the characteristics of an orbiting laboratory should this be an option for active consideration for future MSR studies. Hence, considerable effort was devoted to development of an appropriate series of tests to be performed on the sample (the quarantine protocol) and to design of the facility in which these tests would be conducted. Because of the complexity of the system to be designed and the limited time available to complete this study, some details and contingencies may have received only superficial treatment. Furthermore, the study was limited to the design of a system presenting minimal risk, rather than an absolutely fail-safe system able to deal with every conceivable eventuality. We believe, nevertheless, that this report does provide a useful analysis of the major features and characteristics of an orbiting quarantine facility.

The 10-week summer study was conducted at NASA's Ames Research Center and sponsored by the American Society for Engineering Education (ASEE), Stanford University, and NASA. The program format followed that developed during previous ASEE summer studies. Some 20 scientists were selected for the program, which is intended to be an intensive learning experience for the participants as they work on a system design of use to NASA. During the first 2 weeks, a series of lectures provided the basic background needed to begin the project. The next 6 weeks were spent doing design research, individually or in teams, on various subsystems of the orbiting laboratory. In the final 2 weeks, the various subsystem designs were integrated and the first draft of the final report was prepared. No further design work was done following the 10-week program, but various groups and individuals participated in assembling and editing this final report.

DONALD L. DeVINCENZI
Co-Director

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Chapter 1

Summary

A NASA design study examined requirements for handling extraterrestrial samples in an orbiting quarantine facility. The major concepts and findings of the study are outlined in this chapter.

The Antaeus Report describes in detail one approach that could be taken for receiving, containing, and analyzing samples returned from the surface of Mars in a mission analogous to the lunar return missions of the late 1960s and early 1970s. It constructs a general mission scenario and presents an overall systems design, including an approach to cost assessment. Particular attention is paid to the design of system hardware components and to the elaboration of an experimental protocol.

BACKGROUND

With the Viking mission to Mars, a great deal of knowledge has been gained about the surface features and composition of the planet. However, one of the major questions that prompted the mission—Is there life on Mars?—has not been conclusively answered. Automated experiments conducted by instruments aboard the landers did not detect organic carbon or ongoing metabolic processes in the Martian soil, nor did photographs of the area around the two landing sites show any signs of life. But because of the limitations of automated analysis, and because the landers sampled visually only a small fraction of one percent of the planet's surface, there can be no real certainty that Mars, like the Moon, is devoid of organic life.

This uncertainty means that, in the event that samples of Martian soil are returned to Earth for study, special precautions ought to be taken to safeguard them. Moreover, many scientists believe that the samples should be considered to be potentially hazardous to terrestrial organisms until it has been conclusively shown that they are not. The logical extension of this view is that adequate precautions should be taken to protect the Earth's biosphere until

the samples have been proved safe. The question may then be asked, "What kind of precaution constitutes adequate precaution?"

There are three basic alternatives for handling such a sample. The first is to sterilize the sample while it en route from Mars (by heat treatment, for example). The second is to hold it under quarantine in a maximum containment facility on Earth, possibly in a remote location, while it is undergoing analysis. The third is to perform hazard analysis on the sample *before* it is introduced to the terrestrial biosphere. The first two options have known advantages and disadvantages. Little was known about the third option.

In 1978, as part of the planning for a possible future Mars sample return (MSR) mission, NASA convened a summer study. The purpose of this study was to examine the feasibility of designing, constructing, and operating an Earth-orbiting manned laboratory facility suitable for receiving and analyzing Martian soil samples. *The Antaeus Report* presents the findings of that study group.

THE OQF MISSION

Mission Objective

The purpose of the Orbiting Quarantine Facility (OQF) would be to detect the presence of biologically active agents—either life forms or uncontrolled (replicating) toxins—in the sample and to assess their potential impact on terrestrial systems. Only when the sample could be certified safe or controllable would it be transmitted to laboratories on Earth for physical analysis.

The particular technical advantage of an orbiting facility over an Earth-based one is the flexibility it offers in the event that potentially pathogenic agents are present in the sample. With space as a buffer between such organisms and the terrestrial biosphere, the risk of terrestrial contamination is far lower. Complete characterization of the hazard such organisms might represent could thus be carried out without

fear of a containment failure and possible contamination of the biosphere. Depending upon the results of testing, the options available for subsequent disposition of the sample would include (1) unqualified release, (2) sterilization *prior* to release to Earth laboratories, (3) indefinite retention in orbit for prolonged study, and (4) in one extreme case, boosting the sample-containing facility into a distant orbit. A terrestrial quarantine facility could not offer such margins of security.

Mission Scenario

The scenario for such a mission includes several novel features, all of them resting upon technology which is now available or will be available by the time a MSR mission could take place. The OQF mission has been designed so as to be compatible in all its elements with the most likely MSR mission profile as currently projected by planners at the Jet Propulsion Laboratory (JPL).

The mission plan calls for the Space Shuttle to deliver the OQF, one or more components at a time, into near Earth orbit, where it will be assembled and manned. While awaiting the arrival of the Mars sample return vehicle (MSRV), the crew will conduct system tests and protocol review. The incoming MSRV, bearing the sample in a sealed canister in its crown, will be inserted into the same orbit in the vicinity of the OQF. An orbiting transfer vehicle comprised of an inertial upper stage engine (IUS) and remote-teleoperated-manipulator system (TELLE) will then link up with the MSRV, extract the sample canister, and deliver it to the OQF. Resupply of the laboratory, replacement of crew members if necessary, and eventual transport of the sample and crew to Earth will all be carried out via the Space Shuttle.

SYSTEMS DESIGN AND CONFIGURATION

Design Options

A number of general approaches to hardware system design were investigated. For example, the option of developing a completely new system for the OQF mission was analyzed in depth, and was rejected for reasons of cost and available time. The final determination was that the most practical and cost effective approach would be to utilize modified

Spacelab components, principally the Spacelab pressure vessel and its subsystems, to construct the OQF.

Modules

The proposed facility will consist of five Spacelab-derived modular units, each dedicated to a specific function or group of functions. The overall OQF will be free-flying and will have a pinwheel configuration, with four of the cylindrical modules connected spoke-fashion to a central hub. Such a design produces low aerodynamic drag and is easy to assemble; it also allows efficient intermodule movement.

Central to the OQF mission is the *Laboratory Module*, in which the quarantine testing protocol will be carried out. This unit is equipped with a centrally located containment cabinet system for sample handling and processing. To obtain greater containment reliability than is offered by rubber gloves, specially designed metal bellows manipulative arms will be employed for access to the cabinets. Provision is made to maintain portions of the cabinetry under simulated Martian environmental conditions, and a variety of other controlled environments required by the protocol can be produced. Clean air is continuously passed down the face of the cabinets, which are kept under negative pressure to eliminate leakage into the laboratory.

The high-hazard containment facility at the Center for Disease Control (CDC) served as a model for design of many of the physical features and procedures employed in the Laboratory Module. Based on CDC practices, the module itself acts as a barrier to contamination. All equipment and materials leaving the laboratory must be sterilized and packaged in leak-proof containers. Personnel entering or leaving the module must pass through a decontamination area, where they disrobe and take an air shower. The laboratory has independent life support, waste storage, and air filtration systems, and its atmospheric pressure is slightly lower than that of the other modules—all features that ensure effective containment. It is fully equipped for the performance of the quarantine protocol. A variety of microscopes, including scanning electron microscope, are provided. Cameras, spectrophotometers, centrifuge and vacuum devices, autoclaves, refrigerators, and all other necessary laboratory equipment and instruments are present as well.

The *Habitation Module* is the crew's living quarters. In addition to small, private cabin spaces, it contains exercise and personal hygiene facilities and

provides equipment for medical support. An environmental control and life support (ECLS) system housed in this module provides waste management, atmosphere regeneration, and water purification for the entire OQF (except for the Laboratory Module, which has an independent ECLS system so that contaminants can be contained within the laboratory). The Habitation Module is also the location of a command console that provides centralized systems control for the overall OQF. The functions of the command console include systems monitoring, control of both internal and external (ground) communications, guidance control, power distribution, and data handling.

The OQF's source of power is the *Power Module*. By means of wing-like solar cell panels this unit is capable of generating up to 35 kw of electric power, which is stored in batteries for use throughout the facility. Distribution of this energy is controlled remotely by the command console. A second function of the Power Module is thermal control. Heat produced throughout the system is dissipated to space by radiators mounted on the exterior of the module, thereby maintaining both air and equipment at desired temperature levels. In addition to these functions, the Power Module provides attitudinal and orbital control for stabilizing the OQF.

A general purpose *Logistics Module* provides storage for supplies and for waste materials generated in the Habitation Module (the Laboratory Module has independent waste storage). Sufficient storage space is provided in the Logistics Module for supplies necessary to support a 30-day mission.

A fifth unit, the *Docking Module*, serves as a common interface linking the other four. It permits unhindered crew access between modules, as well as access to space through an airlock and EVA hatch. Docking facilities for the shuttle orbiter are provided, and the module can accommodate up to two additional modules if necessary.

Personnel

The determination that the proposed OQF should be a manned facility, rather than a completely automated one, was based primarily on the consideration that man's manipulative and judgmental skills would be essential for experiments requiring situational decisions. Particularly in the event that life forms are detected in the sample, the testing protocol would require a free-form responsiveness that completely automated systems could not provide.

The crew would probably consist of five members: a commander (an astronaut/engineer) and four scientists (a medical doctor, a geobiologist, a biochemist, and a general biologist). Their tasks would be of two general types: facility operation and maintenance, and laboratory work. The allocation of functions and the scheduling of activities have been carefully worked out for each crew member.

Contingency Planning

In its final design, the OQF will have redundant systems as well as emergency procedures available in the event of equipment or system malfunctions. If the ECLS system in the Habitation Module were to fail, for example, the Laboratory Module's life support system could be interconnected with it to support the entire facility—or the reverse. There is also a backup ECLS in the Logistics Module that can be activated if necessary. Similar planning has been devoted to such eventualities as module depressurization, fire, illness of a crew member, and containment failure.

EXPERIMENTAL PROTOCOL

All the hardware components of the OQF system, both modules and onboard equipment, as well as the structuring and scheduling of the crew, are focused on the primary mission: the performance of life-detection and characterization tests on the quarantined sample. The design of the experimental protocol is therefore critical to the success of the mission.

The OQF protocol has the advantage of a precedent: the lunar sample quarantine. The quarantine of Apollo mission return samples at the Lunar Receiving Laboratory (LRL) provided an important model for the formulation of the experimental tests and procedures to be applied to Martian soil samples. It also provided insights into ways to avoid some of the many problems that may emerge during a quarantine mission.

A number of factors impact the experimental design. For example, the protocol must take into account the limited amount of sample available for testing (probably about 100 g). In addition, it must ensure that the untested portion of the sample remains unaltered. It must include a sufficient range of tests to allow biologically active agents to be detected with a high degree of confidence. Equipment and experiments alike must be appropriate for use in the zero-g

environment. The potential for human error must be minimal. And there must be enough flexibility designed into the protocol to permit a thorough characterization of life forms that might not closely resemble terrestrial forms.

The proposed quarantine testing procedure meets those criteria. It consists of five separate phases or analytical approaches, with data from each contributing to a comprehensive assessment of the sample material. Individual tests are specified in detail to permit assessment of engineering feasibility, equipment requirements, etc. Decisions about the subsequent course of sample disposition will rest on the outcome of this overall analysis.

Preliminary Handling

The protocol begins with receipt of the sample canister from the IUS-TELLE. A collapsible structure in the OQF guides the transfer vehicle into position so that a trigger mechanism and clamp can acquire the canister and draw it into the OQF's airlock. The sample canister is punctured with a needle and a sample of the gas within the canister is taken. A mechanism similar to a can opener then removes the bottom of the canister so that further gas sampling and removal of a subsample can take place. The subsample, consisting of approximately 100 g (or 10 percent) of the returned sample, is first analyzed for radioactivity and then transferred by a manipulator to a sample processing unit.

This unit is specially designed to permit the subsample to be manipulated in the absence of gravity, by means of centrifugal force. In the processing unit, the sample is sized and larger particles are viewed under a stereomicroscope to determine whether organisms or fossils are present. The larger-sized material is then evenly ground and the entire subsample is recombined and mixed. This mixture is dispensed to the five testing phases. Of the 100 g subsample, 46 g will be used in the various tests; 54 g will be held in reserve for possible further series of tests. The remaining 900 g of sample material is stored, unopened, under Martian environmental conditions for later delivery to Earth (if approved).

The Testing Protocol

The five testing phases, and the specific experiments they include, are:

- Chemical analysis
 - pH, Eh, and conductance tests
 - aqueous extraction/element analysis
 - organic mass spectrometry
 - amino acid analysis
- Microscopy
 - stereomicroscopic examination
 - scanning electron microscopy
 - light microscope examination
 - ultraviolet microscopy
- Metabolic testing
 - gas exchange: dry
 - CO₂ fixation: dry and moist
 - enriched O₂ metabolism
 - autoradiography of labeled samples
- Microbiological culturing
 - growth on solid media
 - impedance changes in liquid media
- Challenge culture.

The challenge culture phase involves the introduction of Martian soil into cell cultures representing a cross section of terrestrial species. Although a number of organisms have already been tested in zero *g* to date, additional research is necessary to determine the most appropriate species to include in the challenge system. Such organisms must not only be representative of the Earth's major phyla, but must also have a minimal reaction to zero *g*.

If results of the preceding series of tests show no evidence of nonterrestrial life forms or replicating toxins, the sample will be approved for delivery to Earth, where more extensive physical, chemical, and biological studies will be undertaken. However, in the event that biological agents have been detected, a second order of tests would be initiated. The precise character of second-order testing cannot be established in advance. The type of tests would be determined on the basis of characteristics such as organisms or toxins might present.

Protocol Planning

The protocol is a complex network of interdependent tests, with many activities being dependent upon the outcome of previous tests. To illustrate the sequence of events in the protocol, a tracking technique known as Graphical Evaluation and Review Technique (GERT) is used. GERT charts present test activities and information flows in their proper

sequence, and use GERT symbology to indicate the logic that determines each protocol step. By this means, it is possible to calculate the probabilities associated with different experimental outcomes, and thus to calculate the detection sensitivity of various tests. Detailed GERT charts are presented for each testing phase, along with tables of associated outcome probability analyses.

SYSTEM COST ASSESSMENT

The cost of designing and building the OQF, launching it, and carrying out the quarantine mission is difficult to estimate with any certainty, particularly since the impact of certain variables (such as overall mission length) cannot be predicted. Moreover, a detailed and accurate cost analysis was not a prime objective of the design study. However, a method for estimating costs is presented, based largely on previous cost-estimate calculations for similar system concepts.

The approach involves a breakdown of the mission itself into separate phases: design, development, testing, and evaluation (DDT&E); production; and operations. A work breakdown structure is used to subdivide each phase into particular activities and hardware procurements. These expenditures are then spread out over the time period in which they will be required. Since overall mission length is uncertain, costs are expressed on the basis of two possible mission scenarios: a maximum mission length of 6½ years, and a minimum mission length of 2 years.

ADDITIONAL USES OF THE OQF

Beyond its value in a Mars sample return mission, this facility has great potential value for use in subsequent long-term studies in space. With its modular construction it is structurally adaptable to a variety of needs. As equipped, the Laboratory Module

already contains most of the instruments required to support life sciences study programs. The other OQF modules, by contrast, are independent of the mission type and mission objectives that they support. They can be docked with modules dedicated to any purpose.

Currently planned Spacelab missions will have a 7-day duration. The OQF could offer much longer times in orbit for investigation of such questions as the effect of zero g on processes in developmental biology, and biomedical studies of weightlessness. The superior containment afforded by an OQF could make it attractive as a site for the pursuit of currently prohibited recombinant DNA research or other research on hazardous systems. Research on the management and processing of materials in space is yet another area that could benefit from the availability of a long-term base in space.

CONCLUSION

The facility and the experimental protocol described here offer a strong margin of protection against the possibility that a Mars sample would contain hazardous agents. They also offer a powerful hedge against the unknown, and against the fears that could easily develop if organisms showing signs of pathogenicity were detected in a sample undergoing study in a laboratory on Earth. With such a sample held in orbit, its disposition could be determined on the basis of analysis rather than emotion, and the scientific value of the returned sample could thus be maximized.

The Antaeus Report represents a thoroughgoing study of a facility and a protocol capable of accomplishing such a mission. In the event that a Mars sample return mission takes place, the report will provide decision makers with a basis for judging the merits of this option.

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Chapter 2

Mission Perspectives

The advancement of scientific knowledge through space exploration continues to be one of the fundamental goals of an active national space program. In pursuit of this goal over the past 18 years, NASA has conducted a highly successful program of planetary investigation. As in any research, however, the value and quantity of information that can be gained is limited by the kind of investigative techniques employed. Thus, while telescopic and even fly-by examination of planetary objects (e.g., Mercury, Venus, Mars, Jupiter, the asteroids, and—most recently—Saturn) has provided some data on their general characteristics, numerous questions concerning surface composition and environment remain unanswered.

Perhaps of all the planets, Mars has stimulated the most interest in its nature and composition. Curiosity about this planet has touched the public as well as the scientific community. Because of its relative proximity to Earth, telescopic and other examinations of Mars have been particularly rewarding. But, again, these techniques have had limitations. The questions left unresolved by remote investigations prompted a second phase of planetary reconnaissance: the landing of an automated instrument package on the planet to transmit information back to Earth. The Viking mission to the surface of Mars has now been successfully concluded, and has provided a wealth of pictures and data on surface features in the vicinity of the landers.

In any area of scientific investigation, however, the acquisition of additional knowledge always stimulates new questions. The Viking mission was no exception. By providing so much information, it has opened whole new areas of research that were previously not apparent. In addition, while the Viking experiments did not indicate the presence of life, that question cannot yet be considered settled. It is still possible that organisms are present on the planet but were not detected by the automated test equipment (ref. 1). Thus, to advance our understanding of the physical science (and, possibly, the biological science) of our

solar system, the next phase of Martian research must involve a thorough, detailed investigation of surface material from Mars.

A manned voyage that would last several years is well beyond the scope of practicability in the immediate term; furthermore, unless the astronauts were able to perform extensive scientific experiments on the planet's surface, their primary function on such a mission would be to collect samples for return to Earth. However, man is not essential for sample collection. Experience with the Viking and the Soviet Luna 16 spacecraft has shown that automated documentation, sampling, collection, and return of surface material to Earth (Luna 16) can be carried out. Because of the detailed chemical and mineralogical experiments that must be performed on Martian materials, returning samples to Earth laboratories is the preferred means of thoroughly analyzing Martian soil. Sample return is considered to be the best option for conducting an intensive search for Martian life forms (living or fossilized) or determining, in their absence, why Martian life failed to evolve. The results of analyses conducted in a laboratory by trained investigators will be far more conclusive than results obtained by automated means in a mission such as Viking.

Recognizing the potential for a Mars sample return (MSR) mission, NASA planners have developed the preliminary design concepts for MSR vehicles and equipment. As this planning evolves, parallel plans for receiving and handling the samples on Earth must be developed. Because there is still a possibility of life on Mars (ref. 1), there is also a possibility that these organisms could find a suitable niche on Earth and somehow upset the terrestrial ecosystem. While the existence on Mars of organisms that are pathogenic for humans is the most often cited fear, the existence of organisms that are pathogenic to, or would displace, certain terrestrial microbial or botanical forms could be of equal consequence to man. Thus, prior to the release of Martian samples, it will have to be determined either that they are free of life forms or that any

forms of life that are present are not harmful to terrestrial life.

This study suggests handling the Martian samples by requiring that they be subjected to a complex protocol designed to detect life, which, if present, will then be assessed for its effects on terrestrial life forms. Sample testing must be performed within facilities that ensure that such Martian organisms cannot be accidentally introduced to Earth's biosphere during the assessment process. This study represents a thorough analysis and description of an Orbiting Quarantine Facility (OQF) designed to permit the detection and characterization of Martian life forms while affording the Earth and its inhabitants the maximum level of protection.

INTRODUCTION OF ALIEN SPECIES

An alien species usually will not survive when introduced into a new ecosystem because it is unable to compete with native species which are better adapted to the environment. Occasionally, however, introduced species flourish because the physical environment is ideal and indigenous species are not able to defend against the foreign life forms. When this occurs, the result may be an irreversible perturbation of the ecosystem, with severe environmental and, often, economic consequences. Indeed, modern societies have in many instances been profoundly affected by the accidental yet successful introduction of alien species into new areas.

The introduction of alien species is not in itself undesirable. For example, the cultivation of countless European and Asian fruits and vegetables in the United States has resulted in economic and social gain sufficient to easily offset the ecological and cultural turmoil caused by their introduction. In other cases, the introduction may have little noticeable effect, such as the northern range expansion of the armadillo. However, it is apparent that there is always a finite risk involved in introducing a new organism into an existing ecosystem.

Often, the alien organisms that cause species destruction are microbiological forms that, while nonfatal in their native habitat, in a new habitat become unrelenting killers of hosts not adapted to them. For example, the chance introduction of a fungus (*Endothia parasitica*) into New York at the turn of the century resulted in the total obliteration of the American Chestnut tree (ref. 2). Extinction of this

tree, which had been one of the dominant members of American forests, had a profound effect on the ecosystem and resulted in immeasurable economic and aesthetic loss. A similar, though slower, destruction can be seen today: Elm trees are being killed by a fungus introduced into this country early in the century. Human societies as well have fallen victim to organisms against which they were defenseless; an example is the rapid spread of diseases transmitted to American Indians and Polynesians by European settlers in previous centuries (ref. 3).

An alien organism need not infect man directly to exact a large toll in human life and social upheaval. When the potato blight fungus (*Phytophthora infestans*) was introduced into Europe, it spread throughout the Continent and the British Isles within a year. In Ireland, where the potato comprised a significant fraction of the total food supply for the populace, within 5 years over 1 million people starved to death and at least as many were forced to emigrate (ref. 4).

Obviously, before any species is intentionally introduced into a new environment, it is essential to determine whether the organism is pathogenic to any indigenous species. It is equally important, however, to determine whether the organism will be able to force out existing species, thereby upsetting the ecosystem. For example, the planting of Punkwood trees and Australian pines was intentionally encouraged in Florida by the U.S. Department of Agriculture. Although the trees were not pathogens, their effect was nevertheless detrimental to the environment. They quickly flourished, replacing countless acres of otherwise economically valuable trees. Costly attempts at controlling their spread have proved to be of little value. Examples of successful competition can also be drawn from the animal kingdom. Fire ants and "killer" bees are not considered pathogens, but their aggressive behavior and rapid spread have created economic and social problems, the full impact of which is yet to be determined. The introduction of rabbits into Australia is a classic example of a nonpathogen creating immense problems because of high reproduction rates unchecked by natural predators.

As illustrated in these examples, organisms that are not pathogenic or directly harmful to any species can have a nonetheless dramatic effect on the natural ecosystem, with severe economic implications. They precipitate these changes by simply flourishing in their new environment. Therefore, both pathogenicity and competitive viability would have to be considered

before Martian life forms were introduced into the terrestrial biosphere.

THE VIKING RESULTS

Results from a series of experiments that were conducted on the surface of Mars have indicated that there is no evidence of life in the samples tested. Close-up visual observation of the planet's surface showed only a barren world, devoid of any larger life forms. Images of the two lander areas recorded at 20-day intervals showed no evidence of any objects moving in a manner suggestive of life (ref. 5). A series of three tests designed to detect the metabolic reaction of microorganisms yielded results that are more easily accounted for in terms of nonbiological reactions (ref. 6). The absence of life indicated by imaging and metabolic tests is further supported by the fact that the Viking instrumentation was unable to identify organic carbon within the sensitivity limits of the equipment (ref. 7).

The Viking results are taken by many people as proof that no life exists on Mars, thereby obviating concern over back contamination of the Earth with Martian organisms. Although this conclusion may well be correct, a critical review of the Viking experiments suggests that there is not yet enough evidence to justify it. For example, one of Viking's metabolic tests produced results that could have been caused by a living organism (ref. 8). Furthermore, the incubation temperatures of all the experiments deviated from Martian ambient conditions (ref. 6), an organism with a defined series of environmental stimuli necessary for germination or a specific optimum temperature essential for growth might consequently have remained dormant and thus escaped detection. It is also conceivable that the number of organisms present was low enough to preclude detection by Viking techniques. For example, using laboratory equipment to simulate the Viking experiment, DeVincenzi and Deal (ref. 9) demonstrated that a bacterium would have to attain a population density of at least 100 000 live bacteria per gram of soil before its presence could be detected in the labeled release experiment. Also, calculations based on the sensitivity of the instrument used for detecting organic carbon indicate that the carbon present in 100 000 bacteria per gram of soil could have escaped detection. When samples of soils from harsh terrestrial environments such as Antarctica have been examined, at times fewer than 100 living bacteria per

gram of soil have been detected. However, in addition to bacterial carbon, such terrestrial soils contain about 1000 times more organic carbon locked in nonliving particles (ref. 7). It is conceivable that large quantities of nonliving organic carbon do not accumulate on Mars because of the soil chemistry, because of ultraviolet degradation, or because such carbon is rapidly recycled into living organisms. An alternative hypothesis is suggested by Friedman and Ocampo's discovery of algae sequestered within the interior of Antarctic rocks (ref. 10). No Martian rock samples were tested, so organisms harbored within them could have gone undetected.

Even assuming that the Viking results conclusively showed that life did not exist in the vicinity of the landers, they fail to dismiss the possibility of life hidden in or confined to a protected region of the planet. Collectively, both landers visually sampled about 56 km² of the surface, or 4×10^{-7} percent of the entire planet's surface (ref. 5). The soil sampled in the metabolic tests totaled only a few grams of material. Principles of statistical sampling and our knowledge of terrestrial ecosystems enable us to extrapolate this information to a much broader region, especially since Viking II landed about 150 km north of and 11 000 km west of Viking I. On the other hand, the regions sampled were, by terrestrial standards, extremely harsh. Daytime high soil temperatures were -10° to -13° C and nighttime lows were -82° to -88° C (ref. 11). Mathematical models of the temperature of Mars' surface indicate that there are regions in the southern hemisphere where the temperature could be expected to be above freezing for up to 11 hours per day (ref. 12). It is possible that life may be confined to this warmer region distant from portions of the globe sampled by Viking. In addition, it has been speculated that if water is the limiting factor to growth, life may be restricted to a layer near the permafrost.

The very low soil moisture in the Viking sample (perhaps 1 percent) (ref. 13) appears to negate the possibility of life because current models for the evolution of life require larger quantities of free water. However, indications are that water once flowed on the planet's surface (ref. 13), so it is conceivable that life forms developing in the seas could have gradually evolved mechanisms to permit their survival during the transition of Mars from what it once was—a world with a denser atmosphere and abundant water—to its present state. It is reasonable to hypothesize evolutionary progression of this type because terrestrial life apparently began in freshwater oceans under a

reducing atmosphere and gradually evolved to survive in all terrestrial environments, including the world's deserts. To further illustrate the habitability of Mars, data from experiments in which terrestrial organisms were exposed to simulated Martian conditions indicate that these terrestrial residents could survive on Mars and, if moisture were present, could even grow (ref. 14).

Thus, although the Viking results indicate that life was not present at the lander sites in concentrations high enough to be detected by Viking instrumentation, samples were not taken in locales where life may be more likely to exist, such as more "tropical" regions, areas near the permafrost, and protected low areas. Because Earth organisms can survive under simulated Martian conditions and because living organisms have demonstrated the ability to adapt to unique and severe environments, it is therefore not possible to rule out native life on Mars. Consequently, an MSR mission must continue to address the possibility of life in the sample until tests have conclusively demonstrated the contrary.

CHARACTERISTICS OF POTENTIAL MARTIAN LIFE FORMS

Based on our knowledge of Mars and our understanding of biological mechanisms, certain characteristics of potential Martian life forms can be hypothetically defined. It is then possible to determine the potential impact that an accidental release of such organisms would have upon the Earth's biosphere.

Because many currently accepted schemes for the evolution of life are based on an elaboration of basic compounds found in nonterrestrial bodies such as meteorites, it would be reasonable to assume that Martian life forms are carbon-based and constructed of the same basic compounds as are Earth forms. However, Martian organisms would have to evolve highly efficient mechanisms for obtaining or conserving water: for example, thick walls, the production of metabolic water, a unique means of obtaining moisture from the atmosphere or frost, and the ability to remain dormant except when water is present in ample supply. In addition, given what we know of the Martian environment, Martian life forms must be anaerobic, and they must be able to survive (and probably grow) at subfreezing temperatures.

Considering these characteristics, a general understanding of evolution would suggest that Martian life

forms, if they exist, are poorly adapted for growth on Earth. But while this might be true with regard to terrestrial environments inhabited by man, consideration must be given to other terrestrial regions where a Martian organism could possibly survive. For example, the low moisture levels of deserts (and dehydrated foods), the extreme cold of Arctic regions (and frozen food lockers), and the low oxygen levels of subsoil areas (and the interior of animal intestines) are terrestrial environments that to some degree resemble Martian conditions. Furthermore, it is possible that certain Martian environmental conditions are not essential to native Martian life, but, on the contrary, inhibit its growth. Given the variety of Earth environments and possible Martian life characteristics, it is impossible to identify those terrestrial habitats (if any) that would be suitable for growth of such organisms. Also, lacking this basic knowledge, it is difficult to estimate with any certainty the impact of potential Martian life forms on the Earth's ecosystem.

As was discussed earlier, terrestrial experience has shown that the introduction of an alien organism into a new habitat may result in disastrous consequences to specific native species. However, the pathogenic organisms responsible for these highly "targeted" blights evolved in their original habitat for countless generations with species very similar to their new hosts. In its original habitat, the organism may have been commensal (deriving some benefit from the host at little or no expense to the host) or even mutualistic (with both members deriving benefit from the relationship). Thus, host specificity (i.e., infection of a single host species) is the result of long periods of co-evolution of the pathogen and host species. The more restrictive the specificity or the more complex the interaction of parasite and host, the longer the time over which the co-evolution of the two species probably occurred. For this reason, it can be assumed that if Martian organisms exist they would be either nonpathogenic or pathogenic with general (non-host-specific) reactions, attacking a wide variety of terrestrial species and even isolated cells.

Uncertainties associated with the characteristics of possible Martian life forms make it difficult to predict in what habitat on Earth the organisms would flourish and what effect their growth could have on terrestrial species. Because the possibility of catastrophic consequences cannot be dismissed on the basis of existing information, the return of a Martian sample to Earth poses questions of global significance.

SOLUTIONS TO THE BACK-CONTAMINATION PROBLEM

Sterilized Sample Return

One way to return a sample that is free of organisms that could contaminate the Earth's biosphere is to sterilize the sample during its return from Mars. The sterilization treatment employed must be severe enough to ensure that no life forms, as we know them, could survive. Recently, terrestrial soil-inhabiting microbes have been discovered that show a mere 10-fold reduction in viable organisms after 139 hours at 125° C—a heating treatment 70 times longer than is required to kill most soil organisms (ref. 15). This illustrates the difficulty of defining a suitable moderate heat treatment that could be certified effective even on terrestrial spores adapted to survive long periods of desiccation, while at the same time retaining the scientific value of the sample. It would also be difficult to identify chemical sterilants that would be effective in killing organisms sequestered within a soil as highly reactive as the Martian samples appeared to be during the Viking experiments.

An important consideration in sterilizing a return sample is the effect that the treatment would have on the value of the soil for subsequent geological and physicochemical research. Use of chemical sterilants probably would result in contamination of the sample in a way that would prohibit measurement of certain soil properties. Moist heat may prompt violent reactions within the soil, resulting in significant changes. While dry heat would be expected to have less effect, it too would influence the geological information recovered from the sample. For example, Duke and Reynolds (ref. 16) state that certain volatile elements in the lunar samples could escape at temperatures less than 200° C. Jones (ref. 17) noted that while dry heat sterilization has little effect on some minerals, others are altered (due to a change in oxidation state) at temperatures as low as 150° C for 72 hours. However, he does conclude that although temperatures above 300° C would result in "irrevocable loss of data, few serious chemical and physical changes occur at temperatures below 270° C." Thus, sample sterilization might result in some loss of physicochemical information, although it appears that careful control can limit the impact of sterilization in this regard.

While sterilization of the sample may not seriously affect the geological information to be gained from the sample, it would greatly reduce the amount of

meaningful biochemical information that might be gained. Heat treatment, even at 100° C, results in the loss of nitrogen from proteins. Hochstein, Kvenvolden, and Philpott (ref. 18) observed a 40 percent loss of amino acid nitrogen after heating to 200° C. If organisms had been present in very low numbers in the soil, such losses would mean that very large quantities of soil would have to be chemically extracted to yield measurable amounts of organic compounds. Heat also destroys cellular structure, electron microscopic examination of soil heated to 160° C for 3 hours indicated that bacterial cell structure in the soil was virtually obliterated even though the soil had not been completely sterilized. It is questionable whether significant data of interest to biologists could be gained from studying heat-sterilized samples. Even if a sterilization treatment were developed that killed organisms while retaining their cellular structure, it would drastically reduce the chance of accomplishing a major return sample objective: to compare the basic biological characteristics of Martian life (if present) with the characteristics of life as we know it.

A primary point of interest is the question of whether or not Martian life forms evolved using the same metabolic strategies as did terrestrial forms. Evidence of fundamentally different genetic, metabolic, and molecular characteristics would prove that the terrestrial evolutionary strategies are not universal. One theory is that there are many possible metabolic approaches to life, and that the first-appearing organisms in a biosphere determine which approach is followed by out-competing other developing forms. Returning a sterilized sample would eliminate the potential opportunity for biologists to investigate such major scientific issues in the context of a life form that evolved independently from life on Earth.

Terrestrial Quarantine of Unsterilized Samples

If sterilization of the sample is not acceptable, an alternate solution to the problem of possible contamination of the Earth is to quarantine an unsterilized sample until a full assessment can be made of its potential for disturbing the Earth's ecosystem.

Historically, "quarantine" was a period during which ships suspected of carrying persons with contagious diseases were detained at their port of arrival. The interval—usually 40 days—was adequate to cover the incubation period of most highly infectious diseases. If no symptoms appeared at the end of the quarantine, the voyagers were permitted to disembark.

Recently, the term "quarantine" has acquired a new connotation: holding a suspect organism or a person with a diagnosed disease in strict isolation until they are no longer capable of transmitting the disease. With the advent of the lunar quarantine, the term has taken on elements of both definitions.

A critical question that must be addressed in regard to any quarantine system is whether the containment measures are adequate to hold known or suspected pathogens while experimentation is in progress. Basically, existing maximum containment facilities such as those at the Center for Disease Control have two components:

1. An *isolation chamber* (Class III cabinet) in which the sample is contained and tested. The cabinet is certified leak-tight and is accessible only through the use of attached thick rubber gloves. All material exiting the cabinet is filtered, autoclaved, or incinerated before release.
2. A *secondary barrier* designed to prevent the spread of organisms in the event of their accidental release from the cabinets. The term "secondary barrier" means a completely sealed building. Air flow within the building is designed to filter organisms released from the cabinets. All inanimate objects are decontaminated before they are taken from the facility. Workers enter the lab by controlled access and are required to shower and discard potentially contaminated protective garments before leaving.

A Third Alternative

The technology and procedures for containment have been successfully used for many years in the development of germ warfare agents and the study of highly infectious diseases. In an attempt to ascertain the adequacy of similar facilities to contain potential Martian organisms, Michaelsen (ref. 19) interviewed scientists who worked with various containment facilities throughout the country. The scientists agreed with near unanimity that existing Class III cabinets are adequate to handle the most hazardous terrestrial agents, the potential dangers of which are largely known.

Judging from the large uncertainties associated with potential Martian life forms, however, it is not clear that any containment facility based solely on the physical barriers described in the previous paragraphs will gain wide acceptance by the scientific and

political communities or by the general public. Locating the facility and all laboratory workers in an isolated location on Earth would provide only a small additional measure of protection.

As previously discussed, eco-catastrophes can occur when organisms that are noninfectious to man are released into a new environment. Thus, as has been suggested by numerous authors, efforts should be made to analyze extraterrestrial samples before their return to Earth (see, for example, refs. 2, 19, 20). By eliminating the chance of an accidental crash of an Earth-returning craft, by ensuring that any organisms that escape from the secondary barrier do not enter the biosphere, and by guaranteeing that the workers remain in total isolation, a facility located in space has marked advantages over terrestrial systems.

EXTRATERRESTRIAL QUARANTINE

Systems Evaluation

The purpose of an extraterrestrial quarantine facility is to contain planetary return samples in space while tests (the quarantine protocol) are conducted on them. The quarantine protocol is designed to provide responsible authorities with information that will assist them in determining the ultimate disposition of the sample. Ensuing chapters of this report illustrate a proposed design concept for an extraterrestrial quarantine facility and define a protocol compatible with the proposed facility and suited for a space environment. The remainder of this chapter explores the rationale for adopting an extraterrestrial approach to return-sample quarantine. As such, the discussion that follows will help the reader to evaluate the design discussed in subsequent chapters.

The value of conducting quarantine testing prior to admitting planetary return samples to the Earth's biosphere is best viewed in the context of an overall risk analysis. Figure 2-1 illustrates a possible approach. In this figure, event scenarios for quarantine system success or failure are shown for both terrestrial and extraterrestrial quarantine systems. Existing terrestrial systems provide us with a wealth of experience and serve as convenient "yardsticks" in evaluating the effectiveness of extraterrestrial quarantine measures. The intent here is not to determine a strict numerical value for the worth of an extraterrestrial quarantine system, but rather to develop the major points that must be addressed in the design of such a system.

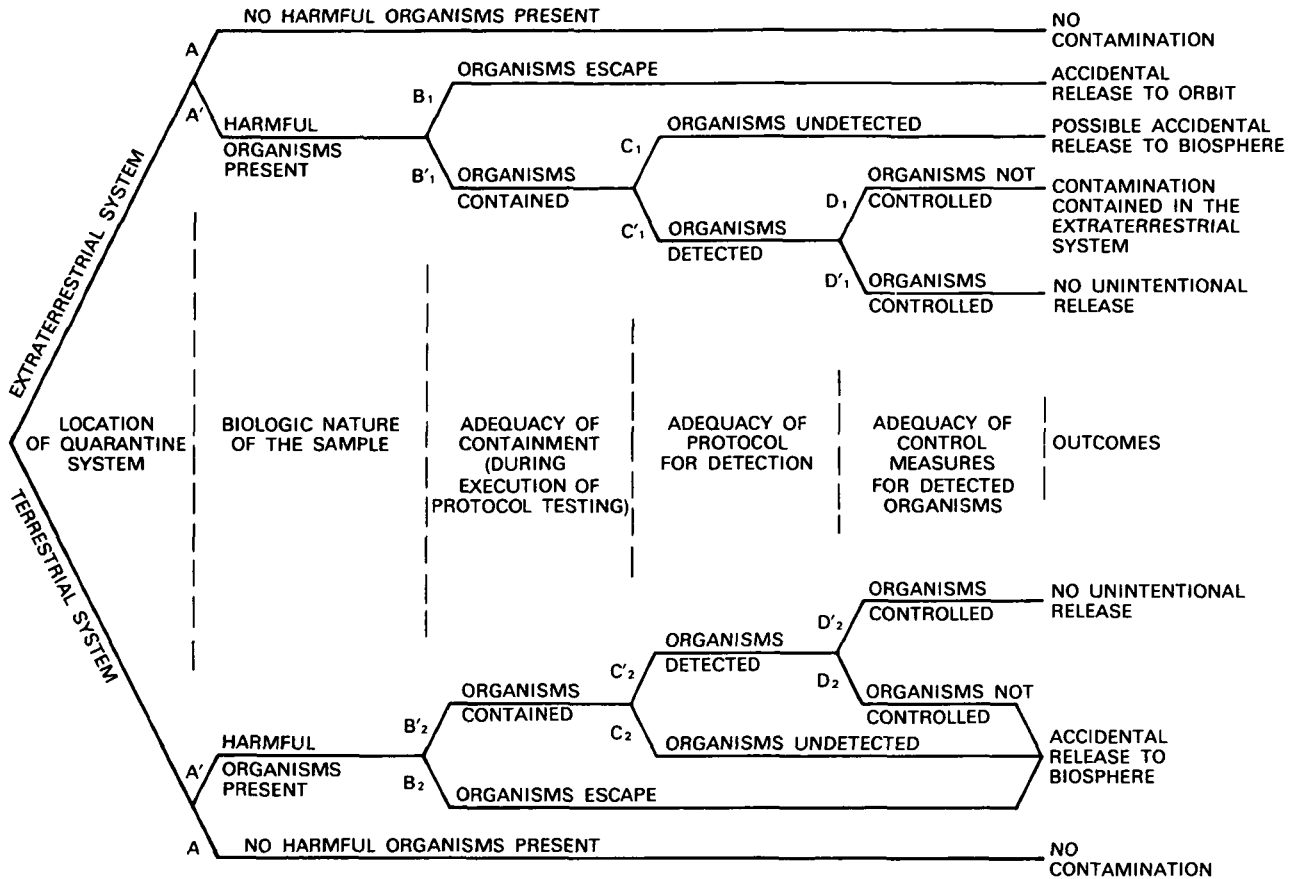


Figure 2-1.—Event schedule for quarantine testing; A comparison of the different outcomes possible, depending on whether the facility is located in space or on the Earth.

As indicated in figure 2-1, terrestrial and extraterrestrial quarantine systems are characterized by different outcomes depending on the stage at which containment failure occurs. To be considered adequate, a quarantine system (terrestrial or extraterrestrial) must be capable of containing all extraterrestrial organisms present in a sample, detecting them during protocol testing, and controlling them after detection until their ultimate (controlled) disposition is realized. The success with which containment is maintained by a quarantine system is a measure of the total system's reliability.

However, system reliability is not the sole factor in determining the expected value of a quarantine system. Evaluation of the system's worth is also dependent upon the consequences of system failure, the cost of the system, and the probability that harmful organisms are present in the return sample.

Several inferences can be drawn from the relationship of these four factors. If the existence of harmful

organisms in a return sample is considered to be more than a remote possibility, and if a large value is placed on the estimated consequences of accidental release of these organisms, then quarantine system cost becomes less important. Under these same circumstances, quarantine reliability becomes the dominant factor in determining the value of a quarantine system, i.e., the optimum system is the most reliable one, and cost will not be a prime consideration. On the other hand, if the existence of pathogens in the return sample is deemed remote and (or) their potential impact on the environment is judged to be small, the importance of cost considerations increases while the importance of system reliability decreases.

These considerations provide insight into the characteristics of an acceptable quarantine system. Previous discussion in this chapter highlighted the uncertainties associated with the existence of Martian life forms and their potential for disrupting the Earth's ecosystem. If conservative assumptions are adopted to

account for these uncertainties, the quarantine system demonstrating superior reliability would be the logical choice despite significant cost savings afforded by competing systems. In fact, it would be difficult to defend a low-cost solution if it sacrificed any significant degree of reliability.

The following discussion addresses factors pertaining to reliability of an extraterrestrial quarantine system, that is, its ability to contain, detect, and control potential Martian pathogens. Where possible, comparisons will be drawn between terrestrial and extraterrestrial quarantine options.

Reliability: Containment Considerations

As depicted in figure 2-1, the first quarantine failure mode that must be considered is violation of containment integrity. In evaluating the reliability of containment systems, three major areas must be considered: the external environment of the system, the physical containment barriers afforded by the system, and the management of containment measures.

An extraterrestrial facility will operate in a relatively controlled environment. The extremely remote possibility of impact by a large meteorite represents the only failure source not directly attributable to system malfunction. This is in contrast to terrestrial systems, which are subject to largely unpredictable (albeit rare) catastrophic occurrences, both "nature-related" (i.e., floods, storms, earthquakes) and "man-related" (e.g., airplane crashes, chemical explosions). The potential impact of these considerations on the design of terrestrial quarantine facilities is not clear. However, the precedent exists in the nuclear industry for requirements to address remotely possible natural and man-initiated disasters in the design of containment facilities. The realization of this design constraint on terrestrial quarantine facilities will depend on the perceived risks associated with containing a return sample. Design of the Lunar Receiving Laboratory (LRL) facilities, for example, did not address these remote possibilities. However, it is more reasonable to expect to find viable organisms in a Martian return sample than in a lunar sample, and that expectation may dictate a more conservative approach to quarantine system design.

In addition to providing a relatively benign environment for maintenance of containment integrity, space provides an additional physical bio-barrier. In the unlikely event of a breach of containment integrity,

even a low Earth orbit provides significant protection against back contamination. If particles accidentally released from a facility in orbit are assumed to have the same velocity as the facility, the particles remain in orbit for a long time. Calculations (M. Duffley, personal communications) based on momentum transfers between released particles and molecules in the rarified atmosphere of near space indicate that a particle 1 micrometer ($1\ \mu\text{m}$) in diameter will take 3 years to reach the upper stratosphere from a 200 km orbit. Similar calculations indicate that because of its greater mass, which resists deceleration due to collisions with air molecules, a 25- μm particle will take 30 years to descend the same distance. Experiments designed to test the survival of microorganisms in space environments indicate that survival capability is primarily a function of shielding from ultraviolet (UV) radiation and length of exposure. Extrapolation of these results to exposure times of 3 years (and greater) indicates an extremely low survival probability for even relatively UV-resistant microorganisms such as *Penicillium roqueforti*. For example, Hotchin, Lorenz, and Hemenway (ref. 21) report a large decrease in *Escherichia coli* and a significant reduction in *Penicillium* populations during experiments conducted on board Gemini IX-A and XII satellites at an altitude of 300 km. Even the microorganisms shielded by 0.4 mm of aluminum throughout the experiments (17 hours for Gemini IX-A, 6 hours for Gemini XII) experienced significant reductions.

Based on these and similar experiments (refs. 22 through 25), it appears highly unlikely that organisms afforded minimum UV protection (i.e., free floating or attached to 1- μm particles) would survive a 3-year descent to the stratosphere. It seems equally unlikely that organisms afforded greater UV protection (i.e., attached to particles greater than 25 μm) would survive a 30-year descent. To be more confident of this last point, additional research will be necessary in the area of the long-term survivability of microorganisms in space. However, breach of containment integrity in a terrestrial system would result in the immediate release of contaminants to the Earth's biosphere. In light of weaknesses evident in terrestrial containment systems, the fail-safe aspect of space quarantine may provide the only acceptable measure of containment reliability for a Mars return mission.

Besides the physical advantages for maintaining containment integrity in space, extraterrestrial quarantine measures provide two significant advantages related to quarantine system management.

First, both the equipment and the crew of the extraterrestrial facility would be dedicated to the execution of the quarantine protocol. This singleness of purpose would alleviate potential problems associated with the conflict of interests between quarantine measures and basic science research or other NASA interests. Conflicts of this nature could be serious impediments to the implementation of effective quarantine measures.

Second, execution of protocol tests in space will facilitate crew quarantine measures. In terrestrial quarantine systems, workers who unknowingly contact organisms leave the lab and return to their communities. On the other hand, extraterrestrial protocol testing will necessarily impose a continual quarantine of the crew, thereby affording an additional measure of protection. Undetected breaches of primary containment result in exposure of only the crew of the extraterrestrial facility. This level of exposure control is significantly greater than that afforded by terrestrial systems, which do not quarantine laboratory workers unless a breach of containment is recognized quickly. That is not to say that crew safety would not receive prime consideration in the design of an extraterrestrial facility. In fact, the design developed in this study provides crew protection that is at least equal to the protection afforded workers in existing terrestrial maximum containment facilities such as those at the Center for Disease Control.

Reliability: Detection (Protocol) Considerations

Several protocols were prepared for the lunar mission, each based on the assumption that a wide variety of species should be tested to ensure that obscure species would not be influenced or harmed. One such protocol, prepared by Baylor University (ref. 26), required representatives of most major phyla to be tested. The LRL protocol that was eventually adopted (ref. 27) called for the testing of approximately 45 species. Obviously, exhaustive testing of the world biota is not feasible in an orbiting laboratory. This raises the question of whether it is possible to develop a protocol adequate to accomplish the quarantine objectives. As will be discussed in succeeding chapters, although the scope of the proposed extraterrestrial protocol is greatly reduced from the LRL experience in terms of the number of species challenged, it has been augmented with life-detection tests that greatly increase the reliability of the protocol to detect replicating organisms.

The emphasis of the Mars return sample quarantine testing is, first, to determine whether life is present in the sample, and then to attempt to assess its impact on terrestrial systems. The first objective is to be accomplished by exposing the soil to various environmental conditions that, it is hoped, will provide Martian organisms with factors necessary for growth: a range of temperatures, photoperiods, nutrients, moisture levels, gas mixtures, and atmospheric pressures. Growth is assessed by a series of techniques including visual observation, conductance measurements, metabolic tests, and chemical analyses. Direct microscopic examination of the sample is included to determine whether dormant organisms exist in the soil. Finally, to detect nonspecific pathogens, isolated terrestrial cells that are devoid of some of the disease-protective mechanisms found in intact organisms will be challenged with the soil. If this basic series of tests is executed and no evidence of extraterrestrial life is obtained, the sample will be certified safe for transport to Earth. If, on the other hand, extraterrestrial life is discovered, a second order of testing is essential to completely characterize the life form, to determine its growth requirements, to assess sterilization techniques, to evaluate containment methods, and to determine pathogenicity or ability to flourish in the terrestrial environment. Only after a complete and thorough analysis of the Martian life forms has been conducted could any consideration be given to releasing the sample from quarantine in space.

While this particular protocol could be performed more conveniently on Earth, its reliability in detecting alien organisms would not improve significantly. This is due to the fortunate circumstance that the life-detection systems and challenge species that will be used in the protocol are relatively easily modified for space operations. Thus, conducting the protocol in space does not result in any significant reduction in the system's detection reliability.

Reliability: Control Considerations

In determining the quarantine system's reliability, the third major factor that must be considered is the ability of the system to control replicating organisms, should any be discovered in the return sample. There are four basic control measures that can be taken subsequent to protocol testing: release of the sample to various science research laboratories, retention of the sample and any sample-indigenous life forms, sterilization of the sample and all contaminated

equipment, or ejection of the sample and contaminated equipment and facilities from the vicinity of the Earth's biosphere. One measure of quarantine control adequacy is the flexibility provided to responsible authorities in selecting the appropriate course of action.

If the life forms detected are clearly unable to cause harm to terrestrial systems, the appropriate option would be the first one—to release the organisms to scientists for additional study. For example, if the Earth's atmospheric pressure or moisture content were fatal to the organism, its accidental release into the biosphere would have no effect because suitable terrestrial habitats do not exist. The emphasis of sample containment would then switch from protecting the Earth to protecting the sample and Martian life forms. The second control possibility would be to retain the sample in absolute containment while scientific examination of the organisms continues. This option would be followed if there was insufficient proof that the extraterrestrial organisms were harmless. The third and fourth control measures, sterilization and ejection from the biosphere, would be appropriate if characteristics of the Martian organisms observed during the protocol demanded a level of containment reliability beyond that provided by existing systems.

CONCLUSIONS

The preceding discussion illustrates a major benefit to be derived from adopting extraterrestrial testing that a search for replicating organisms in a Martian return sample and the identification of their physical and chemical characteristics can be conducted *before* that sample is admitted to the Earth's biosphere. The increased reliability of an extraterrestrial system reduces the chances of accidental release of the organism into the Earth's biosphere during protocol testing. Test results could be used to assess potential dangers posed by the sample in order to determine if terrestrial containment measures are reliable enough to cope with these dangers. With an orbiting facility, there is additional flexibility in determining the disposition of the Martian sample. For example, three hypothetical results of extraterrestrial tests could be:

1. No replicating organisms were discovered.
2. Replicating organisms that are not a threat to the Earth were discovered.

3. Replicating organisms demonstrating potentially harmful effects were observed.

On the basis of these results, policy-makers might decide

1. That the risk is minimal and (or) that terrestrial containment facilities are adequate and that, therefore, the sample should be transported to Earth.
2. That terrestrial systems cannot assure positive protection of the Earth's ecosystem, but testing of the sample should continue in space.
3. That continued research represents an unacceptable risk, and therefore, the sample should be sterilized or otherwise rendered harmless to the Earth's biosphere.

The enhanced flexibility of a system employing extraterrestrial testing increases the likelihood that a decision to release the sample will reflect an appropriate balance between the benefits of studying the organisms and the requirement to protect the Earth's ecosystem.

REFERENCES

1. Klem, H. P. The Viking biological experiments on Mars. *Icarus*, Vol. 34, 1978, pp. 666–674.
2. Alexander, M. Quarantine for samples from Mars. In *Theory and Experiment in Exobiology, Volume 2* (ed. by A.W. Schwartz). Wolters-Noordhoff Publishers, Groningen, The Netherlands, 1972, pp. 121–146.
3. Dubos, R. The evolution of microbial diseases. In *Bacterial and Mycotic Infections of Man, 4th edition* (ed. by R. J. Dubos and J. G. Hirsch). J. B. Lippincott Co., Philadelphia, 1965, pp. 20–36.
4. Klinkowski, M. Catastrophic plant diseases. In *Annual Review of Phytopathology, Volume 8* (ed. by J. G. Horsfall and K. F. Baker). Annual Reviews Inc., Palo Alto, California, 1970, pp. 37–60.
5. Levinthal, E. C., Jones, K. L., Fox, P., and Sagan, C. Lander imaging as a detector of life on Mars. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4468–4478.
6. Klem, H. P. The Viking biological investigation: General aspects. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4677–4680.

7. Biemann, K., Oro, J., Toulmin, P., 3rd, Orgel, L. E., Nier, A. O., Anderson, D. M., Simmonds, P. G., Flory, D., Diaz, A. V., Rushneck, D. R., Biller, J. E., and Lafleur, A. L. The search for organic substances and inorganic volatile compounds in the surface of Mars. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4641-4658.
8. Levin, G. V., and Straat, P. A. Recent results from the Viking Labeled Release experiment on Mars. *Journal of Geophysical Research*, Vol. 82, 1977, 4663-4667.
9. DeVincenzi, D. L., and Deal, P. H. *Studies Related to the Development of the Viking 1975 Labeled Release Experiment*. Ames Research Center, NASA, Moffett Field, California, April 1976, 19 pp. (NASA-TR-R-460; A-6408)
10. Friedmann, E. I., and Ocampo, R. Endolithic blue-green algae in the dry valleys: Primary producers in the Antarctic desert ecosystem. *Science*, Vol. 193, 1976, pp. 1247-1249.
11. Hess, S. L., Henry, R. M., Leovy, C. B., Ryan, J. A., and Tillman, J. E. Meteorological results from the surface of Mars: Viking 1 and 2. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4559-4574.
12. Averner, M. M., and MacElroy, R. D. *On the Habitability of Mars. An Approach to Planetary Ecosynthesis*. NASA, Washington, D.C., 1976, 105 pp. (NASA SP-414)
13. French, B. M. *Mars: The Viking Discoveries*. NASA, Washington, D.C., October 1977, 36 pp. (EP-146)
14. Foster, T. L. *Response of Selected Microorganisms to Experimental Planetary Environments, Semiannual Progress Report No. 5, July 1, 1974-December 31, 1974*. Hardin-Simmons University, Abilene, Texas, January 1975, 44 pp. (NASA Grant NGR 44-095-001)
15. Bond, W. W., Favero, M. S., and Korber, M. R. *Bacillus* sp. ATCC 27380 A spore with extreme resistance to dry heat. *Applied Microbiology*, Vol. 26, 1973, pp. 614-616.
16. Duke, M. B., and Reynolds, M. A. Lunar sample quarantine procedures: Interaction with non-quarantine experiments. In *Life Sciences and Space Research XII*, Proceedings of the Open Meeting of the Working Group on Space Biology of the 16th Plenary Meeting of COSPAR, Constance, F.R.G., May 23-June 5, 1973 (ed. by P. H. A. Sneath). Akademie-Verlag, Berlin, 1974, pp. 203-208.
17. Jones, I. *Study of the Effects of Dry Heat Sterilization on Inorganic Phases of the Returned Martian Surface Sample Analogs*. University of Houston, Houston, Texas, 1975. (NASA Grant NGR 44-005-131)
18. Hochstein, L. I., Kvenvolden, K. A., and Philpott, D. E. *The Effect of Sterilization on Biological, Organic Geochemical and Morphological Information in Natural Samples*. Ames Research Center, NASA, Moffett Field, California, April 1974, 74 pp. (NASA-TM-X-72883)
19. Michaelsen, G. S. Safety of containment systems: State-of-the-art—Biobarrier technology. Paper presented at the AIBS Planetary Quarantine Panel, Cocoa Beach, Florida, June 11, 1974, 13 pp.
20. Young, R. S., and DeVincenzi, D. L. From Mars with love. *Science*, Vol. 186, 1974, pp. 495-501.
21. Hotchin, J., Lorenz, P., and Hemenway, C. L. The survival of terrestrial microorganisms in space at orbital altitudes during Gemini satellite experiments. In *Life Sciences and Space Research VI*, Proceedings of the Open Meeting of Working Group V of the 10th Plenary Meeting of COSPAR, London, July 27-28, 1967 (ed. by A. H. Brown and F. G. Favorite). North-Holland Publishing Co., Amsterdam, 1968, pp. 108-114.
22. Lorenz, P. R., Hemenway, C. L., and Hotchin, J. The biological effectiveness of solar electromagnetic radiation in space. In *Life Sciences and Space Research VI*, Proceedings of the Open Meeting of Working Group V of the 10th Plenary Meeting of COSPAR, London, July 27-28, 1967 (ed. by A. H. Brown and F. G. Favorite). North-Holland Publishing Co., Amsterdam, 1968, pp. 100-107.
23. Frankenberg-Schwager, M., Bucker, H., and Wollenhaupt, H. Survivability of microorganisms in space and its impact on planetary exploration. *Raumfahrtforschung*, Vol. 18, No. 5, 1974, pp. 209-212.
24. Bucker, H., and Horneck, G. Survival of microorganisms under simulated space conditions. In *Life Sciences and Space Research VIII*, Proceedings of the Open Meeting of Working Group V at the 20th Plenary Meeting of COSPAR, Prague, May 11-24, 1969 and The Symposium on Biological Rhythms, Prague, May 13, 1969 and The Symposium on Nutrition of Man in Space,

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- Prague, May 14, 1969 (ed. by W. Vishniac and F.G. Favorite). North-Holland Publishing Co., Amsterdam, 1970, pp. 33-37.
25. Petras, E., and Bsa, K. Microbiological studies on the radiation environment of the ionosphere and stratosphere. In *Life Sciences and Space Research VI*, Proceedings of the Open Meeting of Working Group V of the 10th Plenary Meeting of COSPAR, London, July 27-28, 1967 (ed. by A. H. Brown and F. G. Favorite). North-Holland Publishing Co., Amsterdam, 1968, pp. 115-122.
26. Baylor University College of Medicine. *Comprehensive Biological Protocol for the Lunar Sample Receiving Laboratory, Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas*. Houston, Texas, June 16, 1967, 572 pp. (NASA-CR-92209; MSC-DA-68-1)
27. Kemmerer, W. W., Jr., Mason, J. A., and Wooley, B. C. Physical, chemical, and biological activities at the Lunar Receiving Laboratory. *BioScience*, Vol. 19, 1969, pp. 712-715.

Chapter 3

Systems Overview and Design Methodology

The primary focus of the mission hardware described in this report is to support a quarantine procedure for a proposed unmanned Mars sample return mission. There are several current options for acquiring a sample from the surface of Mars, ranging from a "grab-and-run," or undocumented, sample return to a fully documented, selected-site, multisample mission. Although the Orbiting Quarantine Facility conceived in this study was designed for one of the more likely mission plans (a documented collection of many subsamples), the facility is suitable for quarantine testing of the sample regardless of how it is acquired on Mars.

SAMPLE RETURN MISSION CONSIDERATIONS

The need for the OQF to be fully integrated with the overall MSR mission means that the timetables for sample return and quarantine testing must be effectively intermeshed (see figure 3-1). The hypothetical mission time frame depicted in figure 3-1 (activities in left-most column) provides a guideline for the timing of activities in the OQF operation (second column). These activities are integrated into a single temporal sequence in the chart itself.

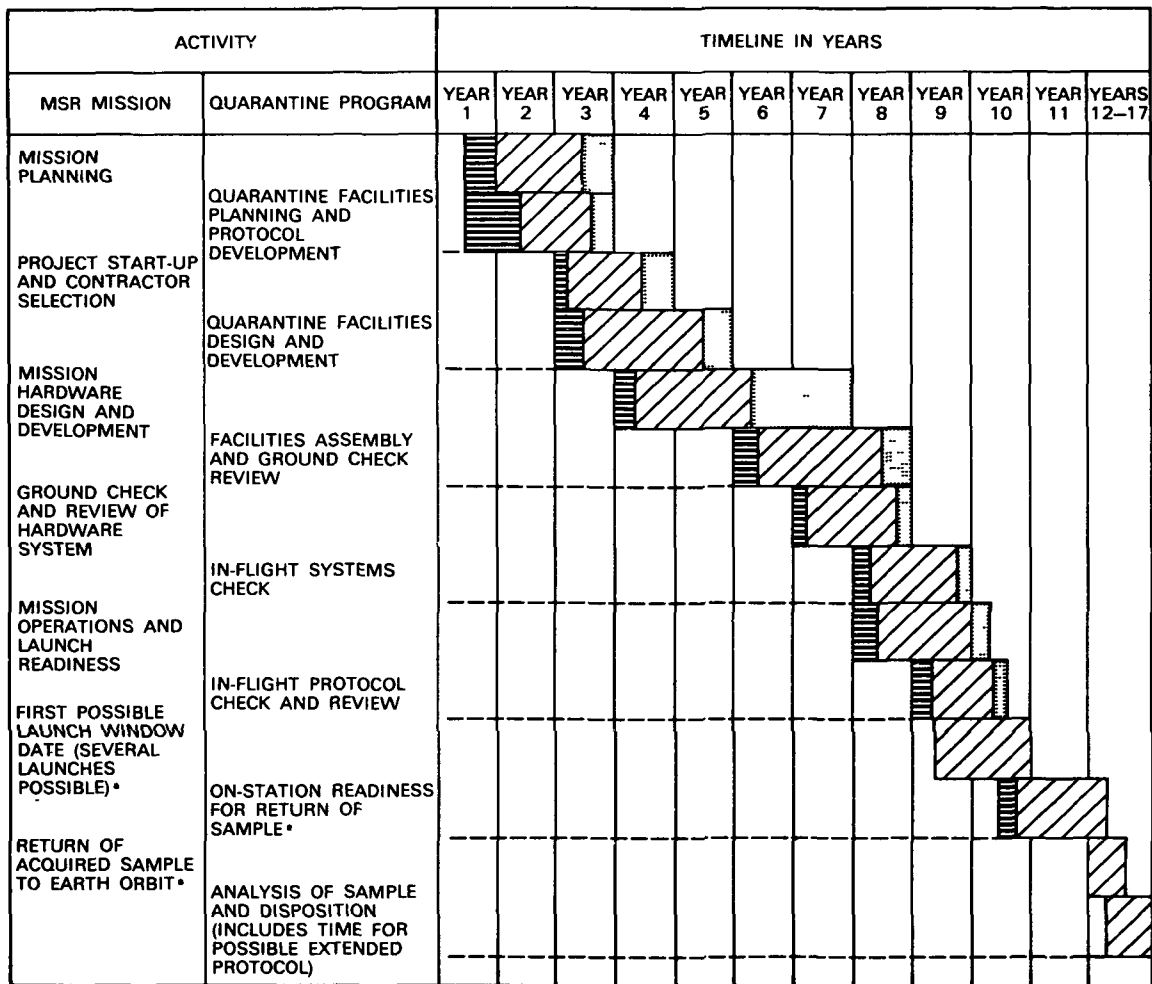
The presumed limited quantity of the sample imposes constraints on the design of the OQF. The complex soil sampling procedures desirable for a well-documented mission mean that a greater mass of the MSR spacecraft will be devoted to equipment, thereby reducing the return payload capacity of the mission. As currently envisioned by planners at the Jet Propulsion Laboratory (JPL), the return payload design calls for a variety of documented subsamples, each sealed in individual gas-tight containers (also called "quarantine vessels") immediately after acquisition on the surface of Mars. These subsample containers will be sealed in a larger canister for return to the laboratory. Examples of this hardware are shown in figures 3-2 and 3-3. The environment within the canister will be monitored

during the return journey to ascertain the degree to which the original Martian conditions are retained. Current projections call for a return sample quantity of 1 kg. In view of this constraint on sample size, full consideration was given to developing test procedures and hardware for the OQF that would utilize the minimum amount of sample. As designed, the protocol will require between 5 and 10 percent of the 1 kg sample (about 50 to 100 g) while protecting the remaining 90 to 95 percent from contamination by terrestrial organisms or chemicals.

Because the exterior of the return vehicle and the canister will have been on the surface of Mars, both must be considered to be contaminated with particulate soil matter that can potentially contaminate the OQF's orbit envelope. Thus, a means of sterilizing the canister's exterior surface will be required. Levin and Hall (ref. 1) have suggested extracting the canister from the return vehicle en route from Mars and burning off an exothermal covering at high temperature.

Another consideration involved transfer of the returned canister to the orbiting facility. For design purposes, it was assumed that the Mars sample return vehicle (MSRV) would deliver the sample just to the orbital vicinity of the containment laboratory. This constraint dictated the need for a craft capable of orbital transfers beyond the limited capabilities of the OQF itself, to retrieve the sample.

A design (ref. 2) has been proposed for a remote-teleoperated-manipulator (TELLE) utilizing an inertial upper stage (IUS) delta engine. This propulsion unit is designed to be remotely operated and, once delivered to orbit by the Space Shuttle, will be capable of orbital changes as well as orbital plane changes. For its use in the quarantine mission, the IUS-TELLE must be capable of being programmed and remotely controlled; it must have propulsion and navigation capabilities to reach the orbit of the MSRV; it must be able to "grab" the sample canister; and it must then successfully return to the OQF to deliver



*NO SLIP TIME



Figure 3-1.—A time line which integrates the quarantine and sample acquisition schedules.

the canister into the sample acquisition port of the lab. (See figure 3-4.)

PROTOCOL CONSIDERATIONS

It became apparent early in the design process that the thrust of the design effort should be toward developing a protocol that can be performed within tight constraints on available power supply, equipment weight and volume, and crew size, while providing adequate, reliable information to those responsible for deciding the sample's ultimate disposition. The facility must provide safeguards against back

contamination (contamination *by* the sample, through the release of alien organisms into the facility at large or into the Earth's biosphere) as well as forward contamination (*of* the sample, by contact with organisms or chemicals from Earth).

The design of the system must therefore be responsive to the protocol and its outcome in four distinct ways. First, the results of an initial battery of tests (a planned minimum protocol) may dictate that the facility be rapidly modified or expanded to permit additional testing before the sample is returned to Earth. Second, the facility must be capable of long-term continuous operation, thus ensuring adequate

MARS SAMPLER VEHICLE

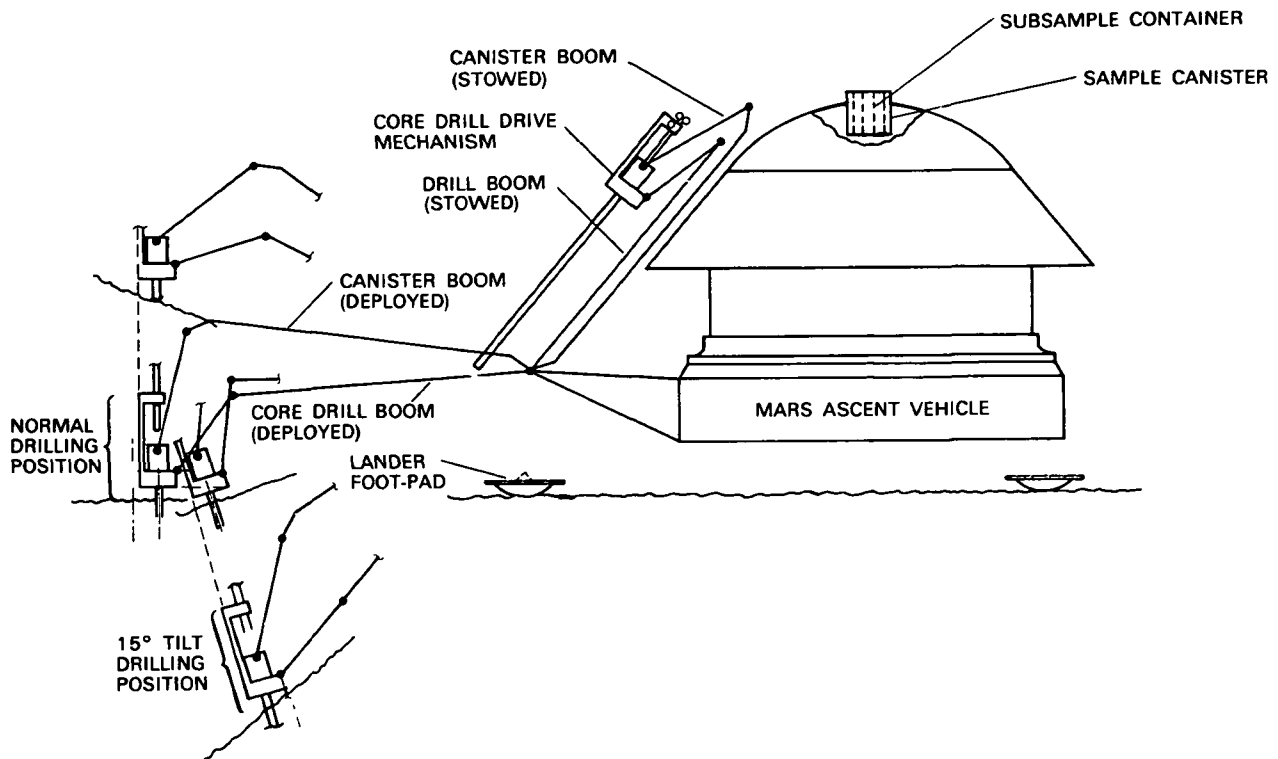


Figure 3-2.—One concept of a Mars sample return vehicle capable of taking up to 10 subsamples from the surface and subsurface of Mars. The craft possesses the flexibility to permit taking core samples even where the terrain is unfavorable. Two booms work together to drill and collect samples from a variety of slopes and then deposit the samples in the craft's crown. (Adapted from JPL studies)

flexibility in evaluating and reacting to initial test results. Third, because the characteristics of potential Martian organisms are unknown, it must be assumed that the hazard they present is equal to that of terrestrial Class IV pathogens (i.e., the organism is capable of being spread rapidly among humans, no vaccine exists to check the spread of the pathogen, no cure has been developed, and the organism produces high mortality in infected persons). Thus, the facility must be capable of providing the very high level of containment and protection of the crew that is afforded terrestrial workers in Class IV facilities. Finally, the facility design and protocol procedures must provide protection against forward contamination of the sample.

HARDWARE CONSIDERATIONS

General

The design considerations discussed in the following sections stem from existing state-of-the-art hardware technology, with a reasonable allowance for advances over the next 5 to 8 years. To achieve the degree of system flexibility required to ensure MSR mission compatibility and execution of a responsive quarantine protocol, a manned facility was deemed necessary. Records of over 100 unscheduled in-flight maintenance tasks performed by Skylab crew members indicate that man is capable of providing a significant measure of flexibility in a space environment and that effective in-flight man-in-the-loop maintenance systems are realizable. On the other

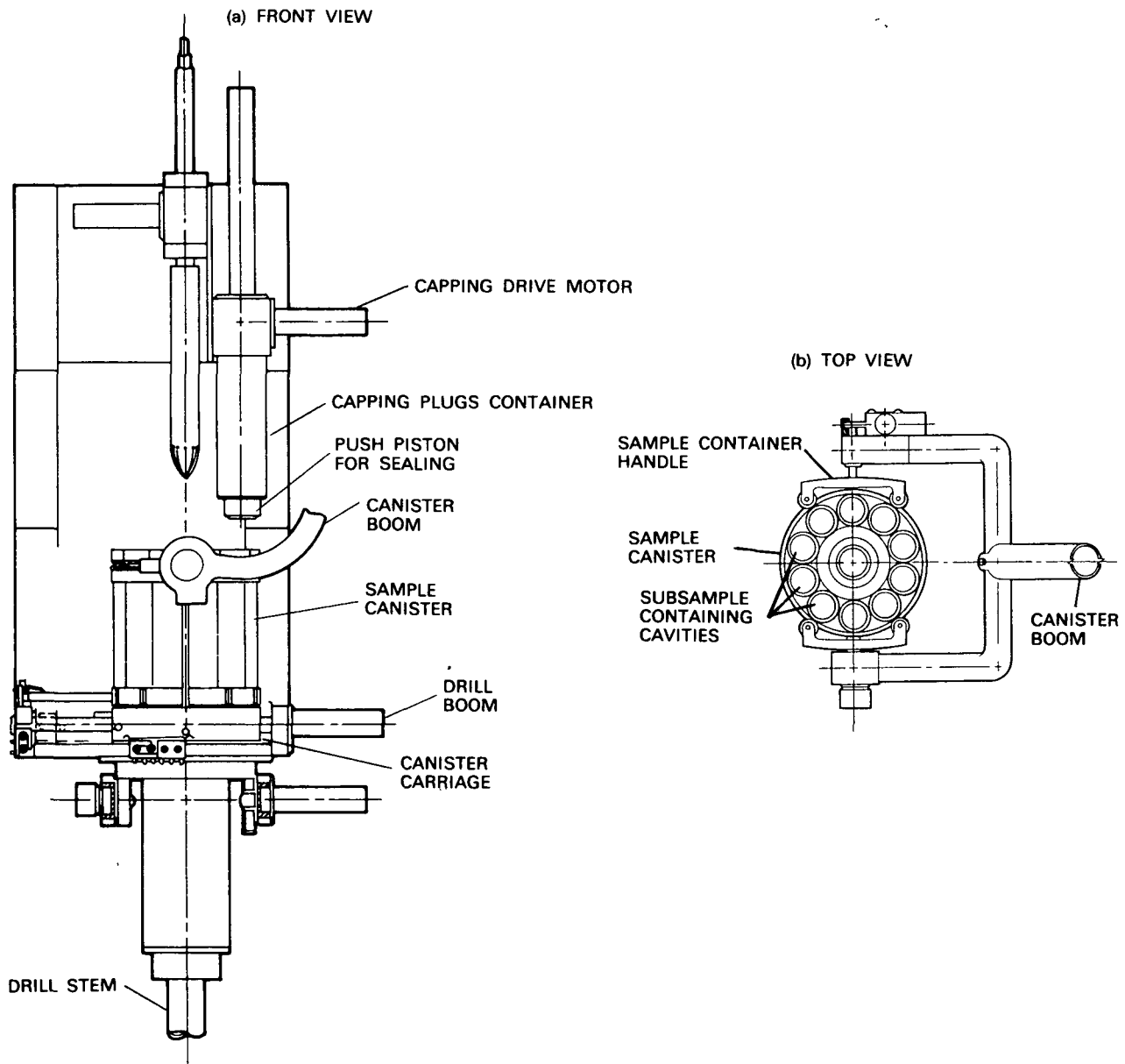


Figure 3-3.—MSR core sampler as viewed from the front (a) and top (b) The unit is designed to permit the automatic drilling of 10 subsurface cores that are then stored in individual quarantine vessels within the canister. Each sample vessel is sealed with a plug, and the entire canister is removed and stowed at the top of the return vehicle. (Adapted from JPL studies)

hand, the Viking lander experience illustrates the relatively limited degree of flexibility provided by state-of-the-art unmanned systems. Although the Viking landers demonstrated a remarkable degree of reliability, they could adjust to initial test results only within narrowly defined design capabilities. For the quarantine mission, it was decided that an unmanned

design concept which adequately anticipates every desired mode of system response was not achievable without an unrealistically large increase in the complexity and cost of equipment. Therefore, it is desirable to have humans do the detailed manipulatory work and to interpret, evaluate, and modify experiments during protocol procedures.

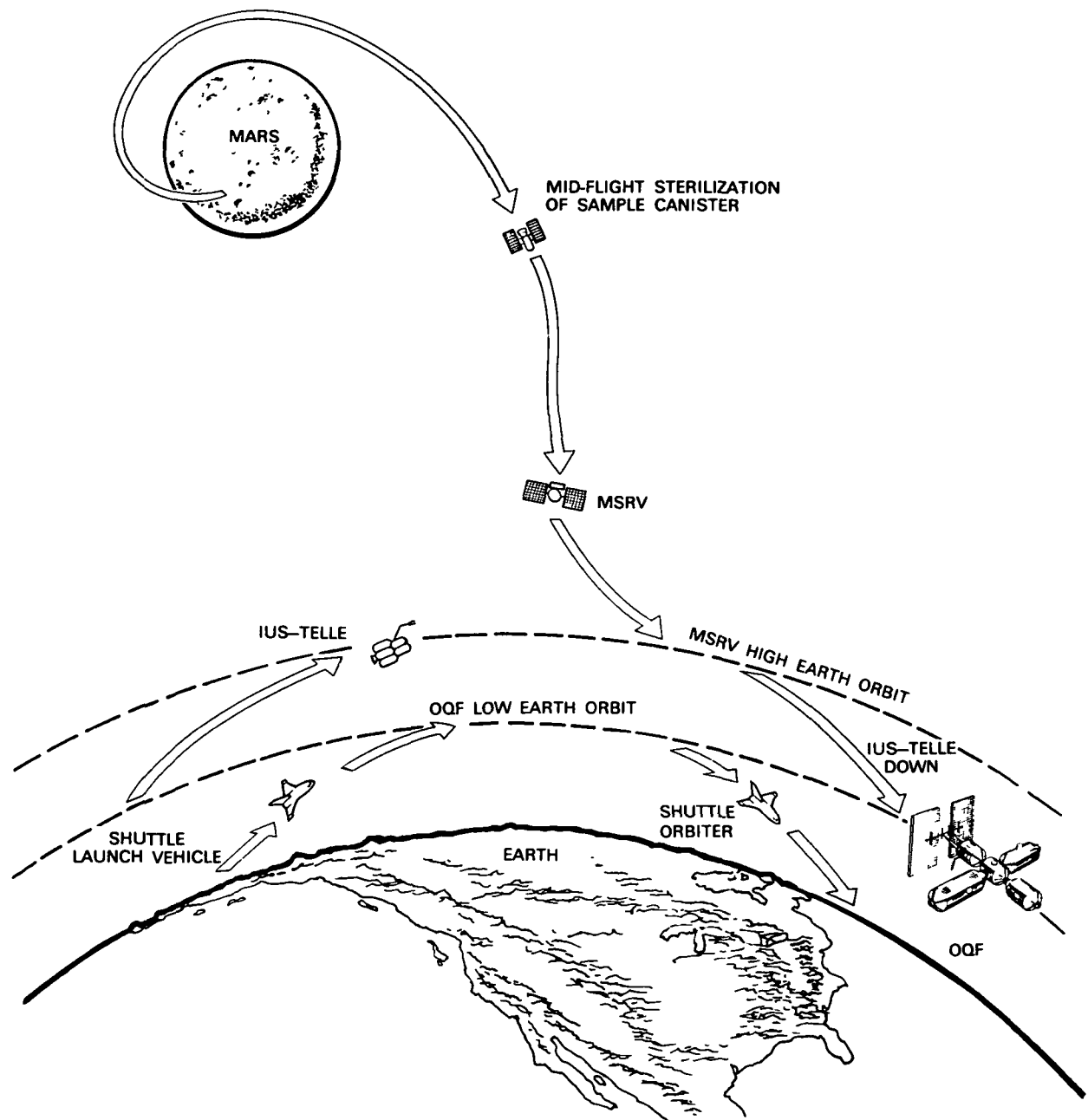


Figure 3-4.—A Mars sample return mission. After its voyage from Mars, the MSRV is inserted into a high Earth orbit where it couples with an IUS-TELLE. This rocket system returns the sample to the OQF, where the sample undergoes quarantine testing.

The presence of humans aboard the OQF places a number of constraints on the design of the OQF system. For example, because prolonged laboratory studies in the confines of an orbiting facility under weightless conditions impose a high degree of stress on human researchers, it was deemed highly desirable to

maintain a “shirtsleeves” environment in the OQF. This requires an Earth-normal atmospheric pressure, a breathable gas mixture, and a comfortable temperature range, along with systems to regenerate and maintain them. The ability to move freely (without the encumbrance of a positive pressure suit), to breathe

normally and communicate by direct voice, and generally to function in as normal a fashion as possible will greatly facilitate the crew's performance.

Another constraint in the hardware design was the infeasibility, within the time frame of this mission, of developing a laboratory capable of induced gravity. Human physiological problems associated with rotating environments dictate the use of large, slowly rotating systems to develop artificial gravity. Even systems rotating as slowly as 3 rpm necessitate prolonged periods for physiological adaptation following entry into the system (ref. 3). To avoid these adaptation periods while simulating a gravitational force only one fifth as strong as Earth's, the habitation and laboratory facilities must be over 20 m from the center of rotation. The hardware development and space construction costs associated with an artificial gravity facility of this magnitude would greatly exceed the costs of designing laboratory equipment for zero-g conditions. Based on cost effectiveness and optimum utilization of available resources, a zero-g laboratory was deemed appropriate for the mission. Although laboratory testing in zero g presents many unique problems, these considerations were taken into account in the design of specific laboratory hardware. The experience gained in the Skylab flights shows that it is possible to conduct a wide variety of experiments in zero g.

Several orbit locations for the OQF were considered, including lunar orbit, libration points L₄ and L₅, geosynchronous orbit, and near Earth orbit. It became readily apparent that locating the facility at a great distance from Earth significantly increases the complexity of mission operations and hardware. For example, locating the system in a lunar orbit is infeasible because of energy requirements (see Appendix A). Although the higher (more distant) orbital options would increase the mission life of the facility and afford a greater degree of safety in terms of back contamination, selection of the near Earth orbit for the OQF was, in fact, a direct function of the upper orbit limits of the Space Shuttle. Thus, options other than low Earth orbit were rejected primarily because of limitations in the hardware available for resupply and for reasons of overall cost effectiveness.

The Delivery System to Earth Orbit

NASA's future Earth orbital mission flights are based on the Space Transportation System (STS), in which the shuttle is the transport vehicle. The shuttle,

which will be in full operation many years prior to an MSR project launch date, is designed to deliver to low Earth orbit an "orbiter" (the glider-like orbiting component) carrying experiment packages weighing up to 29 483 kg (65 000 lb). Its round trip flights follow the sequence shown in figure 3-5. This "commuter" capability is ideal for transporting crew members and materials to and from an orbiting station. Thus, the orbiter became the first component subsystem in the evolution of the MSR mission hardware design, and the design of OQF components was based upon its capabilities.

Four major payload constraints of the Space Shuttle impacted the design of the overall system's hardware. They were (ref. 4): (1) a 14 500 kg (32 000 lb) payload maximum during launch (current limitation), (2) the center of gravity envelope of the payload and orbiter, (3) the effective geometric envelope of the orbiter cargo bay, and (4) the reentry bending moment flexure characteristics of the orbiter. (See Appendix B for a discussion of the impact of these constraints on mission and hardware designs.)

Other payload constraints of the shuttle system (ref. 5), such as power and usage potential, payload attachment locations and load characteristics, vibration and acoustics spectra, and thermal environment, did not significantly impact the design of the project.

Options for Developing an OQF

After investigating the compatibility of many possible hardware systems both with the orbiter and with mission goals, the study group selected three conceptual approaches for detailed analysis

1. Designing a totally new system,
2. Modifying and refitting Skylab (which was still in orbit at the time of this study),
3. Modifying spacelab designs such as those proposed by McDonnell Douglas, North American Rockwell, Grumman, and ESA-ERNO (European Space Agency and ERNO Raumfahrttechnik).

In the selection of the shuttle as the delivery system for the OQF, it was assumed that orbiter modification was not an option (ref. 6). This fact significantly enhanced the importance of OQF/orbiter compatibility in the design of system hardware. Orbiter payload constraints nullified several preliminary considerations and thus accelerated the process of selecting among the three alternatives. The selection process is outlined below.

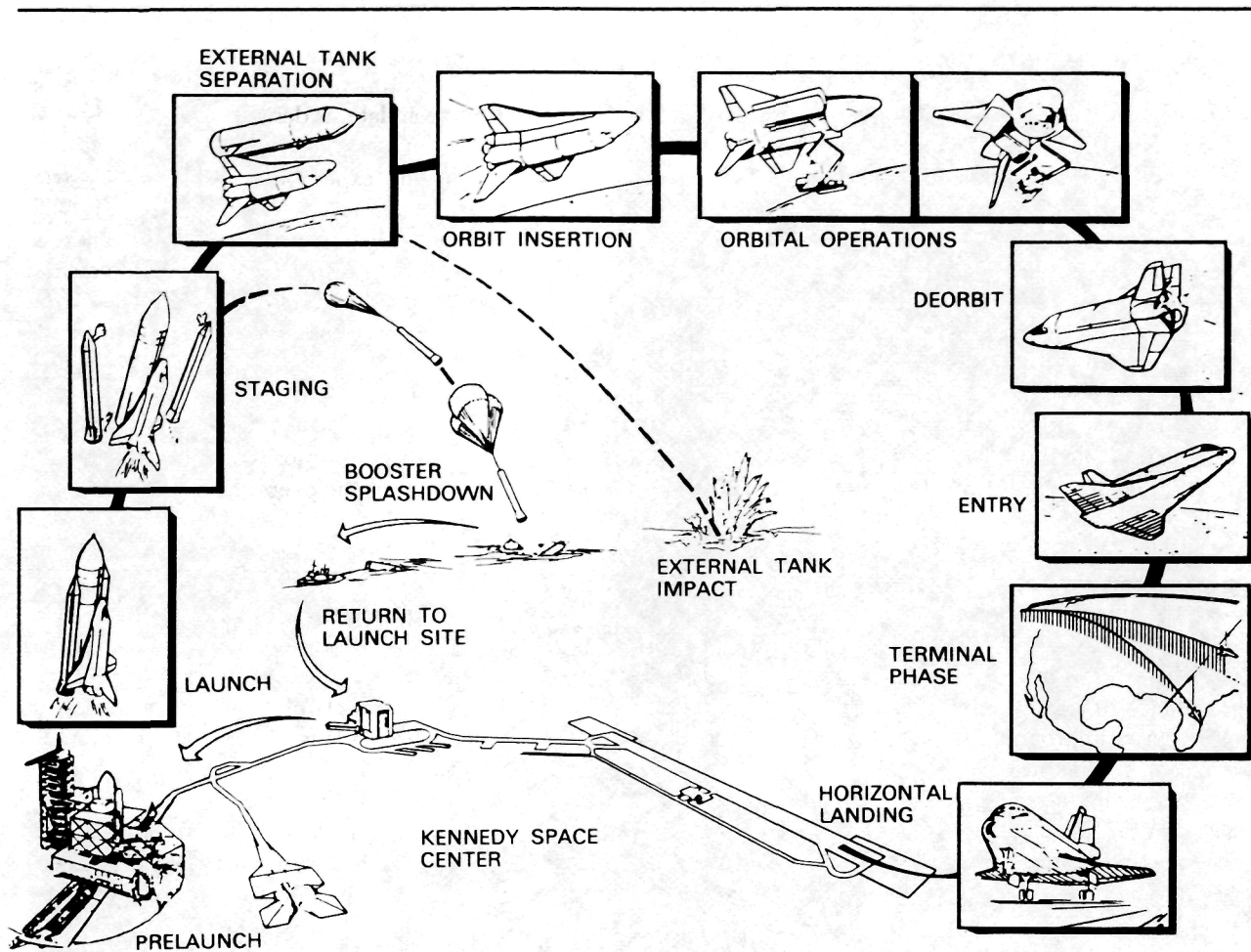


Figure 3-5.—A typical mission profile of the Space Shuttle (ref. 5).

Option #1—Design a Totally New System

An in-depth analysis was made of the problems involved in designing a totally new hardware system for the quarantine mission. However, this line of investigation was not pursued beyond the stage of analysis because, under the time-frame assumptions that prevailed during the study, there would be insufficient time to develop an entire new system. In addition, it is more cost efficient to use existing hardware and technology where possible and to update subsystems as new developments in space hardware technology become available. As a consequence, this option was rejected early in the design development phase of the project.

Option #2—Skylab Refitted

There was a strong desire to use Skylab (figure 3-6) as part of the total orbiting system because it was assumed that reutilization of this equipment would provide significant cost savings. Although Skylab has since reentered the atmosphere and been destroyed, it was in orbit at the time of this design study, and plans for preventing its demise were in progress. Skylab was seriously considered for use in the total OQF but was rejected for several reasons.

Because Skylab was relatively small and would have provided far too little power to permit it to function as a self-contained quarantine facility, it would have been necessary to mate Skylab with additional power modules. However, Skylab's docking port was incompatible with the orbiter and other proposed modules and would not have been large enough to accommodate crew members wearing

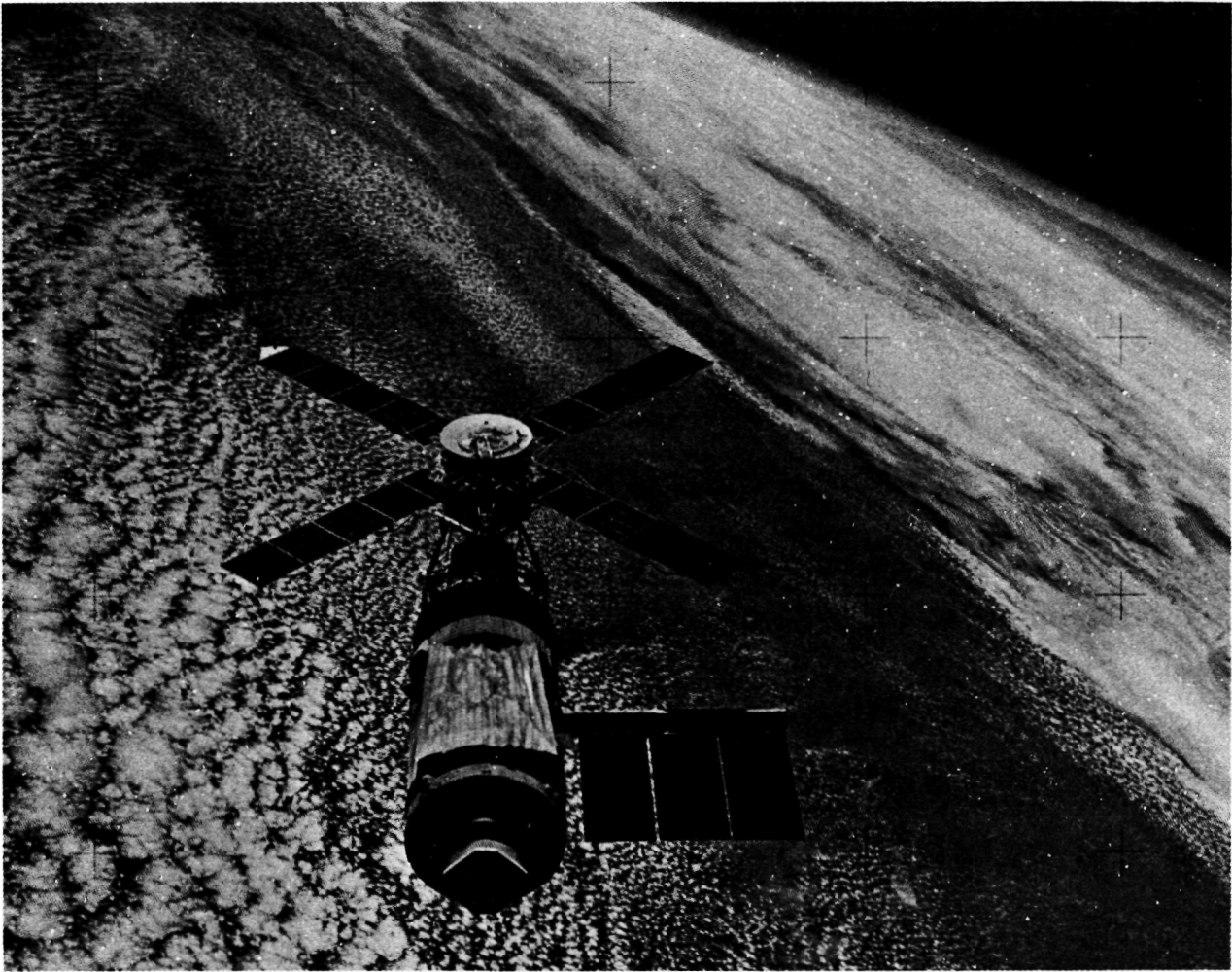


Figure 3-6.—Skylab.

extravehicular activity (EVA) gear; the extensive refitting that would consequently have been needed to restructure Skylab as a biocontainment laboratory—replacing entire subsystems in space—would have required EVA operations of untested magnitude. Skylab was also deemed impractical for use as crew quarters because it used a two-gas system maintained at 0.34 atm; the rest of the system would have had to operate at 1 atm to ensure adequate heat transfer from the extensive laboratory equipment. Therefore, crew members entering Skylab would have required a 2-hour decompression and nitrogen-adaptation period. Of equal importance is the fact that the structural strength of Skylab would have been unknown, because by the time the quarantine mission began Skylab already would have been in orbit for twice as long as its designed lifespan. Finally, as delays (because of

problems in developing a booster engine) in the shuttle launch schedule became apparent, it was felt that there was little chance that Skylab would be available for the quarantine mission. For all these reasons, Skylab was rejected as a viable option.

Option #3—Spacelab Modified

Spacelab is a joint NASA-ERNO experimental laboratory designed to be carried into space in the orbiter cargo bay, where it will remain for the duration of the mission. Utilization of a modified Spacelab design was considered by this design group to be the best option to investigate in depth. Because design studies by McDonnell Douglas (ref. 7), North American Rockwell (ref. 8), Grumman (ref. 9), and others have already been conducted, these studies

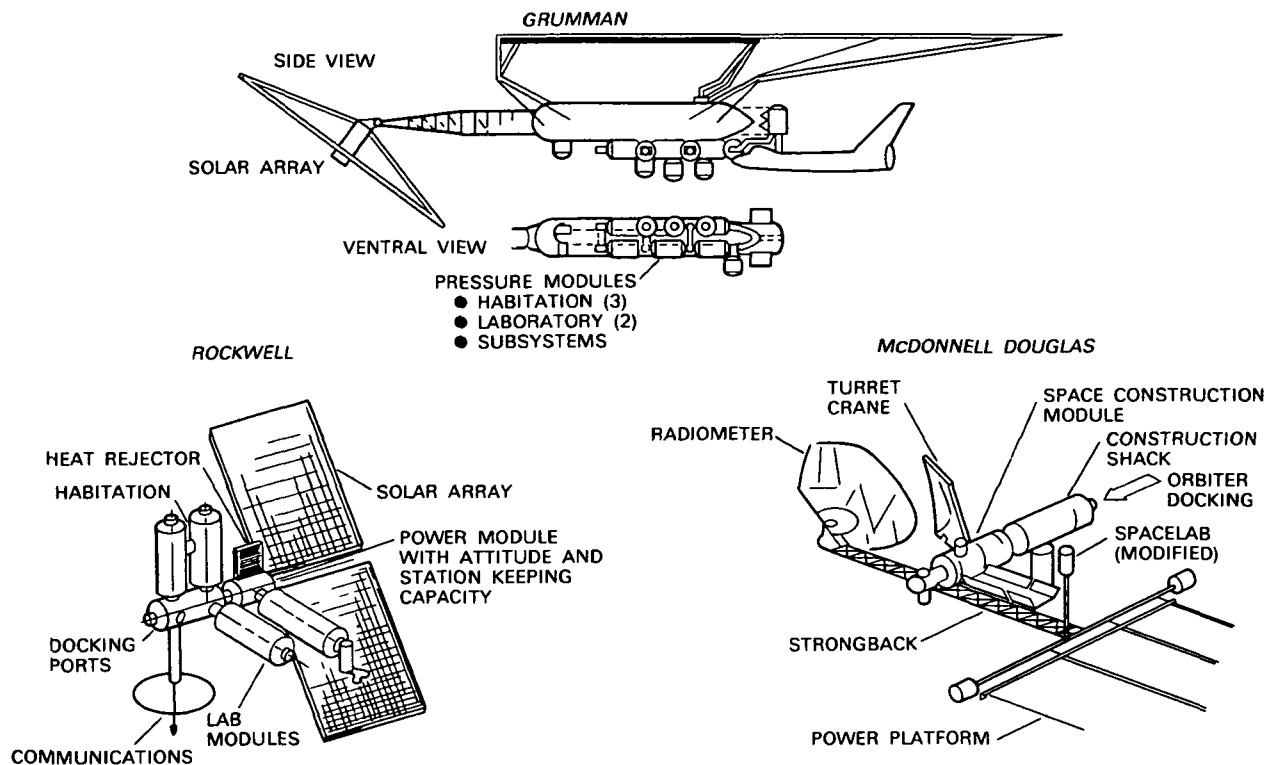


Figure 3-7.—Three concepts of freely orbiting space stations (refs. 7, 8, and 9).

were reviewed and analyzed as possible conceptual models of station systems (figure 3-7).

These reports documented various approaches to space station design, with varied design constraints, mission durations, mission goals, etc. In yet another study, the European Space Agency evaluated these studies (ref. 10), comparing the various station design concepts and their feasibility. The ESA report suggested employing the STS as the *prime delivery system* for a free-flying orbiting laboratory constructed by assembling several modified Spacelab pressure vessels (see figure 3-8).

All of these studies were taken into consideration when the major design parameters for an effective, feasible OQF were determined by the design study group. Those features of the OQF are:

- It will be a manned system.
- It will be free-flying, rather than permanently docked to the orbiter. (It was felt that if the OQF were docked to the orbiter, the orbiter would be more likely to become contaminated by crew contact or orbital contamination from the MSR.V. In addition, it is unrealistic to consider using one of

the limited number of orbiters in the shuttle fleet solely to maintain the OQF throughout the lengthy period of quarantine testing.)

- It will be constructed of Spacelab-type components, principally the Spacelab pressure vessel module and its concomitant subsystems.
- It will be kept in low Earth orbit.
- A "shirtsleeves" environment will be maintained within the facility
- The orbiter will be used as presently designed.
- The orbiter will use its remote manipulator system to hard berth each component module into position.
- The OQF, with monthly logistics support from the orbiter, will be capable of supporting continuous operations for an indefinite period.

SYSTEMS DESIGN AND CONFIGURATION

Module Overview

The OQF consists of five modules, each constructed from Spacelab components and modified to meet

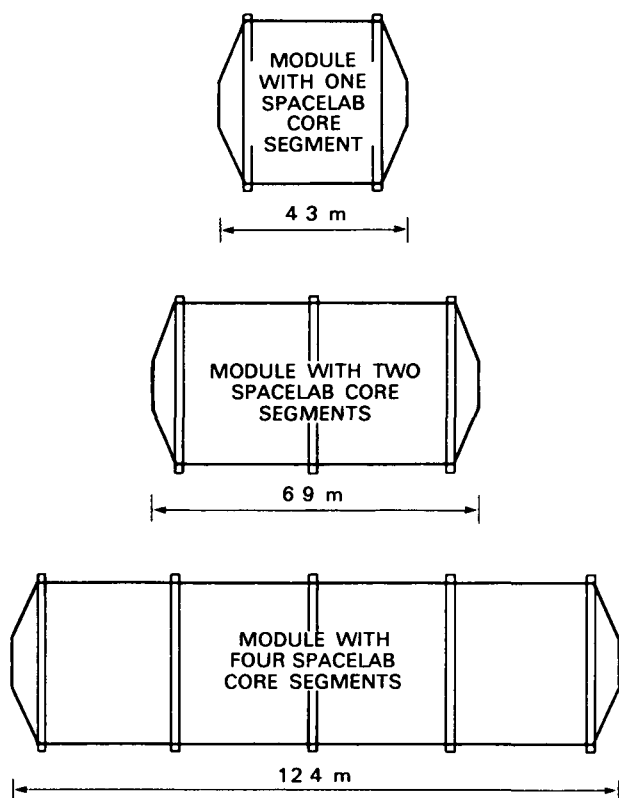


Figure 3-8.—The use of Spacelab-derived pressure vessels to construct three sizes of modules.

the specific requirements of that module's mission (figure 3-9).

The *Power Module* provides 25 to 35 kw of power from solar collectors, controls the orbital attitude of the entire system, dissipates heat generated within the OQF, and provides communications with Earth.

The *Habitation Module* will provide the crew with quarters, food service, exercise and personal hygiene facilities, medical support, and a command console. It will also provide an environmental control and life support (ECLS) system to support the OQF's atmosphere regeneration (except in the laboratory).

The *Laboratory Module* is designed to contain the equipment, instrumentation, and supplies necessary to carry out the chemical and biological testing protocol on the Martian sample. These experiments will be conducted in sealed cabinets that both protect the sample from terrestrial contamination and prevent exposure of the personnel to potential Martian contaminants. Additionally, this module is isolated from the remainder of the OQF because it has independent life-support and waste storage systems. The docking port at the end of the Laboratory Module is available

for the berthing of additional laboratory sections if an expanded protocol or an abort propulsion kit is required.

A general purpose *Logistics Module* provides storage for supplies and for waste generated in the Habitation Module. At approximately 30-day intervals, the logistics unit will be removed and replaced with a module containing new supplies.

These four modules will be linked in their final configuration (see figure 3-10) using a pressurized *Docking Module*. This unit will be able to connect five to six modules of various designs, permitting the crew members unhindered access between each area. It would contain an EVA hatch and airlock as well as docking facilities for the orbiter.

A sixth module, the *Laboratory Abort Propulsion Kit*, will not be orbited with the OQF unless the need arises to place the system (or the Laboratory Module) in a higher Earth orbit. The kit will consist of one or more IUSs, depending on the altitude desired for the abort action. (See Appendix A.)

System Configuration Options

The specific layout of the OQF was adopted after consideration of personnel safety, functional facilitation, the minimum facility needed to meet mission objectives, maximum cost effectiveness, and capability for alternative uses and (or) expansion of the baseline configuration.

Two basic configurations considered in the design of the OQF were an in-line design, which did not require a pressurized docking module, and a "pin-wheel" design, in which all the modules were attached to a common pressurized docking module. The pin-wheel design (figure 3-10) was selected because:

- It provides a berthing port for the Logistics Module and for the berthing of additional modules.
- Its final assembly is easier.
- It has less aerodynamic drag (and consequently requires less fuel for attitude control and orbit maintenance).
- It provides emergency escape routes via the unberthed end cone of each module.
- It permits any module to be nonfunctional or depressurized without interrupting movements throughout the rest of the system.
- Its compact design facilitates the movement of personnel, equipment, and supplies through the modules.

MANNED FREE-FLYER

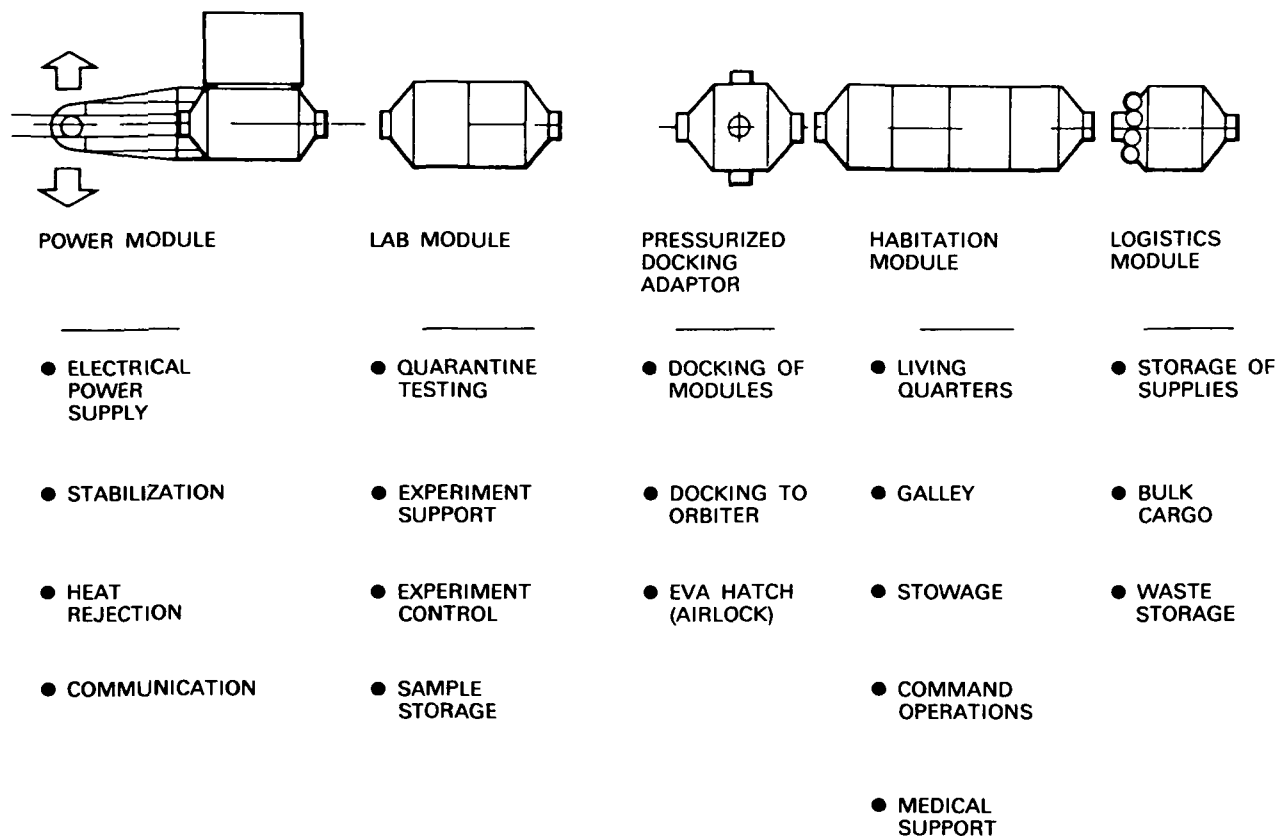


Figure 3-9.—Adaptation of Spacelab modules to produce the five major component sections of a free-flying manned Orbiting Quarantine Facility (adapted from ref. 10).

Because crew members will move between the Habitation and Laboratory Modules most frequently, these two modules were placed on a direct line with each other. This will help crew members to maintain a frame of reference and will eliminate disorientation.

SPACE TRANSPORT AND ASSEMBLY OF MODULES

The number of shuttle flights required to transport the OQF modules into a low Earth orbit depends upon the cargo mass and the altitude selected for the OQF. The orbiter is currently limited to 14 500 kg (ref. 11), although approximately twice that capacity may be realizable by the late 1980s. However, in this study, the current cargo mass limits were used as a design

constraint, thus necessitating at least four shuttle missions to assemble the entire OQF. Details concerning the payload limitations and center of gravity requirements can be found in Appendix B. The Docking and Logistics Modules will constitute the cargo on the first flight; once in orbit, the pressurized Docking Module will be berthed to the Logistics Module using the orbiter's remote manipulator system (RMS). (See Appendix C.) The second flight will orbit the Power Module, which will then be attached to the Docking Module. On the third flight, the Habitation Module will be coupled with the Docking Module, permitting the station to be manned for systems checkout. The Laboratory Module will then be transported to the facility and berthed with the Docking Module to complete the OQF.

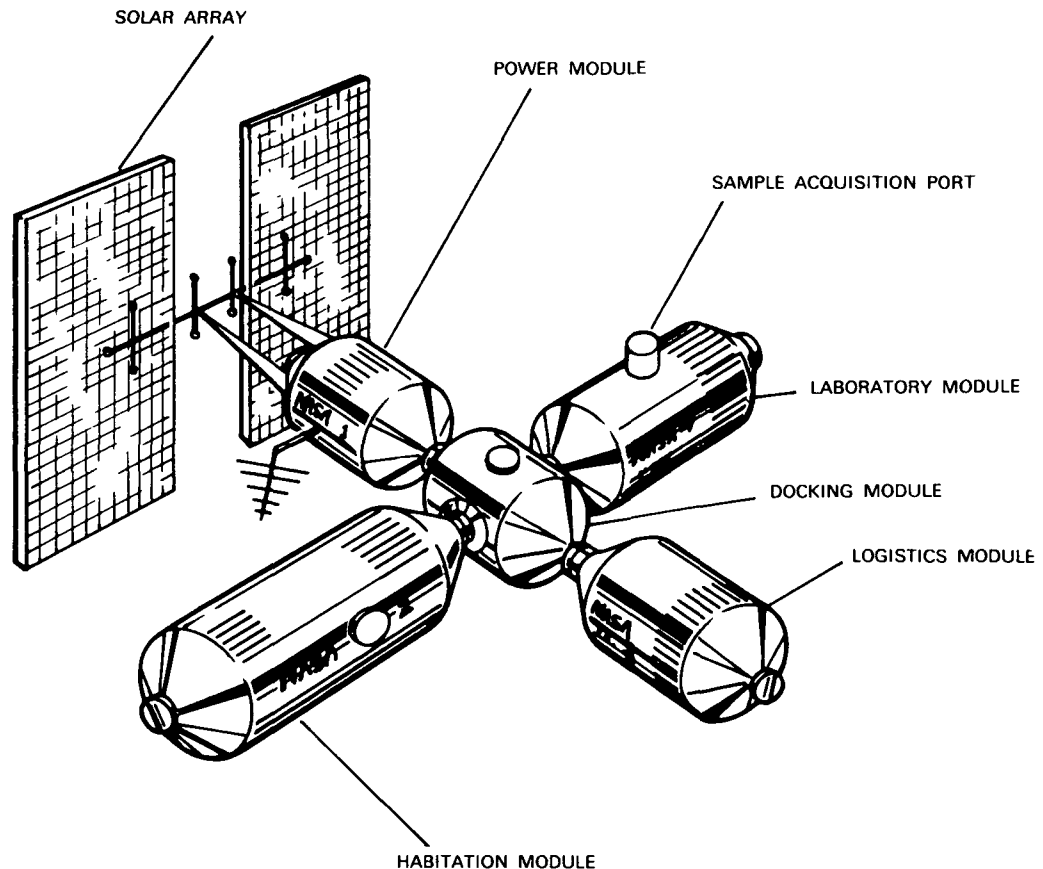


Figure 3-10.—The proposed configuration of the OQF.

OQF Orbit and Orbit Maintenance

Selection of an orbit for the OQF is predicated on the altitude-payload capabilities of the orbiter and the aerodynamic drag of the OQF; in addition, the OQF orbit must be compatible with the orbit of the MSR/V.

Because the MSR/V return orbit has not yet been established, the most desirable inclination of the OQF cannot be specified at this time. However, unless an orbital maneuvering subsystem (OMS) is used to provide a higher orbit, the maximum altitude possible is 463 km (287 mi), based on the current launch mass limits and an orbit inclination of 28.5 degrees (ref. 11). Increased launch weights may require the orbit to be lowered by approximately 12 percent, while different inclinations further reduce the altitude. The orbit will

be maintained using the altitude control system located in the Power Module.

CONCLUSIONS

Given the numerous constraints described in this chapter (shuttle/orbiter limitations, use of humans in the system, cost considerations, etc.), there is surprisingly little flexibility remaining in the design possibilities of the quarantine system. However, with proper integration of the quarantine into the sample-return schedule, a system based on current technology can be constructed which provides an environment that is safe from both forward and back contamination, affording the Earth the greatest possible degree of protection, and yet permits the execution of a credible and thorough testing program for the Martian samples.

TABLE 3-1.—ESTIMATED MASS OF THE OQF COMPONENTS

<i>Module</i>	<i>Mass</i>
Laboratory	13 600 kg ^a
Habitation	13 600 kg
Power	13 600 kg
Docking	2300 kg
Logistics	4500 kg
Large Motor IUS (1st stage)	11 400 kg
Large Motor IUS (2nd stage)	11 400 kg
Small Motor IUS	3100 kg

^a 13 600 kg = 30 000 lb.

Appendix A—Energy Requirements for Various Orbits

TRANSFER TO LUNAR ORBIT

One of the options investigated was the possibility of placing the OQF in a circular lunar orbit. To accomplish this, the OQF would be injected from Earth orbit into an elliptical transfer orbit (Mohman's orbit) around the Moon using a velocity correction of 3.1 km/sec (ref. 12), and then inserted into the desired circular lunar orbit using a correction of 1.0 km/sec. These velocity impulses represent the minimum energy transfer conditions. Any other Earth escape trajectories (i.e., parabolic or hyperbolic) require a much higher escape velocity and significant velocity reductions for insertion into a circular lunar orbit.

Considering the total mass of the OQF and a two-staged, large motor IUS to be 70 400 kg (table 3-1), the maximum velocity impulse that can be achieved after expending both stages of the large motor IUS is 1.15 km/sec (ref. 13). This is much less than the velocity of 3.1 km/sec required to transfer the OQF from an Earth orbit into an elliptical transfer orbit. In addition, independent insertion of each of the OQF components into lunar orbit cannot be accomplished with a two-staged IUS: The heaviest module could be accelerated to only 2.8 km/sec. Thus, the lunar orbit option is not possible.

TRANSFER TO HIGHER EARTH ORBIT (GEOSYNCHRONOUS)

To transfer the OQF to a higher, geosynchronous Earth orbit will require two velocity corrections, one

to transfer the OQF into an elliptical transfer orbit (V_1) and the other to place the OQF in a circular geosynchronous orbit (V_2). Using the equations of space mechanics, and assuming an initial altitude of 296 km and a final altitude of 550 km, the magnitude of these velocity corrections is $V_1 = 7.2 \times 10^{-2}$ km/sec (160 mi/hr) and $V_2 = 7.1 \times 10^{-2}$ km/sec (158 mi/hr). The magnitude of the velocity impulse supplied by the small motor IUS is 21×10^{-2} km/sec (467 mi/hr). Thus, a small motor IUS is sufficient to allow the OQF to be placed in a higher Earth orbit.

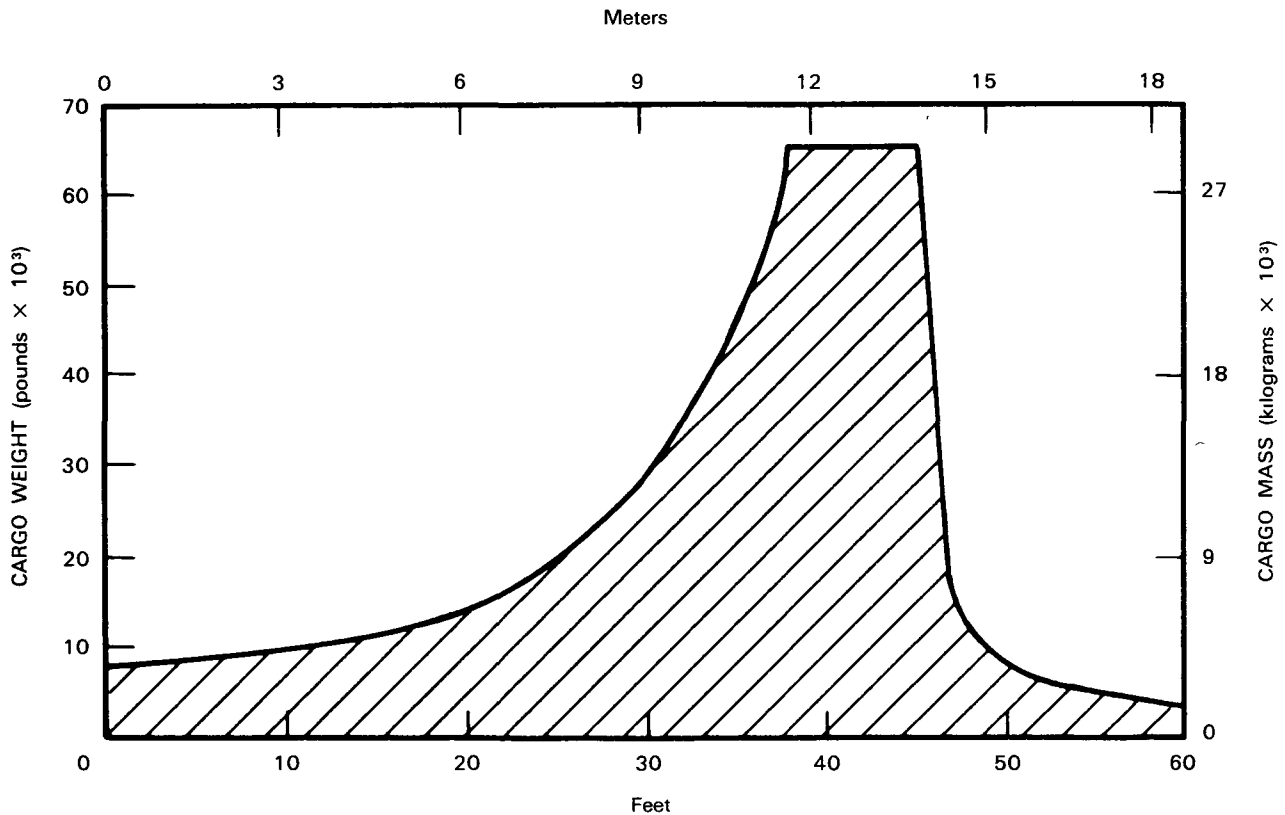
EMERGENCY BOOSTING OF THE LABORATORY MODULE

The design study group believed that the OQF should have the capability of removing the Laboratory Module from the immediate vicinity of the Earth in the event of a serious emergency. One option, expulsion of the module from the Earth's solar system, would mean inserting it into a hyperbolic escape orbit with a velocity impulse equal to 3.5 km/sec. Because the two stages of the large motor IUS can together achieve only 2.8 km/sec, it is not possible to eject the Laboratory Module from our solar system.

However, the velocity correction of 2.4 km/sec required to transfer the Laboratory Module from an Earth orbit of 296 km to one of 8000 km is well within the capability of the two-staged large motor IUS. This appears to be a reasonable option in the event of a serious problem stemming from a containment failure during quarantine testing.

Appendix B—Orbiter Payload Weight Constraint

The orbiter is designed to land carrying a maximum of only 14 500 kg (32 000 lb) (ref. 11). Currently, this mass limitation also serves as the maximum that can be launched, since a malfunction could necessitate an emergency landing with full load. Therefore, although the craft is designed to launch 29 500 kg (65 000 lbs), permission to orbit a maximum payload may not be given until after years of successful flights (if ever). In addition, in this mission the maximum payload is further reduced by 900 kg (2000 lb) because of the necessity to include a second remote manipulating system (Appendix C) and the orbiter docking port. In this study, the lower, currently acceptable weight was



CARGO LONGITUDINAL CENTER OF GRAVITY—
DISTANCE FROM FORWARD CARGO BAY BULKHEAD

Figure 3-11.—Orbiter longitudinal center of gravity constraints as a function of cargo mass (ref. 11).

assumed to be mandatory (i.e., a maximum module mass of 13 600 kg, or 30 000 lb), although calculations of the influence of the greater cargo mass were also made (i.e., a maximum module weight of 28 600 kg, or 63 000 lb).

During landing, the orbiter cargo must also be positioned so that its center of gravity is located around a point approximately 12.8 m behind the forward bulkhead (ref. 11). As the cargo mass increases, placement of the payload near this position becomes more critical (see figure 3-11). The cargo must also be symmetrical about the orbiter's center line and occupy an area no greater than 16.2 m by 4.0 m. Finally, the cargo must be arranged to permit a certain degree of bending flexure about the craft's longitudinal axis (ref. 6).

Considering both current and projected cargo launch weights, the center-of-gravity constraints are given in table 3-2.

TABLE 3-2.—CONSTRAINTS ON THE CARGO'S CENTER OF GRAVITY

Type of Constraint	Kg of Cargo Launched	
	Current 14 500	Projected 29 500
Longitudinal distance from forward bay bulkhead (figure 3-12)	9.8-13.8 m	11.0-13.1 m
Vertical: distance below payload bay centerline	0.7-1.22 m	0.15-0.51 m
Lateral: distance from payload bay centerline	±8.9 cm	±6.4 cm

If equipment and materials are properly located within the module, they can be mounted within the cargo bay in accordance with these requirements. Furthermore, the longitudinal position of the module within the bay can be adjusted by attachment to fittings located at 10 cm increments. Ballast can also

be added to the cargo bay to adjust the center of gravity.

With the current launch limits and the assumed module masses (see table 3-1), a minimum of four separate launch missions would be required to orbit the five components, since the Logistics and Docking units could be flown together (figure 3-12, top). However, if the masses of the fully equipped Habitation, Laboratory, or Power Modules (estimated to be 13 600 kg each) actually exceed the current orbiter payload limit (also 13 600 kg) by a moderate amount, then enough equipment would be removed to reduce

the weight of that module to an acceptable level. The excess equipment would then be launched separately for installation in space (perhaps along with the lighter Logistics and Docking units). If the mass estimates are incorrect by, say, a factor of two, then the modules would be subdivided, launched separately as major subcomponents, and coupled in space.

On the other hand, if the higher cargo limit (28 600 kg) is eventually allowed, then up to three smaller modules can be launched simultaneously (figure 3-12, bottom). However, because the length of the Habitation Module necessitates its solo flight, the remaining

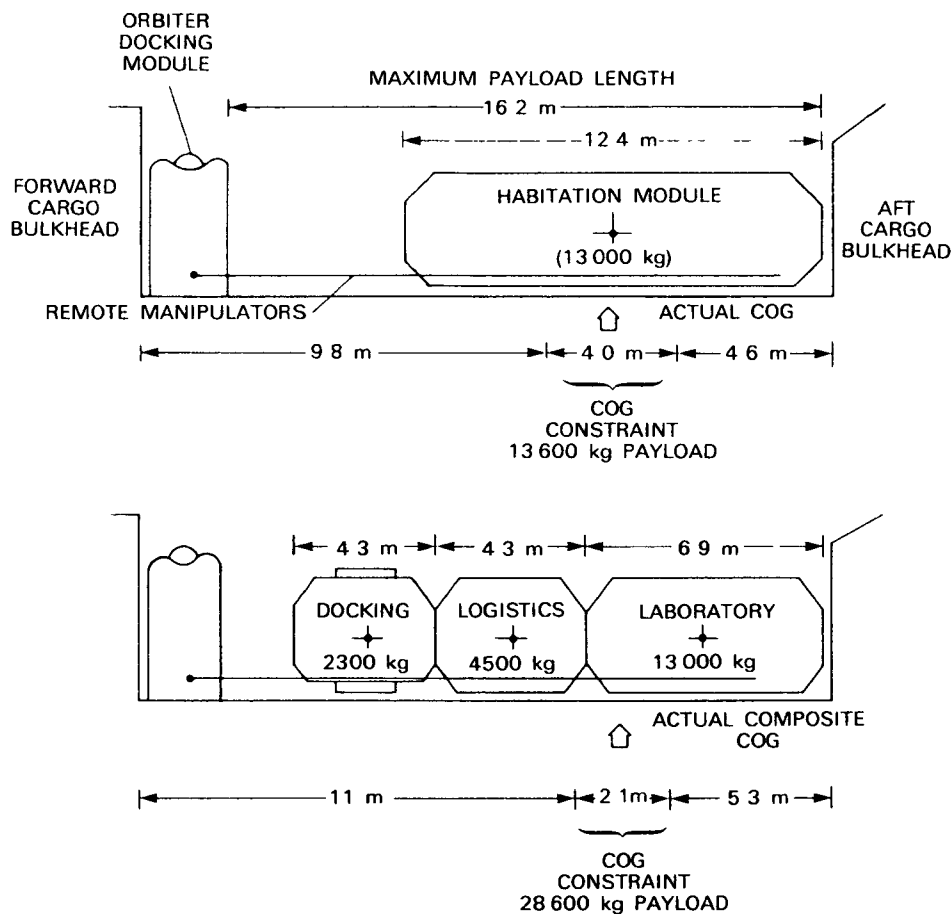


Figure 3-12.—The location of the actual longitudinal center of gravity (COG) in the orbiter bay, and its relation to the COG constraint. Top: Assuming a maximum launch cargo of 14 500 kg (32 000 lb), only 13 600 kg (30 000 lb) would be available for quarantine facility payload. The actual COG for the longest module (Habitation) would be 11.6 m behind the forward bulkhead. Bottom: With a launch limit of 29 500 kg (65 000 lb), the maximum OQF payload is 28 600 kg (63 000 lb). The COG with 3 modules is 12.3 m behind the forward bulkhead.

four modules would require a minimum of two flights for a total of, at the minimum, three launches. The net saving with the higher cargo limit is thus only one launch. The major advantage afforded by increasing the payload maximum is that the modules can be equipped fully without fear of exceeding the mass limits.

Appendix C—Remote Manipulators

Berthing of the modules will be accomplished with the use of two remote manipulator systems (ref. 5), as shown in figure 3-13. Although orbiters include one

manipulator arm mounted on the port side of the vehicle, a second manipulator arm must be installed on the starboard side, adding a weight of 450 kg. The manipulators are capable of deploying a payload 4.5 m in diameter, 18.3 m in length, and 29 500 kg in weight to a position clear of the orbiter. During berthing operations one manipulator will be used to hold the already-emplaced portion of the OQF while the second manipulator (controlled remotely from the orbiter) moves the module being berthed into position. If an EVA effort is required during the berthing maneuver, space construction personnel can egress through the orbiter's docking port to assist.

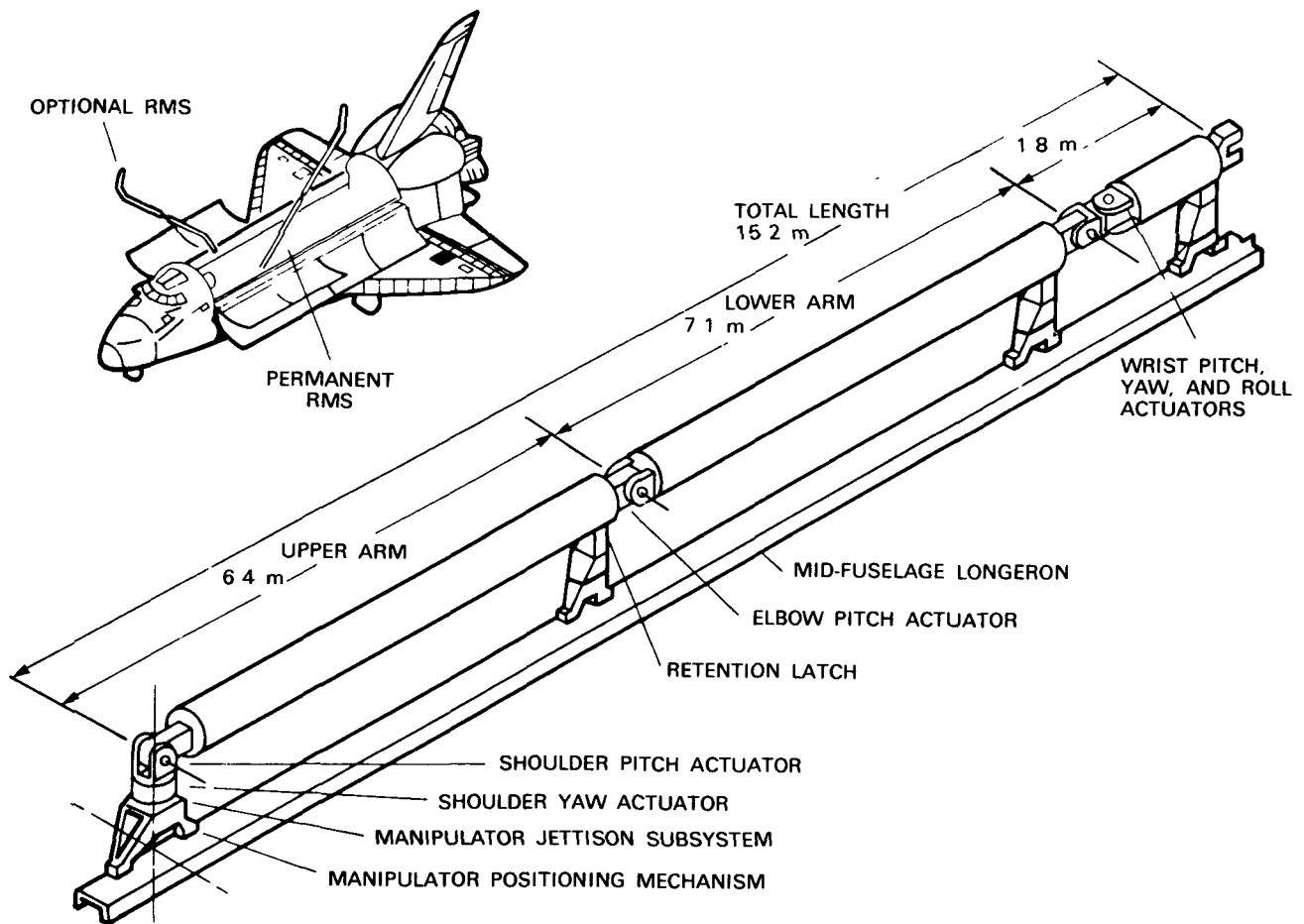


Figure 3-13.—A detailed drawing of a remote manipulator system. The insert depicts an orbiter with two manipulators (ref. 5).

REFERENCES

1. Levin, G. V., and Hall, J. M. Quarantine concepts for a Mars return sample mission. In *Life Sciences and Space Research, Volume XV*, Proceedings of the Open Meeting of the Working Group on Space Biology of the 19th Plenary Meeting of COSPAR, Philadelphia, Pennsylvania, June 8-19, 1976 (ed. by R. Holmquist and A. C. Stuckland). Pergamon Press, New York, 1977, pp. 15-19.
2. McDonnell Douglas Astronautics Co. *Space Station Program Executive Summary*. Huntington Beach, California, December 1971, 131 pp. (MDC-G2587)
3. Burgess, E. Rotating space station could be made livable for crew. *The Christian Science Monitor*, March 18, 1970, p. 15.
4. Rockwell International. *Space Shuttle System Summary*. Downey, California, 1976, 207 pp. (SSV-76-32)
5. National Aeronautics and Space Administration. *Space Transportation System: User Handbook*. Washington, D.C., June 1977.
6. European Space Agency. *Spacelab Payload Accommodation Handbook*. Paris, France, July 1978, 569 pp. (NASA-TM-79937; ESA-SLP/2104)
7. McDonnell Douglas Astronautics Co. *Space Station Systems Analysis Study. Part 3: Documentation. Volumes 1-4*. Huntington Beach, California, July 1977. (MDC-G6922)
8. Rockwell International. *Extended Manned Space Activities. Status Report*. Downey, California, June 13, 1977. (PD77-20)
9. Grumman Aerospace. *Space Station Systems Analysis Study. Part 3: Final Report. Volume 1: Technical Report*. Bethpage, New York, 1977. (NSS-SS-RP-021)
10. Natenbruk, P., Kowalke, F., Schulte, L., Friedrich, H., Meyer, I., Heidmann, H. J., Gericke, W., Ward, A., and Mukrowsky, W. *Study of the Use of Spacelab Derived Elements within Different Possible Steps Towards a Space Platform. Final Report*. ERNO Raumfahrttechnik, Bremen, West Germany, April 1978, 343 pp. (PRV-6-2/78; ESA-CR(P)-1093)
11. Lyndon B. Johnson Space Center. *Space Shuttle System Payload Accommodations—Revision B*. Houston, Texas, December 1973. (JSC-07700-Vol-14)
12. Roy, A. E. *The Foundations of Astrodynamics*. The Macmillan Co., New York, 1965, 385 pp.
13. Thompson, W. T. *Introduction to Space Dynamics*. John Wiley & Sons, New York, 1961.

Chapter 4

Quarantine and Protocol

PURPOSE AND SCOPE

The purpose of the Orbiting Quarantine Facility is to provide maximum protection of the terrestrial biosphere by ensuring that the returned Martian samples are safe to bring to Earth. Thus, the protocol described in this chapter is designed to detect the presence of biologically active agents in the Martian soil; basic scientific investigations unrelated to hazard detection are not included. The protocol determines one of two things about the sample: (a) that it is free from nonterrestrial life forms and can be sent to a terrestrial containment facility where extensive chemical, biochemical, geological, and physical investigations can be conducted; or (b) that it exhibits "biological effects" of the type that dictate second-order testing.¹ The quarantine protocol is designed to be conducted on a small portion of the returned sample, leaving the bulk of the sample undisturbed for study on Earth.

The experiments suggested for the quarantine protocol were selected because they maximize the chance of detecting life if it exists; because they do not involve the kind of activities that commonly cause barrier systems to fail (i.e., the use of sharp instruments, open flames, and live animals is unnecessary for the completion of this protocol); because they use, when possible, equipment that already has been (or is expected to be) flight qualified; and because they can be performed by a small crew operating in zero g.

The protocol operates at two levels. First, it seeks to detect the presence of *any* replicating organisms or toxic substances through a four-pronged approach consisting of: direct observation of the sample, analysis for the chemicals comprising living organisms, metabolic experiments patterned after the Viking tests, and microbiological culturing attempts using different

¹Second-order testing is initiated if nonterrestrial life forms or uncontrolled toxins are detected in the sample. Because the nature of second-order testing depends upon the results derived from the OQF protocol, a sequence of tests cannot be specifically defined in this protocol. However, the protocol set forth in this chapter will generate the information necessary to develop second-order testing procedures, if they are required.

environments. Second, a "challenge system" is employed to determine whether agents or organisms present in the Martian soil are hazardous to terrestrial life forms. This is accomplished by adding samples of soil, or agents/organisms detected in previous tests, to challenge cultures of terrestrial species. In the event that a nonterrestrial life form or replicating toxic agent has been detected at any stage of the protocol, second-order testing is initiated to characterize it more fully.

The experimental methods to be employed in the proposed protocol are presented in this chapter. They are specified in enough detail to permit a thorough assessment of the particular equipment, space, and personnel requirements for operating that system in the zero-g OQF. Such planning is essential to ensure that, in addition to being able to successfully detect life if present, the experiments are compatible with the total constraints of the space facility.

THE LUNAR RETURN EXPERIENCE

The quarantine of extraterrestrial soil is not unique to the return of Martian material. The Lunar Receiving Laboratory (LRL) at Houston provided quarantine facilities for 2 years during the Apollo program. This experience has provided an important model for formulating the OQF protocol described in this report.

Located at Johnson Space Center (JSC), the LRL was designed to permit quarantine testing and containment of the returning lunar samples, astronauts, and equipment. The entire LRL program was conceived, built, put into operation, and concluded in a relatively short period of time—between February 1966 and April 1971, when the Apollo 14 samples were released from quarantine. The lunar sample quarantine did not run its course without mishap, however. Lessons were learned that can be profitably applied to any facility for the quarantine of extraterrestrial material.

In a quarantine mission, three aspects of the mission that are particularly important to mission success are: mission planning, experimental protocol, and equipment integrity. Weaknesses or poor performance in any of these areas can lead to failure of the

mission through a breach of quarantine. In the Apollo quarantine program, weaknesses in all three of these areas were in evidence (refs. 1 through 3), and a review of the program in this light is of value in planning for a Mars sample quarantine.

Mission Planning

During the planning of a planetary mission it is essential that the quarantine phase be allotted sufficient time to develop and execute a credible testing program. In the case of the lunar quarantine, the official decision that a scientific advisory committee should be established and that funding for a facility should be sought came just 6 months before LRL construction was to begin. In that time it was necessary to recruit a qualified directorate, establish experimental protocols, and design facilities suitable for mission execution and containment. The initial schedule also allowed only 13 months for facility construction, testing, certification, personnel training, mission simulations, and preparation for sample receipt (ref. 1).

Although most of the researchers who were employed in the program were very familiar with the procedures to be followed during quarantine, many of the principal investigators did not arrive at the LRL until sample receipt (ref. 1). The thorough training of all participants in an MSR mission, both direct mission members and supporting persons, would have to be mandatory. Such personnel must participate in the various mission simulations and have a primary dedication to the execution of the protocol.

A potential danger in the lunar quarantine was that the location of the LRL near a major city presented the possibility of a rapid spread of infection, as workers who might have unknowingly breached quarantine went home in the evening. A quarantine facility for future extraterrestrial return samples must be physically isolated from population centers, and the workers should be held in quarantine throughout the mission.

Experimental Protocol

In the lunar protocol, the emphasis of the testing was on demonstrating that terrestrial plants and animals were not harmed by exposure to the sample material. With Martian samples, especially in view of the greater likelihood of life forms being present, the emphasis should more properly be on first detecting life forms—dormant as well as active—before initiating

extensive challenges of terrestrial systems with the sample.

One criticism of the LRL protocol has been that quarantine testing consumed an excessive amount (528 g, or 1.5 percent) of the lunar sample (ref. 3). With a much smaller Martian sample, the OQF protocol will clearly not be able to consume as much material, but the percentage will nonetheless be higher than in the lunar case. Probably 100 g, or 10 percent, of the returned Martian sample would be available for use in the protocol—less than one fifth the amount used in the lunar protocol. The limited amount of material for testing is another strong argument for emphasizing an initial sequence of tests that concentrate on life detection (ref. 4) before challenging species for possible harmful effects. The test protocol should involve the minimum number of challenge organisms that can be used without entailing a loss of credibility in the test results (refs. 1, 3). Simulated trial runs of the protocol using pathogen-contaminated soil are highly advisable. Simulations would allow the protocol to be debugged and would train all laboratory personnel under realistic conditions, so that sample-wasting errors could be avoided. Such trial runs were recommended for the LRL protocol but were not performed, partly because of limited time.

Bagby (ref. 1) noted that a source of problems in the LRL was that the samples were used by both geologists and biologists, whose needs and interests sometimes conflicted. If quarantine testing is established as a first priority, with the interests of physical scientists protected by careful planning and proper protocol, it is possible to accomplish all of the very diverse scientific objectives of a planetary sample return. Basic science investigations of the sample must await its certification and release. On the other hand, the quarantine protocol must ensure that the nonquarantine portion of the sample is not altered or destroyed, so that future investigations remain unimpeded.

Equipment Security

Several physical problems were noted with the equipment used in the lunar quarantine testing protocol. The rubber gloves used for access to the containment cabinets, for example, were a source of sample contamination. Under negative pressure such gloves pass sizeable amounts of water and oxygen (ref. 3). In future quarantines of extraterrestrial material, sealed

but flexible metal manipulator arms should be used for initial sample handling, since they present a lower risk of contamination (ref. 5). Another problem noted by Duke and Reynolds during the lunar quarantine (ref. 3) was that the pumping systems used to establish a vacuum during various stages of the testing protocol allowed organic contaminants to be introduced into the cabinets. In an orbiting facility, space itself could be used to produce a vacuum, minimizing the risk of contamination from machinery, lubricants, and tubing.

The proper sterilization of the cabinets prior to introducing the sample is an important matter. The cabinets in which the pristine sample is first opened should be thoroughly cleaned and sterilized through the use of dry heat, rather than organic sterilants, because trace residues of formaldehyde or ethylene oxide could contaminate the sample (ref. 3). However, the handling of the quarantine sample, once it has been separated from the pristine portion, should be done in multiply-decontaminated areas to reduce the chance of forward contamination. Microbes surviving cabinet decontamination could lead to puzzling results and delays in sample release. Use of surface sterilants in these areas is recommended before samples are received to remove all residue and organisms remaining from trial runs of the protocol with pathogen-contaminated soil. Dry heat should follow.

Quarantine Priority

Mars has a complex atmosphere. There is evidence that at some point in the planet's history water flowed across its surface. Although the automated soil testing performed by the Viking lander in a single location did not find any incontrovertible signs that life was present, the existence of life forms on the planet cannot yet be ruled out. Thus a sample quarantine is necessary, both to perform definitive life-detection tests and to protect the Earth's biosphere from possible harm. If this basic principle is accepted, then the quarantine must be considered a crucial phase of a Mars sample return mission and careful steps should be taken to ensure that the program is not compromised (ref. 4). Early in the mission planning phase, an independent commission should be established, similar to the lunar program's Interagency Committee on Back Contamination (ICBC) but with sole authority to coordinate, evaluate, and approve quarantine activities (ref. 4).

By its nature, a quarantine excites impatience among scientists eager to sample the fruits of what will

have been a long, difficult, and successful sample return mission. The quarantine must not be vulnerable to the pressure to take short-cuts and make premature judgments. To ensure that its integrity is maintained, it must be equal in priority to sample acquisition and to subsequent scientific investigations (refs. 1, 2).

THE VIKING EXPERIENCE

The Viking mission provided much information that had a significant effect on the design of this protocol—primarily the negative results in various tests designed to search for life. The most dramatic indication that Mars is without life comes from images that portray the planet's surface as barren and devoid of large life forms. Detailed studies of these images by Levinthal, Jones, Fox, and Sagan (ref. 6) concluded that no evidence, direct or indirect, has been obtained for macroscopic biology on Mars. This statement may be qualified by the fact that total visual coverage for both landers was an area of 56 km², representing 4×10^{-7} percent of the planet's surface. In addition, the resolving power of the camera ranged from 1.0 mm at a distance of 1.5 m, to 2 m at the horizon, 3 km away.

Because there are areas on our planet that could yield images as sterile-appearing as the Viking pictures, a more significant series of tests involved searching for microscopic life forms in the soil. Even the harshest and most barren terrestrial locations have microscopic life forms sequestered within soil, rocks, or ice. Rather than attempting direct observation for microscopic cells, these tests attempted to observe chemical changes in the atmosphere and in the soil, changes that could indicate the presence of organisms capable of metabolism (refs. 7 through 10). The three different metabolic experiments were based on the assumption that Martian life would be similar to terrestrial life, and that such life, if present, would be metabolically active under the environmental conditions provided within the spacecraft. The experiments were: carbon assimilation (ref. 7), designed to detect photosynthesis; gas exchange (ref. 8), designed to detect metabolism, and labeled release (ref. 9), also designed to detect metabolism. Although the results of these experiments were not altogether in agreement, the findings could be explained on the basis of inorganic chemical reactions (ref. 10). Because metabolic experiments are perhaps the most sensitive methods available for detecting life (ref. 11), it is imperative that experiments similar to those flown on

TABLE 4-1.—COMPOSITION OF THE LOWER MARTIAN ATMOSPHERE

Gas	Percent Abundance
CO ₂	95.32
N ₂	2.7
Ar	1.6
O ₂	0.13
CO	0.07
H ₂ O (vapor)	0.03 (variable)
Ne	0.000 25
Kr	0.000 03
Xe	0.000 008
O ₃	0.000 003

TABLE 4-2 —THE COMPOSITION OF MARTIAN SOIL

Element	Percent Abundance
O	42
Si	21
Fe	13
Mg	5
Ca	4
Al	3
S	3
Cl	0.7
Ti	0.5
K	0.25

Note Percentages do not total 100 percent. Values shown reflect relatively inexact Viking measurements.

the Viking mission be conducted on return samples, but under more sensitive and controlled conditions.

The negative interpretation of the metabolic experiments appears to be in agreement with the inability of the Viking instruments to detect any organic carbon in the Martian soils (ref. 12). However, this latter result does not necessarily eliminate the possibility of organic life in the samples tested (see the discussion on page 9). If on Mars there is little free organic carbon present in the soil, then a relatively large number of bacteria might not be detectable with the mass spectrometer. If most of the organic carbon were located within bacteria the size of *Escherichia coli*, for example, the soil sample could have contained as many as 100 000 cells and still have yielded negative results in this experiment. What this Viking experiment does indicate is that the search for life during the quarantine will be more difficult because life forms are not likely to be present in large quantities.

In addition to the direct and indirect search for life conducted by Viking, there were several other investigations performed on the Martian atmosphere (refs. 13, 14) and soil (refs. 15 through 17) that yielded information that should be taken into account when planning the experimental design of the protocol. The lower Martian atmosphere has been shown to be composed primarily of carbon dioxide, with little nitrogen and trace concentrations of other gases (table 4-1); its pressure ranges between 0.006 and 0.0077 atm (ref. 14).

Knowledge of these values could be useful in the quarantine analysis. If the preliminary gas sample from the sample canister demonstrates a variation from these data, it could indicate either metabolic processes occurring after containment or leakage of the container to space. In addition, the knowledge of the atmospheric composition and pressure will be used to simulate the Martian atmosphere during several phases of quarantine protocol.

The Martian soil has been shown to contain water; it appears to be weathered, and it is continually blown about by the wind. Table 4-2 shows the major elements detected and their abundance, in percentage of sample weight (refs. 15 through 17); samples taken from both landing sites were found to be approximately the same.

Increased knowledge of the soil composition and its chemistry will assist the quarantine investigations by permitting accurately simulated soils to be prepared to test the various biologic systems in the protocol for compatibility with the material.

RATIONALE FOR PROTOCOL DESIGN

The possibility that living organisms exist on Mars that could directly affect man, animals, plants, or microorganisms, or could in some way subtly upset the Earth's biological or geochemical cycles, can be guarded against by a logical, well-designed protocol (ref. 4). The experience of the LRL and the information gained from the Viking missions provide a significant basis for designing a quarantine protocol. The development of the testing procedure for the protocol was guided primarily by four considerations.

First, protecting the biosphere from back contamination becomes extremely difficult once a sample has entered the biosphere. So-called remote Earth facilities are remote only in terms of human population. There is no such thing as an *ecologically* remote

facility on the Earth. Thus, a nonterrestrial facility can provide significantly greater protection than a terrestrial one.

Second, quarantine testing should consume the minimum quantity of soil necessary to provide accurate hazard assessment, while the remainder of the sample is protected from forward contamination or accidental alteration. Thus, experiments with maximum sensitivity for life and hazard detection should be chosen.

Third, life forms, if they exist on Mars, are most likely to be present in low concentrations. Therefore, any assessment of hazard must be based on attempting to detect such forms. Increasing the population of any forms detected, prior to exposing them to challenge cultures, would provide a more sensitive test than simply exposing a large number of terrestrial species to Martian soil.

Fourth, in a quarantine protocol, human error is the most common cause of failure. Therefore, experiments should be selected that require the minimum number of persons to handle the sample.

THE PROTOCOL

Planning Mechanisms: GERT

Processing of the Martian sample involves a complex series of tests (the protocol) that are interdependent and have a variety of possible courses of action and outcomes, depending on the results obtained at each stage. To illustrate this testing sequence, the Graphical Evaluation and Review Technique (GERT) symbology developed by A. A. B. Pritsker (ref. 18) is used. The advantage of this visual representation method over the traditional flowcharts is that the information can also be used to estimate the probability of certain outcomes occurring (ref. 19).

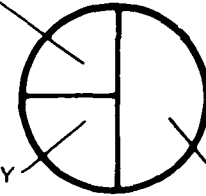
GERT symbology graphically presents test activities and information flows in the sequence in which they are to be executed or generated (in the case of information flows). Activities and information flows are represented in the figures as direct lines that are numbered according to the nature of the activity. An activity is initiated by an event (or events) and ends with the occurrence of another event. In the graphs, the events are represented by a structure (an event node) which may be of two shapes (figure 4-1). A circular event node indicates that at the completion of a given number of the activities leading to the node

DETERMINISTIC NODE

NUMBER OF ACTIVITY COMPLETIONS FOR 1ST NODE REALIZATION

NUMBER OF ACTIVITY COMPLETIONS FOR 2ND AND SUBSEQUENT NODE REALIZATIONS

NODE IDENTIFICATION NUMBER (Keyed to the step within the protocol)



PROBABILISTIC NODE

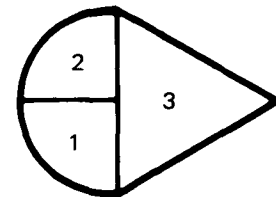


Figure 4-1.—Event node symbolism. Circular nodes indicate that if the required preceding event (or events) occurs, then the event (or events) leading away from the output side will also occur. The pointed output indicates that the subsequent path to be followed depends upon the outcome of the events that led to the node—at least two alternative paths are possible. A node that has been activated by events is said to be realized.

(i.e., the node is realized), the next activity will be initiated: such a node is called *deterministic*. The nodes that resemble horizontal teardrops indicate that the next activity to be initiated depends on the results of the preceding activity. Such a *probabilistic* node has at least two different activities leading away from it, which one is followed depends on the experimental results that activated the node.

In its richest form, GERT permits either analytical reduction or computer simulation of the procedures represented by the GERT network. One may then estimate expected times for completion, expected use of consumables (i.e., sample, time, power, equipment,

etc.), and the probabilities associated with different outcomes. It is the latter use of GERT that assumed a major role in this study because it was possible thereby to calculate the sensitivity of the various protocol tests at detecting different levels of microbes contained within a soil sample. The GERT symbology is used throughout the remainder of this chapter to illustrate the sequence of protocol steps and to show how various experimental outcomes determine subsequent testing and (or) decisions. An overview of the complete protocol is shown in figure 4-2. Subsequent GERT charts present a detailed view of events within each discrete phase of the protocol. Each of these following charts thus elaborates upon a particular segment of the overview shown in figure 4-2. A detailed explanation of how the GERT symbology is applied to a specific protocol, using the chemistry program as an example, is presented in Appendix A. Appendix A also includes estimates of the probability that each of the protocol steps could successfully detect a microorganism.

Outline of the Protocol

The quarantine protocol requires 46 g of soil to complete the first-order testing. Statistical calculations based on the proposed protocol indicate that the 46-g quantity provides reliable results: Regardless of the sample size returned, a representative sample of 46 g is sufficient for first-order quarantine testing.

As was mentioned earlier, the OQF and the quarantine testing protocol have been designed for flexibility regarding the "packaging" of the returned sample. The discussion of sample manipulation and preparation that follows assumes the most likely possibility: that a sample canister is received that contains 10 separately collected and sealed subsamples. In this scenario, a quarantine sample for use in the protocol could consist of either (1) one of the 10 subsamples, with the others held in storage under pristine Martian conditions, or (2) a representative sample formed by mixing portions of all 10 subsamples. Because there are advantages and disadvantages in both approaches, the equipment and procedures described here have been designed to allow for either choice. Whether the 100-g sample used in the protocol is composed of one intact subsample or 10 g from each of the 10 subsamples will not affect the execution of the protocol, except for those preliminary handling

steps that are involved in preparing the sample. For example, if a composite quarantine sample is to be used, then gas samples would need to be collected from all 10 subsample vessels, rather than from just one. Preparation of the composite quarantine sample would follow gas sampling.

Figure 4-3 illustrates a proposed division of soil from a 1 kg sample return, with 100 g dedicated to quarantine testing. Of that amount, 54 g would be reserved for second-order testing if required. Nine hundred grams of the 1 kg sample would be stored under pristine conditions for basic scientific study after the completion of quarantine testing. This distribution of material is deemed essential because the orbiting facility has been developed to certify that the Martian sample is safe to send to Earth, and not to perform basic scientific research. As much sample as possible must be available for research in laboratories on Earth once the sample has been certified as safe; the quantity used for quarantine testing must be kept to a minimum.

When the Martian sample is received in the OQF, this procedure (figure 4-4) would be followed:

- A gas analysis of the contents of the sample canister and individual subsample container(s) will be performed.
- The quarantine sample will be removed and analyzed for radioactive materials. If radioactive levels do not constitute a health hazard, the sample will be prepared (as outlined in figure 4-4), and larger particles will be visually inspected using a stereomicroscope.
- The chemical analyses will be performed.
- The metabolic and microscopic protocols will be initiated using the results of the chemical analyses. (See figure 4-5.)
- The microbiological culture and challenge culture studies will be undertaken.
- The results of the five test phases (chemical, metabolic, microscopic, microbiological, and challenge cultures) will be collected in the data pool for the project and thoroughly analyzed. The results of this analysis can lead to either of two outcomes (figure 4-6): (a) nonterrestrial life forms or uncontrollable toxins (a toxic agent that replicates or is in some manner uncontrolled) are detected, dictating second-order testing; or (b) no such forms are observed, in which case the sample is released to a containment facility on Earth.

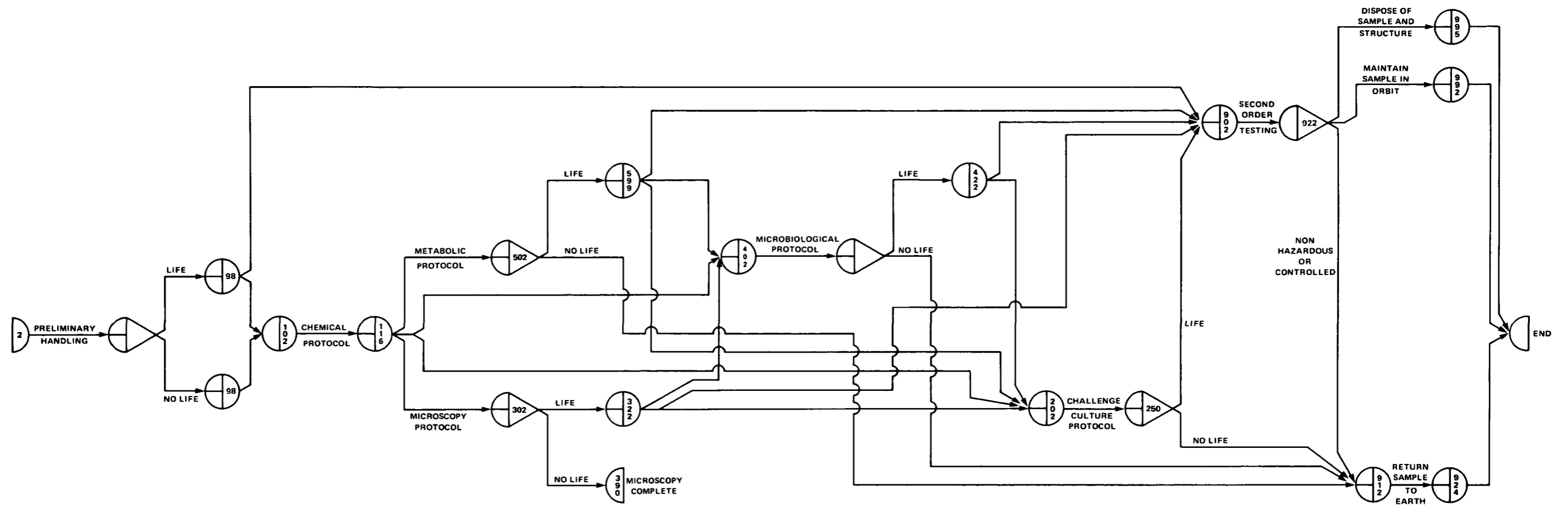


Figure 4-2.—An overview of the entire testing protocol.

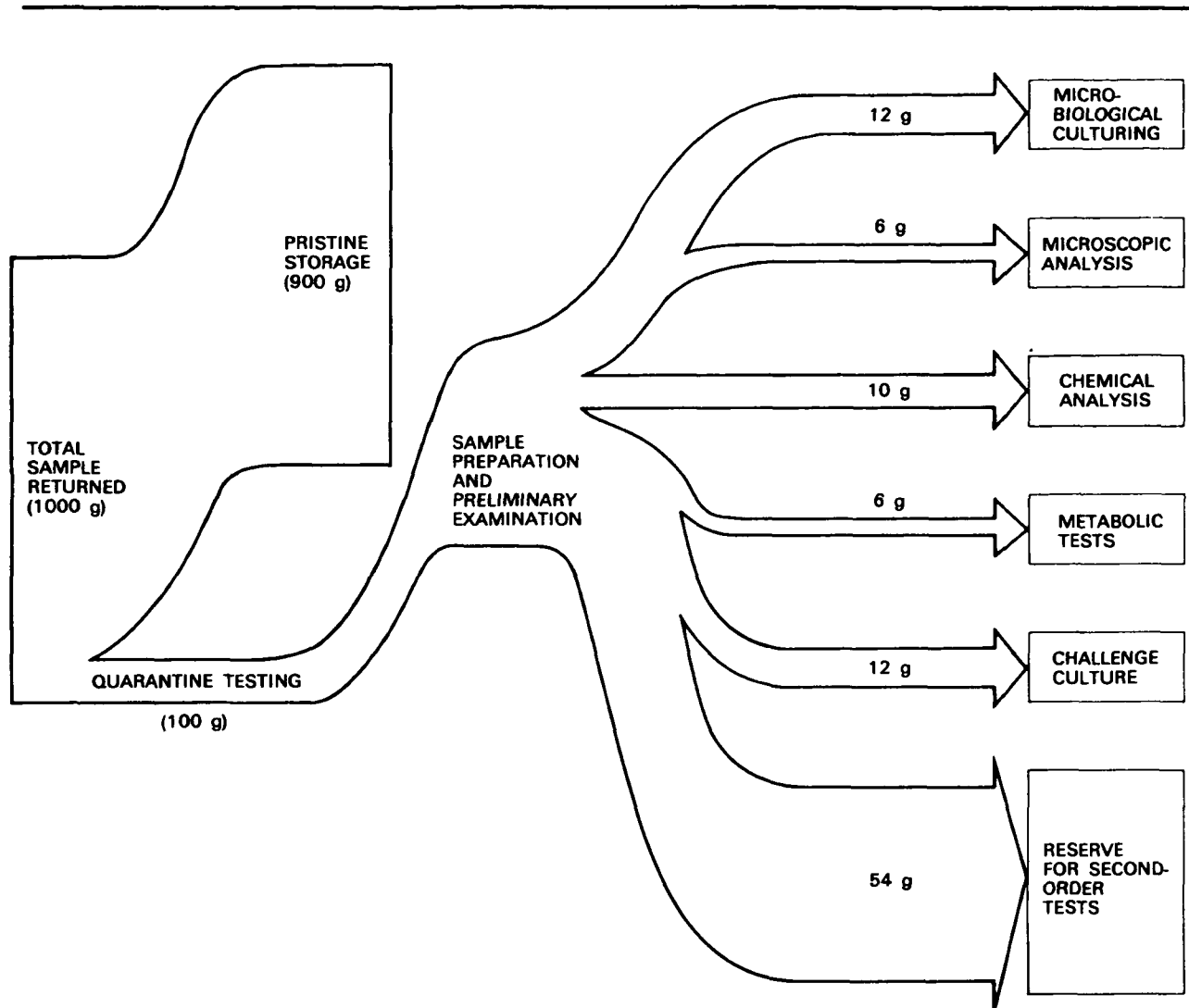


Figure 4-3.—The distribution of the Martian sample to the various experimental protocols.

Preliminary Handling

Prior to sample receipt, the microbial flora of the quarantine facility and the organisms indigenous to the crew will be sampled and identified. The information gained (i.e., species detected) from this procedure will be incorporated into a basic data pool so that, if an organism is detected during the quarantine tests, it can be compared to those species found on board prior to sample receipt to determine if the organism is a terrestrial contaminant.

The preliminary handling of the quarantine sample begins with gas sampling. (See also Chapter 5, Appendix B.) This procedure will provide information regarding the sample history during transit from Mars. The quarantine sample will then be examined for

various forms of radioactivity; because cell cultures may be damaged at abnormal radiation levels, this information will be available to assist interpretation of the cell challenge culture experiments. If by some remote chance the sample is extremely radioactive, provisions have been made for ensuring crew safety.

A cursory stereomicroscope inspection of the quarantine sample, discussed in detail in the microscopy section, is designed to identify unusual portions of the sample that require special handling. Objects such as macroscopic life forms, large fossils, and anomalous structures will either be stored (in the case of fossils) or cultured on media and tissues and investigated with high-resolution microscopy.

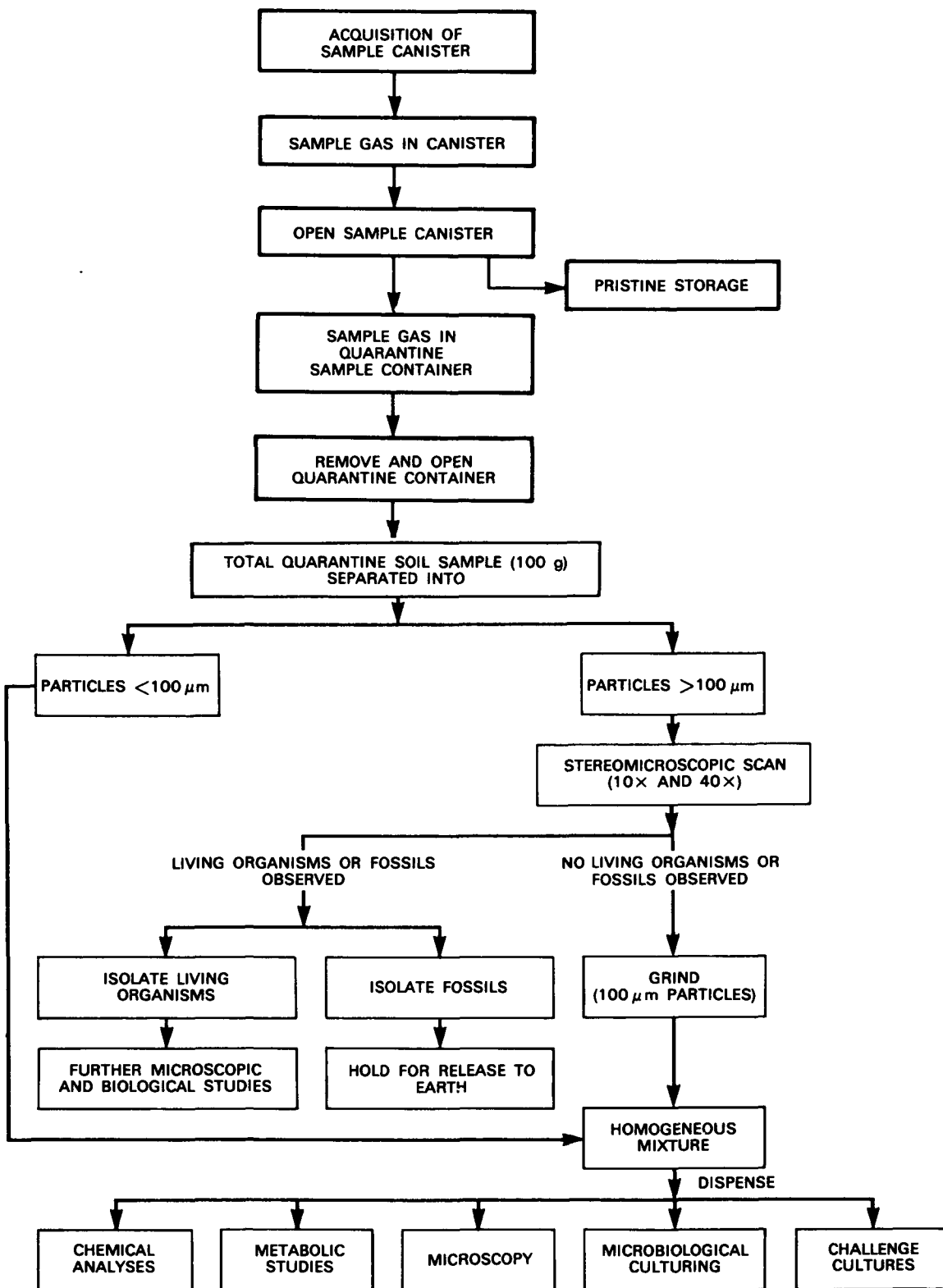


Figure 4-4.—Preparation of the Martian sample for initial cursory microscopic examination and subsequent quarantine testing.

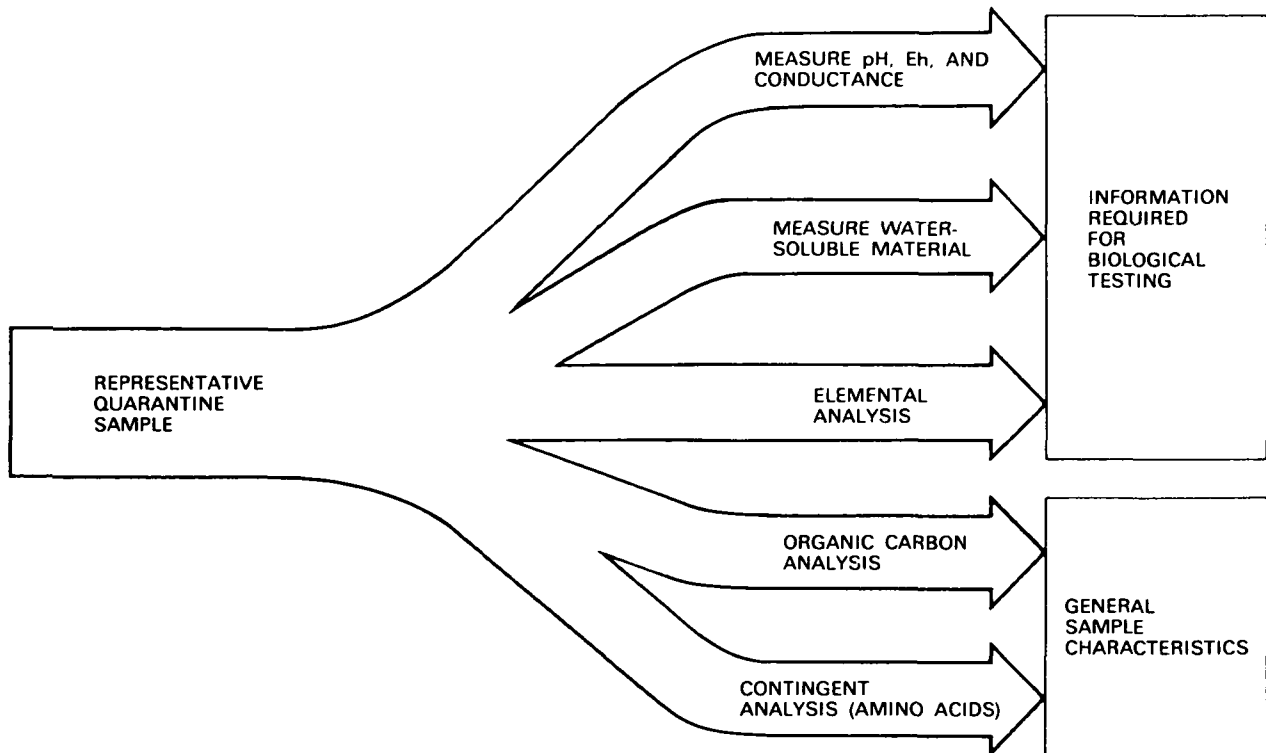


Figure 4-5.—The utilization of information obtained from the chemical analysis protocol.

The remaining sample will be sized, with particles larger than 100 μm reduced to 100 μm size. While grinding soil would appear to be detrimental to organisms in the material, similar procedures performed on Arctic soil (ref. 20) did not significantly reduce the viability of the soil's microorganisms if the temperature was kept below -15°C . The two portions of the quarantine sample will then be recombined and intimately mixed to produce a homogeneous mixture from which samples will be taken for protocol testing. Pooling of the sample will be performed because, statistically, a more precise result is obtained by mixing subsamples and analyzing the mixture than by analyzing the subsamples separately and pooling the results (ref. 21). The homogeneous mixture will be distributed to the five investigation programs, each of which is designed to test for life forms in a different manner: microbiological culturing, microscopic analysis, chemical analysis, metabolic tests, and challenge

culturing. Figure 4-7 illustrates the preliminary handling steps.

Gas Sampling Experiments

Objective: To qualitatively and quantitatively analyze the gases contained in the Mars sample return canister (MSRC) and subsample container(s).

Method: A clean stainless steel sampling container will be connected through a microbiological filter to the MSRC, evacuated, and filled with the sample canister's gas. This gas will be admitted directly into a high-resolution mass spectrometer for qualitative and quantitative analysis and the filter will be retained for subsequent culturing. The bottom of the sample canister will be removed to gain access to the quarantine sample vessels. The gas sampling procedure will then be repeated for the quarantine sample vessel or vessels, as appropriate.

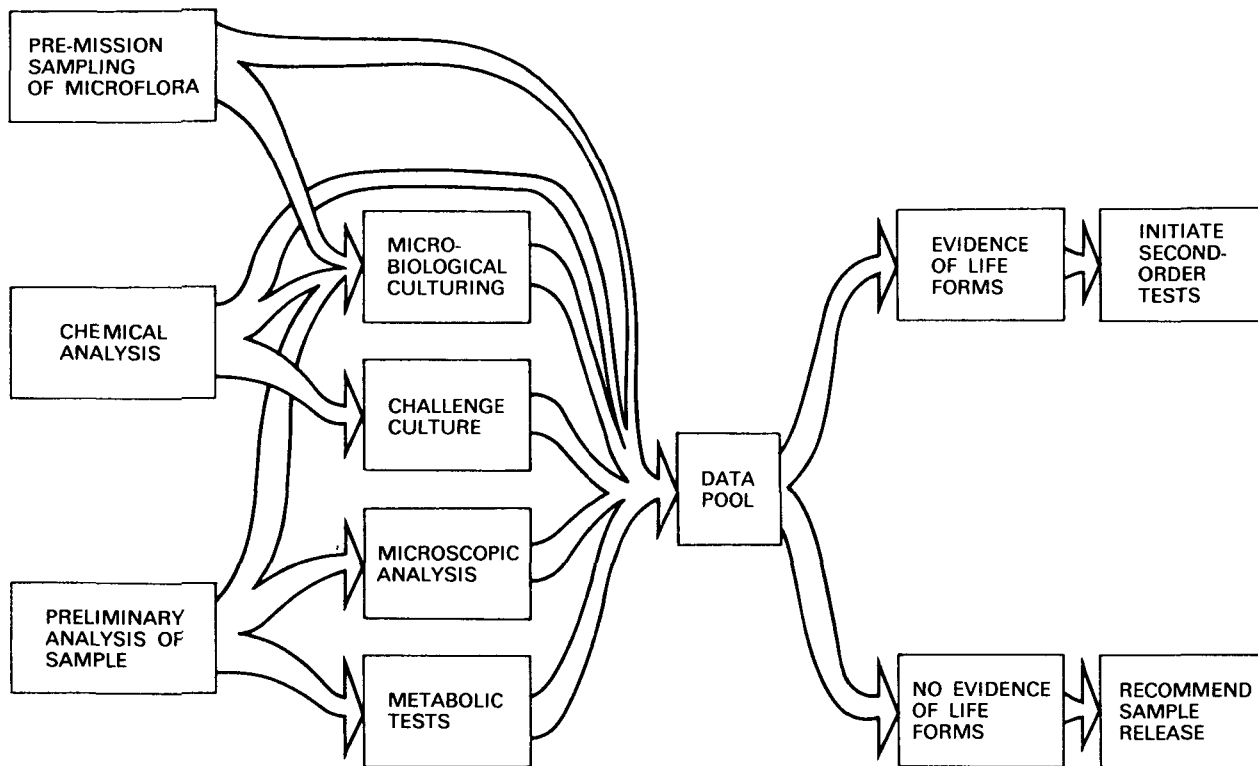


Figure 4-6.—The flow of information from the protocol tests into the mission outcomes.

Rationale: By providing results that can be compared to the atmospheric composition determined by the Viking missions (see table 4-1), this experiment will indicate whether changes have occurred in the atmosphere within the canister or subsample containers during transit. Such changes would be explained in one of four ways: (a) the Martian atmosphere was not in chemical equilibrium with the soil during transit, (b) viable organisms in the container altered the gases, (c) the canister leaked to space during transit, or (d) a combination of possibilities a, b, and c. Any changes in the atmospheric composition could impact subsequent testing in ways that are dependent on the nature of the change.

Even if complete confirmation of the Viking results is obtained, the presence of viable organisms cannot be excluded because organisms could be dormant or present in concentrations so low that atmospheric interactions are negligible.

Design Requirements: Vacuum to 10^{-6} torr, a specialized gas-transfer sample container, and filter and

fittings compatible with the gas chromatograph/mass spectrometer (GC/MS) must be provided. No special procedures are required for zero-g conditions.

Radioactive Decay

Objective To determine the level of alpha, beta, and gamma emission in the Mars return sample.

Method. Signals from scintillation detectors (sensitive to alpha, beta, and gamma radiation) will be amplified and counted (ref. 22). After determining background radiation, replicate 250 mg samples of Martian soil will be counted for 20 min in the alpha-, beta-, and gamma-sensitive wells. Samples found not to be highly radioactive will be returned to the quarantine sample.

Rationale The cell challenge experiments are affected by radiation, so that prior knowledge of the sample's radioactivity could prevent possible misinterpretation of cell challenge experiments. In addition, even though the Viking results indicate low radiation levels,

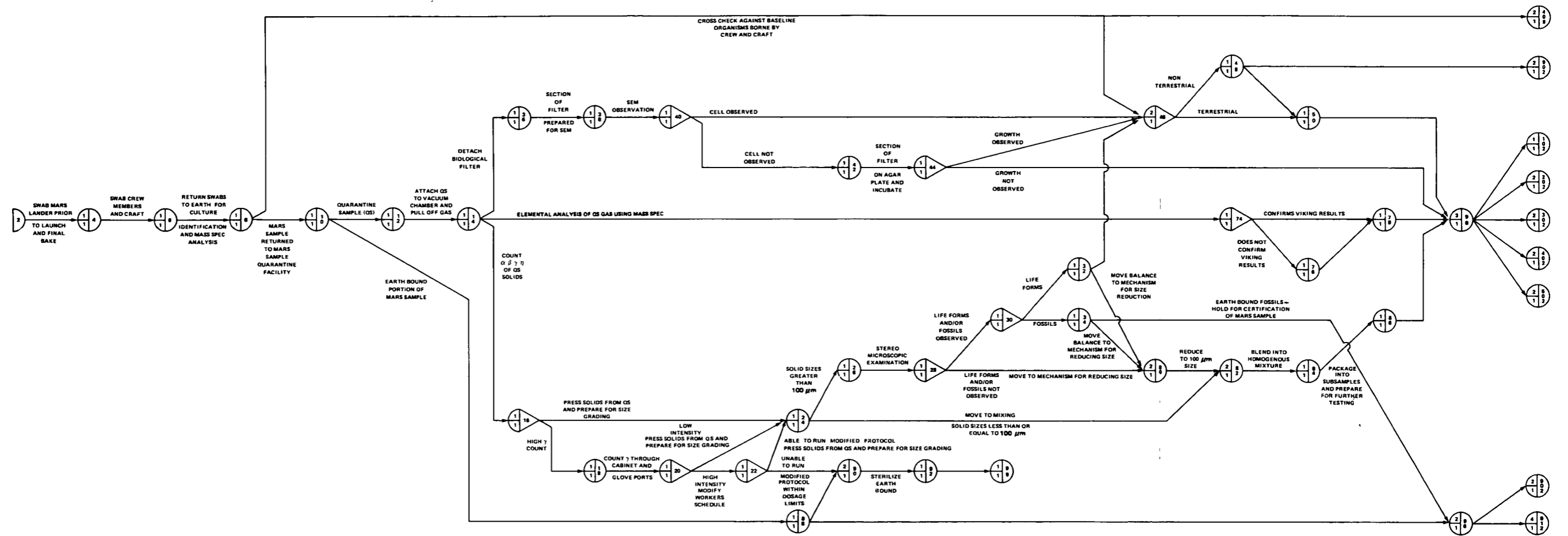


Figure 4-7.—The preliminary handling of the Martian return sample.

ensuring crew safety requires that counting procedures be performed.

Design Requirements: The equipment for this experiment is currently available, although verification of these instruments for space flight would be essential.

Chemical Analysis Protocol

A set of chemical experiments has been developed to support the biological testing sequence as well as to identify organic compounds that could be associated with life processes. Material necessary for all the chemistry experiments will be taken from the homogeneous quarantine sample. It is anticipated that, with replicate experiments, approximately 10 g of the quarantine sample will be used.

A set of five experiments, designed to identify some general soil chemical characteristics, was selected to identify possible adverse reactions of cell culture and media to Mars soil exposure. The pH, Eh, and conductance measurements are to be made by first wetting the soil for pH and Eh analysis, followed by filtration and collection of the supernatant liquid for conductance measurements. The soil sample will be thoroughly extracted with water and, after being evaporated to dryness, the soluble material will be analyzed for its chemical constituents by an alpha particle instrument. This instrument is capable of detecting 99 percent of the elements found in rocks and soil, in most cases to the parts per million range. Organic carbon analysis will be performed by direct pyrolysis of the soil into a mass spectrometer. If fragmentation peaks characteristic of complex organic compounds such as amino acids are observed, an amino acid analysis will be undertaken. This analysis involves a series of extraction and concentration steps, with the final product analyzed by GC/MS techniques. This experiment has the potential for identifying the biotic or abiotic origin of any amino acids found.

Figure 4-8 illustrates the chemical protocol steps.

Measurement of pH, Oxidation-Reduction Potential, and Conductance

Objective: To determine the pH, oxidation-reduction potential, and conductance of the sample.

Method. One gram of sample will be analyzed using Colorado State University Soil Testing Laboratory

techniques (refs. 23, 24). The soil is moistened with distilled water and, after 1 hour, the pH and oxidation-reduction potentials of the slurry are measured with electrodes. The soil paste is then vacuum filtered, and the supernatant liquid is placed in a conductivity bridge. Because these measurements are nondestructive, the sample is stored for future use.

Rationale: Any given species of terrestrial organism survives in a relatively narrow range of pH, oxidation-reduction potential, and dissolved salt concentration. Thus, when preparing media for challenge organisms, it is imperative that these parameters of the Martian soil be known.

Design Requirements:

1. pH and oxidation-reduction potential measurements. A container must be designed that is capable of holding 1 g of Martian soil to which 1 ml of distilled water can be added. This container must be capable of sequentially accepting two sets of electrodes that contact the moistened soil: the standard glass-membrane reference electrode used for measuring pH and an electrode for oxidation-reduction measurements, each compatible with an expanded-scale pH/millivolt meter.
2. Conductivity measurements. The vacuum-filtered supernatant liquid will be placed on a conductivity cell and measured by a standard conductivity bridge.

Aqueous Extraction

Objective: To determine the total weight of aqueous extractable materials and identify water-soluble elements.

Method. A 250 mg sample will be weighed to the nearest 0.1 mg and combined with 5 ml of distilled water. After being agitated for 10 minutes and centrifuged to cause particles to settle, the supernatant liquid is decanted, vacuum-passed through a preweighed fine-porous-glass filtering crucible, and saved. After this procedure is repeated three times, the total sample will be washed on the filter (the wash water is saved), air dried, and weighed in the filtering crucible. The sample will be repeatedly washed, dried, and reweighed until a stable weight is achieved (i.e., within 1 mg). The total weight of soluble material can then be calculated.

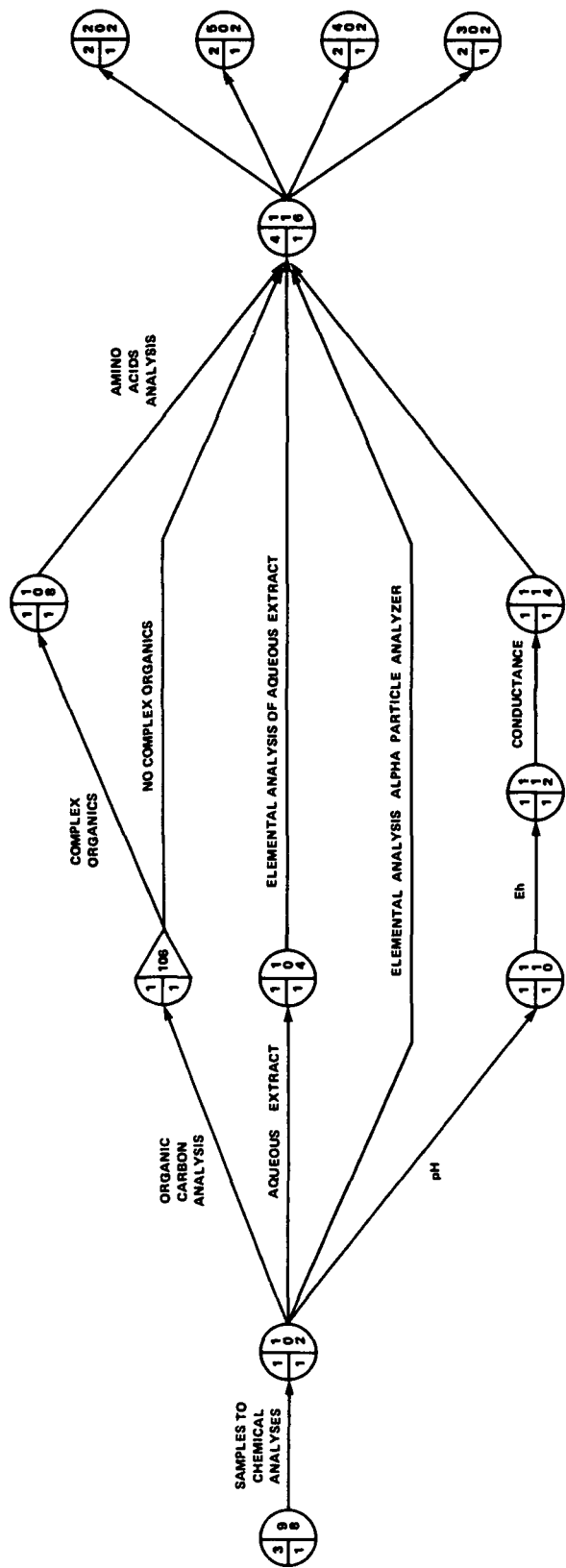


Figure 4-8.—The chemical testing protocol.

The supernatant liquid and the wash water will be evaporated to dryness and the elemental composition of the remaining material determined using the alpha particle instrument (ref. 25).

Rationale. To anticipate possible changes in the challenge cell culture that are caused by certain elements dissolved from the sample, it is important to know what material is extractable by water from the soil

Design Requirements A system must be developed to allow intimate mixing of the soil and water. In addition, a centrifuge, vacuum filtration system, and evaporator will be needed.

Elemental Analysis

Objective. To perform qualitative and quantitative analysis of the elemental content of the quarantine sample.

Method. The analysis is based on the use of an alpha particle instrument with alpha, proton, and X-ray modes developed by Economou and Turkevich (ref. 25). A 600 mg soil sample is held so that it covers the instrument sample tray, the space between the sample and the instrument head is evacuated to 1 torr or less, and the sample is assayed. Upon completion of the analysis (6 to 12 hours), the sample will be stored for possible future use.

Rationale. Elemental analysis is desirable on the quarantine sample to identify concentrations of elements that may interfere with media developed for challenge organisms. The results of this experiment will be compared to similar analyses done on the Viking missions (ref. 17), confirming the soil's elemental composition.

This particular method of analysis was selected because 99 percent of the elements (other than hydrogen) present in igneous or sedimentary rocks can be identified and determined without destroying the sample (ref. 25). The instrument is ideal for space experiments because it weighs only 2 pounds and will be available for other elemental analysis should any be necessary.

Design Requirements: Computer interfacing for control logic and memory storage will be necessary, along with a mechanism for maintaining the sample on the

sample tray during analysis. A vacuum system and a cryostat will also be essential for the functioning of the instrument.

Organic Mass Spectrometry

Objective To measure the volatile organic carbon contained in the quarantine sample.

Method: The analysis for volatile organic carbon in the quarantine sample will be done with a quadrupole mass spectrometer, capable of a resolution as high as 4000, which is controlled by an on-line computer. The computer will also record data, calibrate the mass scale, normalize spectra, and control the visual display of the spectrum.

Approximately 50 mg of Martian sample will be weighed to an accuracy of 0.1 mg and heated to 500° C in a nickel container inside an oven connected to the mass spectrometer ionization chamber. The system will be calibrated with 1, 2, and 3 ppm samples of n-tetracosane.

Rationale. The presence of significant levels of organic carbon in the Martian soil could indicate life forms. If organic carbon is found, attempts will be made to isolate and identify specific amino acids. The absence of organic carbon in the soil sample may be used to add credibility to negative evidence from the biological protocol.

Design Requirements: A method for filling, weighing, and transferring the soil samples to the sample oven must be devised that ensures that the sample is kept free from organic contaminants.

Amino Acid Analysis

Objective. To identify and characterize possible amino acids present in the quarantine sample.

Method. The method is based on reports by Lawless et al. on amino acid analysis of meteorites (refs. 26 through 29). A 5 g sample of pulverized quarantine sample will be sealed in a stainless steel tube with 40 ml of water and heated to 110° C with agitation for 20 hours. Upon cooling, the water will be removed by filtration and the solid washed with additional water. After the sample is dried, the procedure is repeated with 40 ml 6N HCl instead of water. The dried, esterified sample is redissolved in water, charged on a

Dowex 50 (H⁺) ion-exchange column, and eluted with water and 2N NH₄OH. The NH₄OH eluate is evaporated to dryness, and amounts as low as 2 × 10⁻⁹ g of N-trifluoroacetyl esters will then be identified by the GC/MS system.

Rationale: If the quarantine sample is found to contain complex organic compounds, it must be determined whether these compounds arose from life forms (ref. 30). Because amino acids are the building blocks of terrestrial life, the presence of a variety of amino acids in the sample would suggest that they were generated by life forms, although other sources are possible. The lack of amino acids indicates that terrestrial-type life forms, at least, are not present.

Design Requirements: The techniques for extracting and concentrating the sample in zero *g* (i.e., filtration, hydrolysis, reflux, and evaporation) must be developed.

Microscopic Examination of the Martian Soil

For many centuries microscopy has been an important tool for visualizing biological microstructures. The basic power of microscopy lies in the ability to vary magnification, light illumination, and stains to permit enhancing the appearance of a specimen. As has been argued by Soffen and Sloan (ref. 31), microscopic observation can be an important tool for detecting microscopic life forms in Martian soil, especially if Martian life has a chemical basis different from the carbon-based chemistry of terrestrial life forms. Microscopic observations of the sample will offer information about the soil structure (e.g., regularity, size, and morphology) as well as characteristics of replicating, viable, dead, or fossilized biological forms (ref. 32). Assuming that there are microorganisms in the Martian soil, it should be possible to visualize them when using a combination of light, phase contrast, and electron microscopic techniques, especially when different dyes are used to enhance the difference between cells and particulate matter. Thus the burden of research lies in defining what methods will offer the highest levels of discrimination and detection of life forms. Many advances have been made in the techniques for microscopically examining soils, and the methods can be applied to the present protocol.

First, dry untreated soil or stained samples will be microscopically observed *in situ* to determine if cells

are adhering to soil particles. (Terrestrial bacteria often cannot be separated from soils by sonication or centrifugation without destroying cellular membranes or lysing organisms.) Then, if the results are negative, the chances of observing cells will be increased by attempting to wash the organisms off the soil particles so that they will be more visible. A variety of microscopic techniques as well as staining methodologies will be used to provide the maximum chance of differentiating any cellular material from debris. In brief, the methods of microscopic observation selected to examine the Martian soil samples are:

1. Initial stereomicroscopic observation of large, untreated Martian soil particles;
2. Scanning electron microscopic observation of filters on which soil was collected,
3. Light and scanning electron microscopic observation of the homogeneous soil sample (dry soil and supernatant of soil), both stained and in its natural state;
4. Ultraviolet illumination of the sample to observe fluorescent stains and to test for chlorophyll-induced fluorescence.

Figure 4-9 illustrates the microscopy protocol steps. The probability of successfully detecting life using the microscopic protocol is shown in table 4-3 (Appendix A).

Stereomicroscopy

Objective: To provide gross examination of the Martian sample in a pristine condition under a light stereomicroscope.

Method: The sample will be separated according to soil particle size. Soil particles larger than 100 μm will be transferred into a transparent container, examined by a stereomicroscope at 10× and 40× magnifications while under a Mars-like environment, and documented. Any fossils or life forms observed will be transferred into separate containers by a remote manipulator for further observation under high-resolution microscopes. If none are observed, the sample will be ground and homogenized for use by the remainder of the protocol.

Rationale: This step is designed to prevent the grinding of any life forms or fossils that are larger than 100 μm.

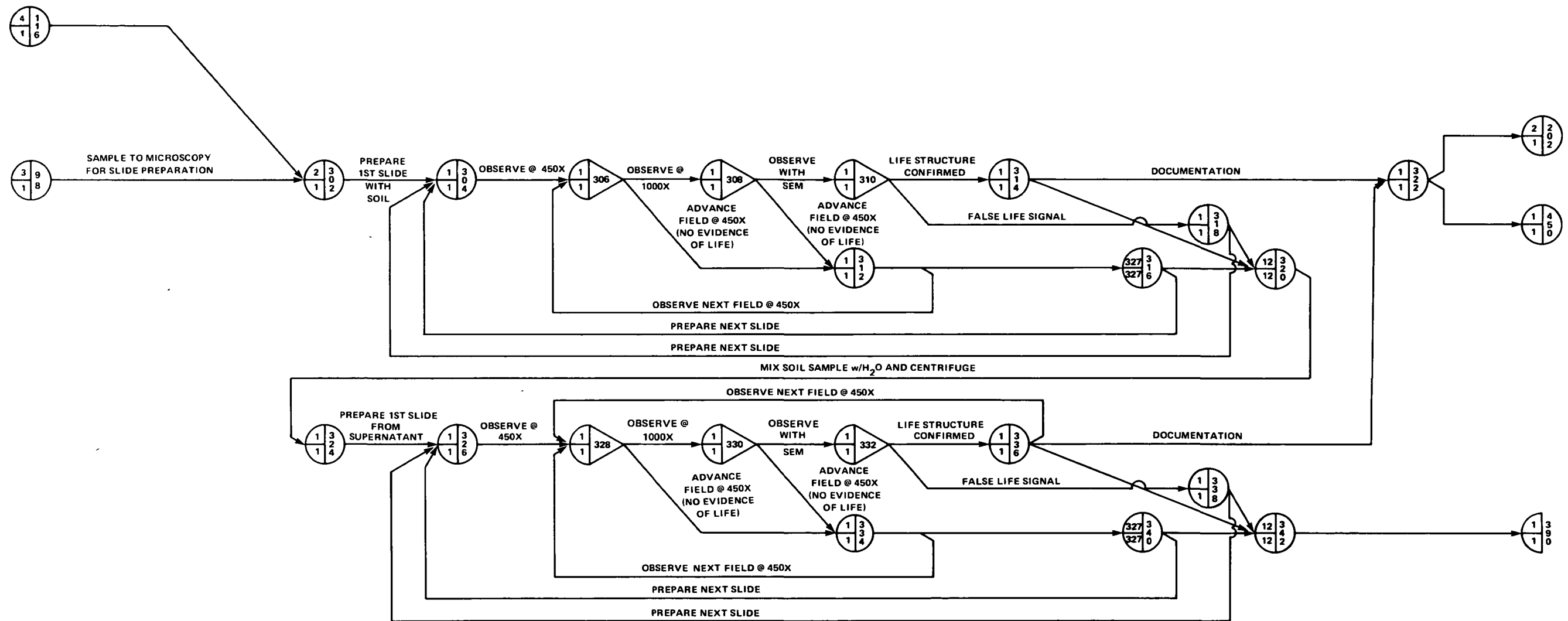


Figure 4-9.—The microscopy protocol.

Design Requirements. Stereomicroscope with photographic and automated video (TV) scanning capabilities, a transparent sample container, and a mechanical means of removing objects from the sample container are required.

Microscopic Observation of Filters

Objective: To search microscopically for life forms that may have become attached to various bacteriological filters that contact the soil during chemical and biological studies.

Method Sections of the filters removed from the sample containers will be mounted on specimen holders and vacuum evaporated with carbon and gold palladium. Scanning electron microscopic observations will be made of randomly sampled fields (10 percent of the entire area) at 500 \times while suspicious areas will be observed and photographed at magnifications of 1000 \times to 5000 \times . Other sections of the filters will be embedded on agar plates, and after incubation the plates will be observed microscopically.

Rationale. During experimentation in zero *g*, soil particles and organisms may have drifted and impacted on the container's filters. Scanning electron microscopy rather than optical microscopy is adopted because a scanning electron microscope has a depth of view about 300 times greater than optical microscopes (up to a few millimeters), has been used successfully for examining filters (ref. 33), and permits viewing at 1000 \times or greater magnification (ref. 34).

Microscopic Observations of the Homogeneous Sample

Objective: To use many different microscopic systems to maximize the chance of visualizing any life forms in the sample (figure 4-10).

Method The initial direct observations of the sample are made on unamended soil specimens. Slides with dry material, a smear of soil suspension (1 g soil with 1 or 2 ml of sterile water), and slides of soil smears prepared with several different stains are suggested for observation. The selection of specific stains should be based on the differential properties of dyes in their capabilities for staining various cellular materials (e.g., membrane, nucleus, etc.) and their ease of application. Actual selection of stain may be made according to the

following dye characteristics: (a) variations in the dye's molecular weight—low (<300), average (300 to 500), and high (>500); (b) acid, basic, or amphoteric dyes, (c) sensitivity to different cellular membranes and cellular material, and (d) the counterstaining properties. Simple stains such as methylene blue, phenolic rose Bengal, aniline blue, carbolfuchsin, India Ink, and capsule stains (e.g., Anthony's stain) have been successfully used to view microorganisms in soil (refs. 35, 36, 37). Nucleic acid dyes such as toluidine blue or azure B may be used to stain cellular materials such as DNA. Fluorescent stains such as fluorescein isothiocyanate, acridine orange, or Mg-ANS are valuable methods for tagging microorganisms in soil because these tend to stain those microbes that do not react to more conventional stains (refs. 38 through 42).

The slides are prepared for observation following standard techniques for staining and fixation, modified for zero *g* use.

1. A smear of untreated sample is observed under light, phase contrast, ultraviolet, and scanning electron microscope.
2. In general, simple stains for light and scanning microscopic observations are preferable.
3. Fluorescent dye stains are also suggested for fluorescence microscopy observations.
4. In addition to the above stains, specific slide preparations for scanning electron microscopy observations are also suggested. Soil specimens for scanning electron microscopy are generally prepared with glutaraldehyde fixation and freeze-drying or freeze-etching methods, and then vacuum coated with gold palladium. Slides prepared for light microscopy can also be viewed by a scanning electron microscope after they are vacuum coated with gold palladium or carbon (ref. 43).

Samples will be observed using a light, phase contrast, and ultraviolet-fluorescent microscope at 450 \times , and at 5000 \times with the scanning electron microscope. For each specific slide, a 10-percent sample of fields should be photographically documented, and suspicious fields observed at a greater magnification. If any cell-like object is observed on a specific slide, repeat observations will be made on duplicate slide preparations. Attempts to culture the organisms will then be intensified while the organism's characteristics are compared to those of the known terrestrial contaminants of the OQF. If the soil specimen slides show no cell-like objects, then a small

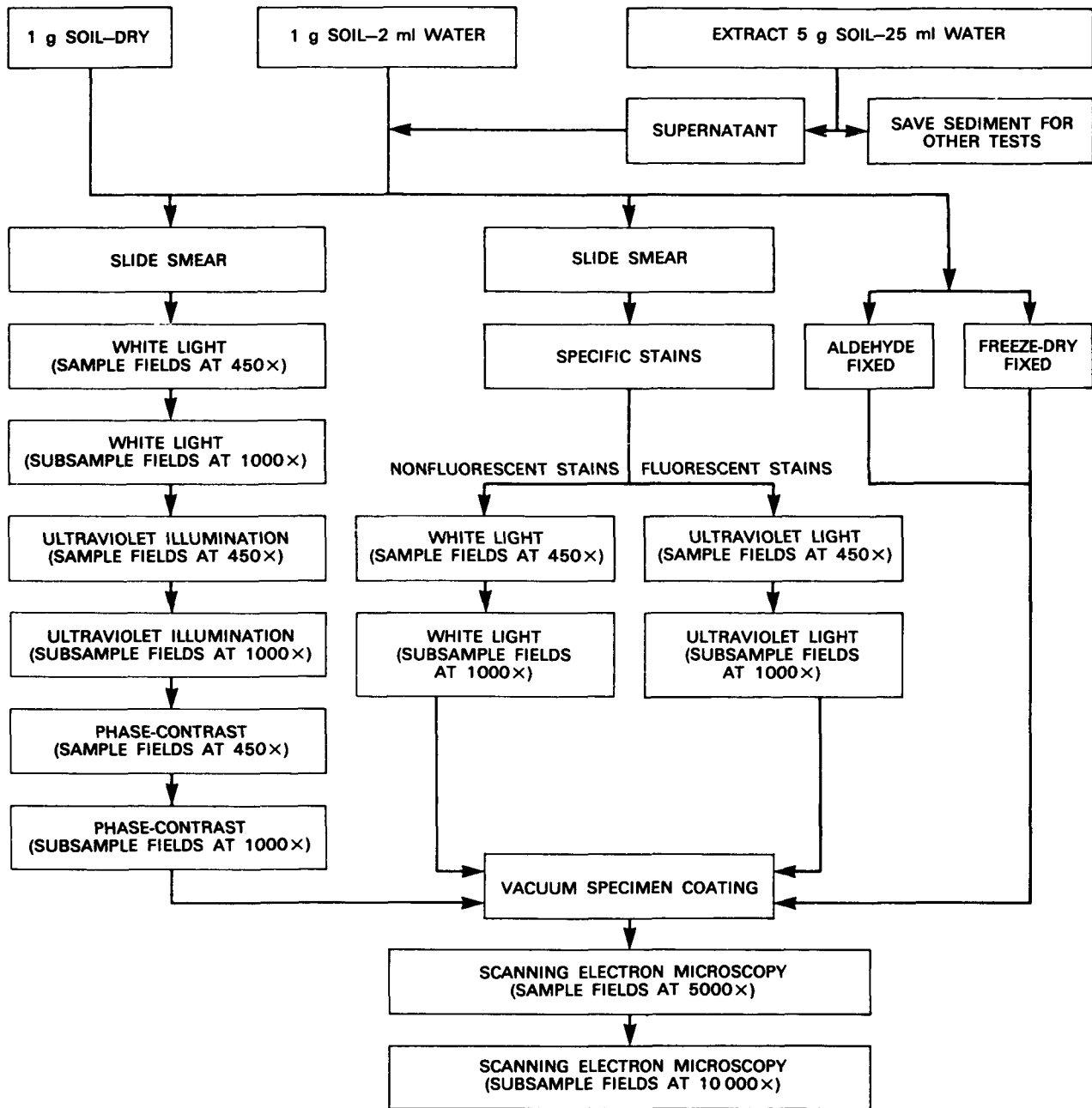


Figure 4-10.—The sequence of events involved in the microscopic examination of the sample.

amount (5 g) of soil will be combined with 25 ml of sterile water and centrifuged to separate the particles and supernatant. This supernatant will be stained and observed as described above.

Rationale: Any living organism that is larger than 100 Å (the limit of resolution of a scanning electron microscope) should be observable under microscopic

light illuminations and (or) electron-imaging systems. Bright-field light microscopy using stained and unstained soil smears has been successfully utilized to identify microorganisms of varying sizes in soil (refs. 35, 44, 45). Infrared color photomicrography of unstained soil smears, using a bright-field transmitted-light microscope, offers an additional imaging system for identifying microorganisms (refs. 46, 47). Phase

contrast microscopy can also discriminate microbial forms from soil mineral fragments when used at varying amplitudes (ref. 48). In addition, ultraviolet fluorescence microscopy, with selected stains, offers an ability to visualize some microbial forms that cannot be detected by white-light microscopy (ref. 44). Although the threshold for microscopically detecting microbial forms depends on their concentration in the soil (refs. 49, 50), it has been suggested that scanning electron microscopy can be used to examine suspect areas observed by light microscopy because higher resolution and magnification permit differentiation of soil particles from microbial forms or microfossils (refs. 51 through 54). Small microbes adhering to soil particles, as well as fractions of microbial forms, can be viewed with a scanning electron microscope more successfully than with conventional microscopy (refs. 55 through 57). In addition, various methods of preparing soil specimens will offer different conditions under which different microbial forms become more visible.

Design Requirements and Instrumentation:

1. *Conditions*—Slides will be viewed under Earth-ambient conditions. The sample must remain in the containment cabinetry while the viewing takes place remotely, from outside the cabinet.
2. *Microscopes*—The optical microscope used should be capable of white-light and ultraviolet illuminations, and should have a phase contrast capability. Magnifications are required at the levels of 100 \times , 450 \times , and 1000 \times .
The scanning electron microscope (SEM) must provide magnifications of 5000 \times to 10 000 \times and the accelerating voltage requirement may be 10 to 50 kv. It is necessary to have a high-vacuum evaporation chamber for specimen coating techniques.
3. *Slide preparation requirements*—This area, enclosed within the specimen holding cabinet, must have the following equipment and supplies: drying oven with a timer and a capability of 50° C to 110° C; freeze-drying chamber, centrifuge, staining kits (like those developed for Skylab) (ref. 58) containing dyes, washing agents, mordants, solutes, and drying agents, and microbial kits containing micropipettes, droppers, blotters, glass slides and covers, and petri dishes. An automated video (TV) scanning and photographic attachment will be available for each microscope, with built-in program for a random

sampling procedure consisting of a specified number of field-photographs per slide.

Ultraviolet Microscopy

Objective. To detect the presence of chlorophyll-like pigments in soil samples by their fluorescence.

Method: During the microscopic investigation of the Martian sample, a long-wavelength, ultraviolet light will be used to illuminate the sample. Any areas that are fluorescing will be viewed with greater magnification to determine if they result from pigment fluorescence.

Rationale: Any technique that could call an observer's attention to potential life forms within the sample would be valuable, especially when the procedure does not involve any additional effort. Because chlorophyll is known to fluoresce at a very characteristic visible wavelength and because chlorophyll that is not actively involved in photosynthesis (such as would occur in a dormant organism) would fluoresce more intensely (ref. 59), the presence of this pigment could be easily detected. Because naturally fluorescing minerals could mask any chlorophyll effect and a nonchlorophyll photosynthetic pigment would not be expected to fluoresce, the possibility of negative results is fairly great. However, the simplicity of the procedure warrants its inclusion in the protocol because it would provide powerful assistance to the microscopic survey.

Metabolic Experiments

The techniques selected for this phase of the work are based heavily on the Viking experiment (refs. 7 through 10) and involve the detection of various metabolically derived products emanating from samples held under a simulated Martian environment. The rationale behind these experiments is that if an organism is provided with the proper growth conditions, it will multiply and eventually its progeny will be numerous enough to alter the sample's atmosphere and soil chemistry, permitting detection of the changes. These proposed experiments, however, rely on analytical equipment that has a much greater sensitivity to various gases and organic compounds than did the Viking instruments, thus reducing the amount of growth or metabolism needed to permit detection. The most general assessment will be for

evidence of any gas change above the soil; the kinetics and patterns of any observed changes can be used to differentiate between biotic and abiotic soil activity. Evidence of CO₂ deriving from various radioactively labeled organic substrates will be measured because carbon-based life forms would be expected to release CO₂ as the substrate is consumed. Furthermore, some of the labeled atoms would be expected to become incorporated into the organisms, thereby permitting their detection by autoradiographic techniques. This latter test phase assumes that autotrophic life forms would have to be an essential component in the soil in order to prevent the eventual depletion of organic compounds due to catabolic activity. Thus, evidence of the incorporation of radioactively labeled CO₂ into organisms will be sought. Finally, soil samples from all tests will be assayed using the GC/MS for changes in organic carbon levels at the termination of each phase of incubation.

To enhance the possibility of life detection, a series of environments that simulate conditions expected on Mars will be used to maximize the probability of inducing germination or permitting growth. Thus, diurnal cycles of light and temperature will be altered gradually from Martian winter to summer conditions. Because moisture may be a limiting factor to a Martian organism, low levels of moisture will be made available to the soil during the winter phase in one experiment and during the summer phase in the other, this dual approach is used because there is some disagreement about the season in which the maximum levels of free water would occur on Mars. In addition to low moisture content, low levels of organic compounds in the soil may also limit the growth of organisms in the Martian soil. Furthermore, it is possible that the low atmospheric oxygen levels may restrict growth, since oxygen could be critical for the production of metabolic water. Thus, experiments involve modifying various aspects of the sample's temperature, light, moisture, and nutritional environment in the hope that conditions essential to Martian organisms will be attained and growth or increased metabolism will result.

The metabolic experiments are designed to be performed in two parallel sequences using a minimal amount of sample. By proper development of the conditions around the sample, a large number of environmental conditions can be established without consuming additional Martian material. Obviously, if at any particular photoperiod/temperature regime/moisture content/nutritional status/gas concen-

tration, evidence of life is detected, these factors will be adjusted to optimize the growth.

The probability of detecting life forms by the metabolic tests is shown in table 4-4 (Appendix A). Figure 4-11 illustrates the metabolic protocol steps.

Gas Exchange Experiment: Dry Phase

Objective: To determine if temperature and photoperiod are environmental factors that limit the growth of Martian organisms (as determined by measuring changes in gas composition).

Method: The soil sample is electrostatically held in the bottom of a metabolic chamber, beneath a window transparent to visible and infrared light. The soil is maintained in a dry state and exposed to a light/dark cycle approximately equal to that of the Martian winter at the sample collection site. The day/night temperature fluctuations within the chamber would mimic those expected on Mars several centimeters below the soil surface. The photic and thermal environment is gradually shifted over several weeks to those conditions assumed to prevail during the Martian summer. Throughout the experiment, a sample of the Mars-like gas above the soil is periodically withdrawn through a microbiological filter and analyzed by gas chromatography for CO₂, O₂, N₂, and an inert gas standard that is used to calibrate the equipment. The microbiological filter will be microscopically investigated for trapped organisms.

Rationale: The germination of many spores and seeds on Earth is dependent on their exposure to the proper temperature and (or) light regime. Thus, by gradually modifying these environmental parameters from winter to summer conditions, the environmental stimulus necessary for germination and growth may be attained. By passively monitoring the gases above the sample, it should be possible to detect any shifts in their ratios (refs. 60, 61). By not adding water initially, a gas release caused by a reaction of the soil with water (such as is believed to have occurred with the Viking experiment) should be avoided. Although the lack of exogenous water may not permit germination, arguments could be made that enough metabolism should occur in its absence to permit noticeable gas changes.

If no gas changes are noticed, the data serve as baseline information for successive experiments. However, observation of gas changes would then be

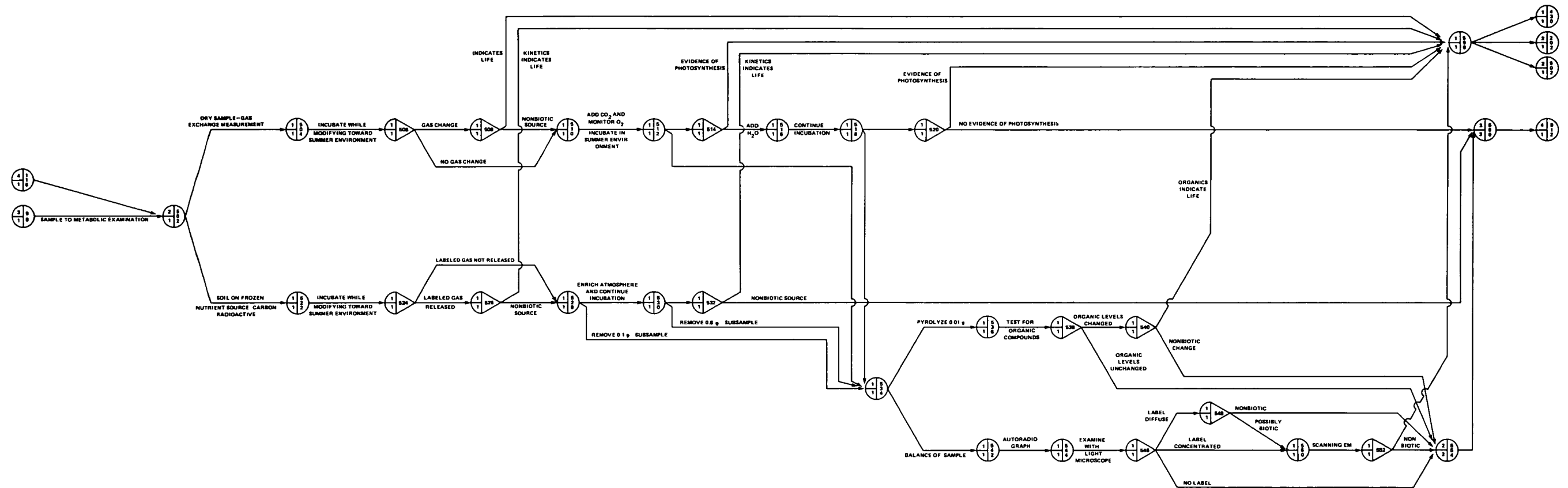


Figure 4-11.—The metabolic testing protocol.

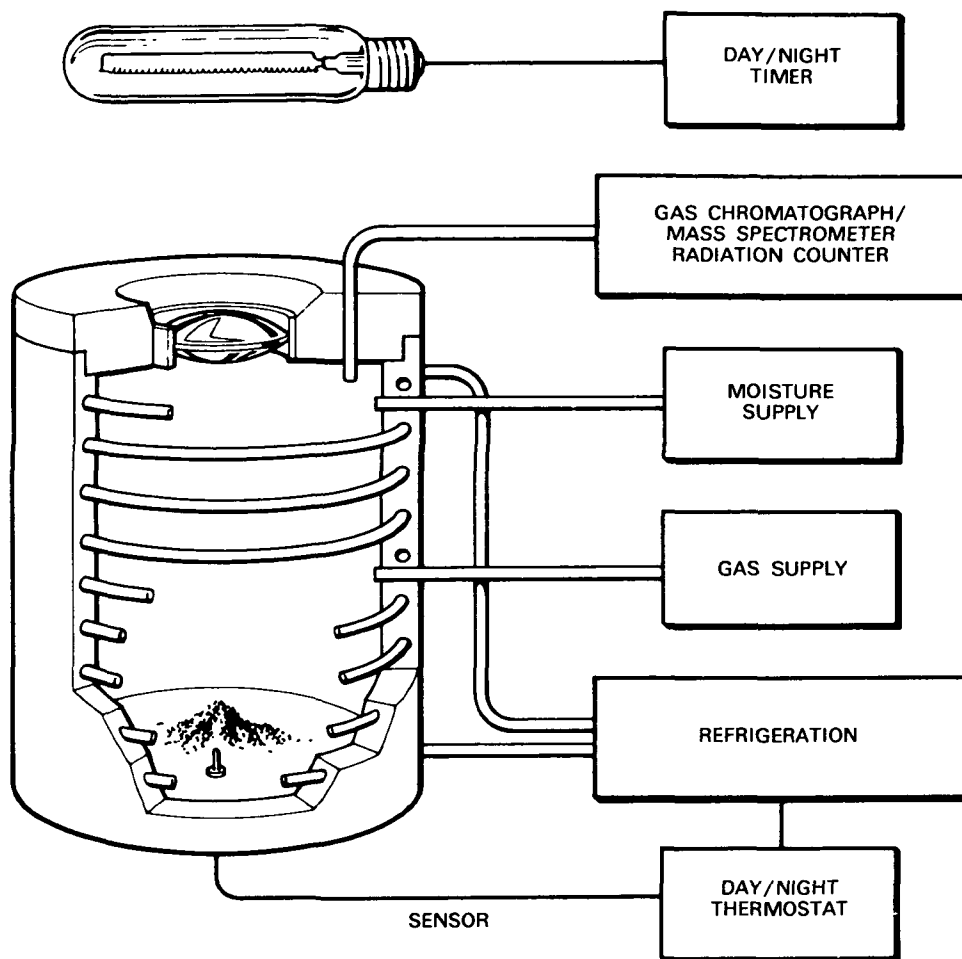


Figure 4-12.—A schematic diagram of the metabolic chamber.

followed by detailed kinetic studies to determine whether they were due to biological or nonbiological activity.

Design Requirements: A gas-tight chamber capable of holding 1 to 5 g of soil and about 50 to 100 cm³ of atmosphere at Martian pressures will serve as the metabolic chamber (figure 4-12). The soil should be held on one surface by electrostatic charge, and the opposing surface should have a window that is transparent over the range of 380 to 2000 nm. A light source that mimics the sun's spectral composition will be used, and the intensity at the soil surface should approximate solar radiation at the surface of Mars. A gas sampling port, sealed with a 0.3- μ m bacteriological filter, will permit samples of the gas to be taken. Two additional filtered ports will permit adding gases or moisture during later experiments. If possible, a soil

subsample could be removed without disrupting the chamber's gaseous interior. The interior of the chamber will be capable of having diurnal temperature cycles that may range from -40° to +30° C.

CO₂ Fixation Experiment: Dry and Moist Phase

Objective: To determine if atmospheric carbon dioxide is incorporated into Martian soil when exposed to diurnal light and temperature cycles.

Method: The dry soil sample within the metabolic chamber will have small amounts of radioactively labeled carbon dioxide gas added to the chamber. The temperature and light cycles will be gradually modified from early Martian spring conditions to midsummer. Periodically, the gas composition above the sample will be monitored to determine if significant

changes of gases occur, especially in oxygen levels. Then the sample will be gradually humidified to provide increased amounts of water, and incubation under summer conditions will continue. At the end of the incubation period, a subsample of the soil will be removed, checked by autoradiography, and assayed for organic carbon.

Rationale Autotrophic growth of organisms would be essential in a world where organic compounds are not readily available in the environment. Thus, if an autotrophic organism that uses carbon dioxide has germinated, it would remove some of the labeled gas and incorporate it into its own organic compounds (ref. 7). Furthermore, because the splitting of water is the first chemical event in terrestrial photosynthesis, moisture levels to which the organisms are exposed may be very critical, therefore, the soil should be gradually changed from dry to humidified.

Photosynthesis would be detected through the presence of labeled organic compounds in the soil, since oxygen is not necessarily released during photosynthesis.

The Viking results indicated that soil chemistry may have caused a nonbiological carbon fixation that could confound gas exchange experiments; thus, in addition to kinetic studies on gas incorporation, and GC/MS analysis of the soil for organic carbon, autoradiographic techniques would be used to permit visualization of any regions fixing carbon, to determine if biologically active organisms were present.

Design Requirements. See "Gas Exchange Experiment: Dry Phase."

Metabolism of Organic Compounds: Nutrient Enrichment Phase

Objective. To determine if organic nutrients are decomposed to CO₂ with kinetics that are indicative of living organisms.

Method: A mixture of organic compounds with labeled carbon atoms will be formulated, based on the organic composition of the Martian soil, if no organics are detected at a level of sensitivity greater than was possible in Viking, then nutrient mixtures based on the content of meteorites will be used. The mixture will be frozen in a metabolic chamber at a temperature that would be expected to occur below the soil during a Martian winter. The light and temperature diurnal

cycles will be gradually modified during incubation to attain Martian summer conditions. The amount of carbon dioxide gas containing a radioactive label will be assayed periodically. Since, according to the Viking results, some labeled gas is expected to be released, kinetic analysis and temperature effects on the rate of production could indicate whether or not the release is the result of biotic reactions. Finally, a subsample of soil will be removed and studied with both autoradiography (to determine if any label is concentrated within organisms) and the GC/MS (to assay for metabolic by-products).

Rationale Under Martian conditions both moisture and organic nutrients may be limiting to growth. By providing both elements over a variety of environmental conditions, it may be possible to establish the conditions essential for growth or metabolism. As metabolism begins, labeled CO₂ should accumulate in the atmosphere, and as growth continues, the levels should reach a point where the gases are readily detectable (ref. 9). Autoradiographic investigations of a soil sample will identify concentrations of label and permit their microscopic visualization. In addition, assay of the organic compounds by GC/MS would indicate if new organic metabolic by-products were formed.

Design Requirements. See "Gas Exchange Experiment: Dry Phase."

Metabolism of Organic Compounds: Enriched O₂ Phase

Objective. To determine if the metabolic destruction of nutrients is enhanced by small increases in O₂ levels.

Method The sample used in the nutrient enrichment phase will have a 2- to 5-fold increase of O₂ added to the atmosphere, and will continue incubation under a Martian spring-to-summer environment. The release of labeled gas will be monitored throughout incubation, and, at the conclusion of incubation, autoradiographs of the soil will be taken.

Rationale: Oxygen is present in very small amounts in the Martian atmosphere. Although such small concentrations could indicate that life forms do not rely on it in their metabolic pathways, it could also be argued that, like CO₂ in terrestrial systems, the gas may be so

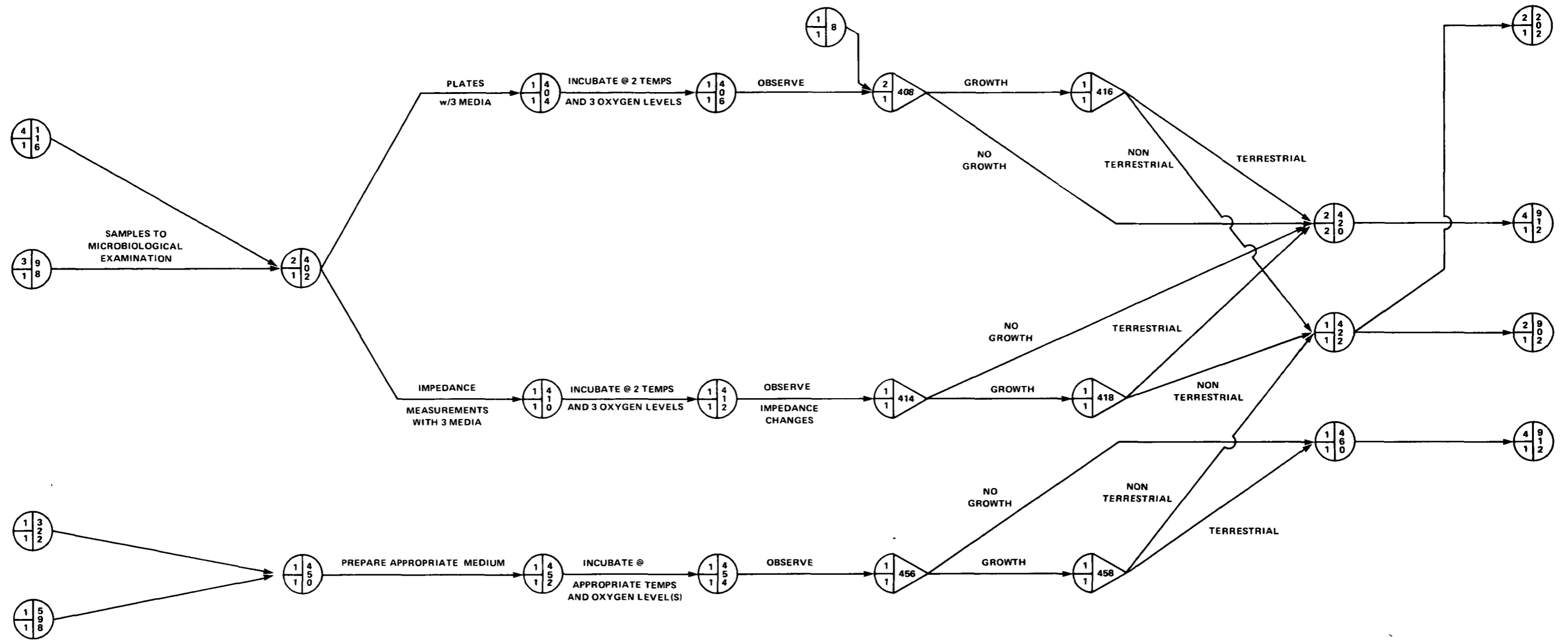


Figure 4-13.—The microbiological testing protocol.

vitaly important to an organism's survival that it is kept at low concentrations by metabolic activity. Given the low moisture levels in the soil, evolutionary pressures would have been enormous for the development of pathways to produce metabolic water using oxygen. Thus, enriching the atmosphere with oxygen may provide the necessary gas concentrations to permit growth.

Design Requirements. See "Gas Exchange Experiment Dry Phase."

Autoradiographic Investigations

Objective: To permit visual localization of radioactive compounds that have been incorporated into the soil.

Method. Soil samples that have been exposed to labeled CO₂ or labeled nutrients will be affixed as a monolayer on a slide. Cursory radiation counts will be used to establish approximate incubation times for exposing the photographic film; a liquid autoradiographic emulsion will be layered over the soil, incubated to permit decaying particles to expose the film, and then developed. The emulsion will be microscopically investigated to determine if there are regions of the slide that have a greater density of radioactive decompositions. Once detected, the soil beneath such areas will be microscopically investigated to determine if the label concentration is the result of soil absorption or biological concentration. Suspicious areas will be more intensely investigated using scanning electron microscopic analysis.

Concurrent with the autoradiographic investigation, a small sample will be chemically analyzed in a manner dependent on its initial treatment. Carbon dioxide incorporation into the soil will be assayed using pyrolysis followed by scintillation counting, if levels of radioactive organic compounds are detected, the sample will be pyrolyzed and analyzed by GC/MS to determine what organic compounds were produced during incubation.

Soil samples to which labeled nutrients were added will be analyzed by pyrolyzing the soil and using the GC/MS to determine if additional carbon compounds were synthesized

Rationale: Incorporation of radioactive compounds into organisms, whether by way of photosynthetic use of carbon dioxide or by metabolic utilization of complex nutrients, results in the organism concentrat-

ing the radioactive label. Photographic emulsion in close contact with the soil will gradually be exposed by the decaying nuclides; microscopic viewing of the emulsion will then permit the localization of areas indicating label concentration.

By focusing through the emulsion, it is possible to investigate the soil regions that resulted in the increased fogging. Such a technique will permit the rapid discovery of soil regions or organisms that are reacting with the various radioactive compounds. Autoradiographic techniques have been successfully used to localize and count metabolically active bacteria present in soils and mixed with debris (refs. 62, 63, 64).

Analysis of the organic compounds within the soil will augment information already obtained on the nature of the metabolic products present in the soil.

Microbiological Protocol

One of the essential parts of the quarantine protocol is to determine whether the Martian soil sample contains viable organisms that can be cultured (refs. 65, 66). Propagation would permit study of the organism's physiology, chemistry, and environmental requirements for growth.

Duplicate assays of the growth experiments will require approximately 12 g of the Martian sample. Subsamples of the soil will be placed on a solid medium that contains a variety of substrates and growth factors. Soil deposited on membrane filters will be either placed on a minimal medium or held in a freezer until other experiments define the proper environmental conditions for growth by demonstrating metabolic activity. Soil subsamples will also be added to various aqueous systems ranging from water to a rich medium and will be monitored for changes in ionic composition (indicating biotic influences) by an impedance device. To find the combination of environmental conditions that permits growth of dormant soil organisms, the cultures will be maintained at two temperature ranges (psychrophilic and mesophilic), while the atmosphere would be aerobic, microaerophilic, or anaerobic. Any indication of growth during these experiments will be pursued by subculturing, microscopic examination, and chemical analysis.

Figure 4-13 illustrates the microbiological protocol steps. The probability of detecting viable extraterrestrial organisms, as predicted by the GERT chart, is shown in table 4-5 (Appendix A).

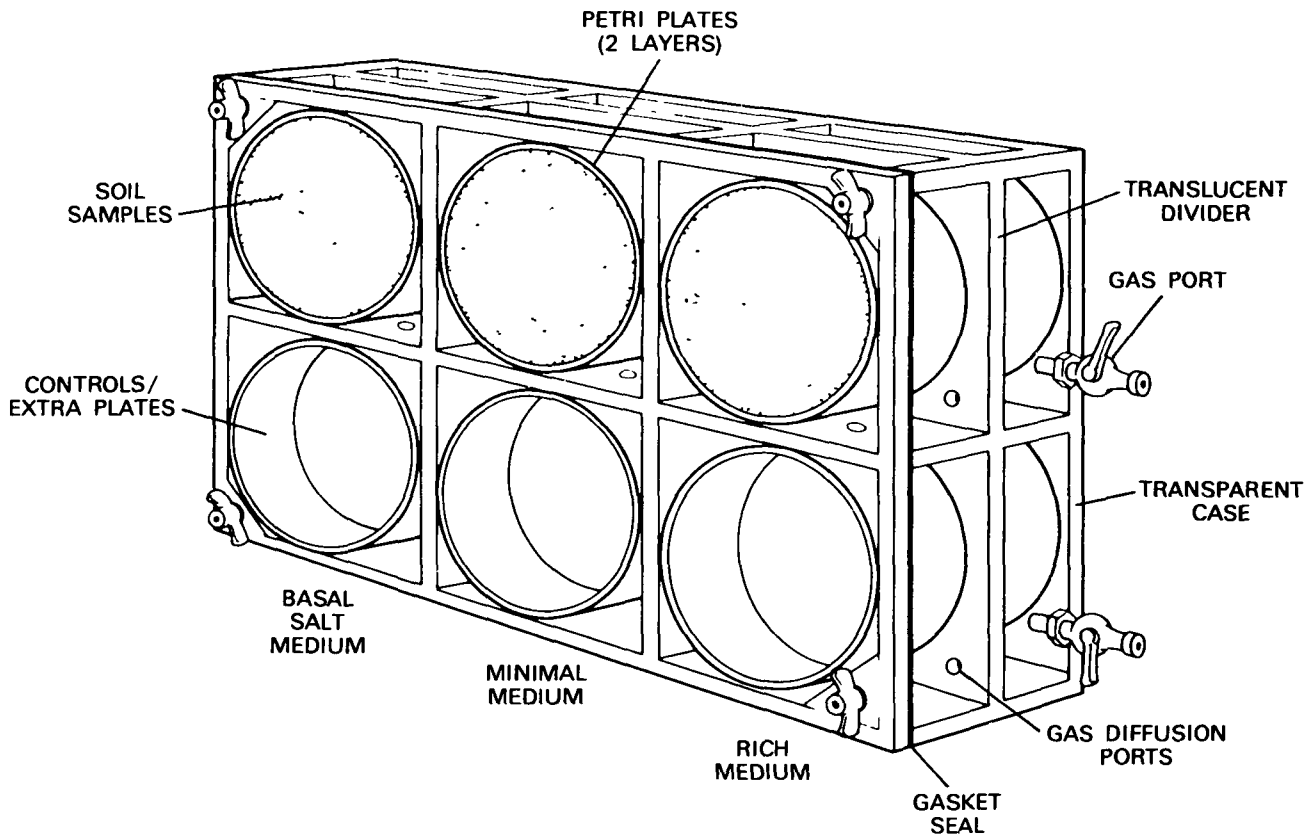


Figure 4-14.—A transparent plastic environmental chamber, designed for maintaining controlled conditions around culture dishes.

Microbial Growth Experiment: Solid Medium

Objective: To determine whether the Martian soil sample contains indigenous microorganisms that are capable of growth under various conditions on a solid medium.

Method: Various types of culture media containing a solidifying agent such as agar or silica gel are prepared on Earth and placed in transparent, gasket-sealed plastic trays to prevent moisture loss, to maintain the gaseous environmental system, and to minimize contamination (figure 4-14). The types of media should include:

1. A basal salt medium based on the Viking soil analyses (ref. 15) containing oxides of silicon, iron, sulphur, and aluminum.
2. A minimal medium containing a few carbon sources such as acetate or formate, glycine, DL-alanine, and basal salts.

3. A rich medium containing several DL-amino acids, vitamins, and growth factors—similar to the M-4 medium used by Oyama, et al., (ref. 60) and to that used in the Lunar Receiving Laboratory at Ames Research Center (ref. 61).

The empirical determination of each type of medium, especially the basal salt medium, will require extensive evaluation.

The soil samples are deposited on duplicate plates of each type of medium in a fashion that disperses them with approximately 3 to 4 mm between soil particles. Two different incubation temperature ranges based on Martian conditions will be used (ref. 67): a psychrophilic range of 0° to 10° C and a mesophilic range of 15° to 25° C. The samples will be incubated under varying gaseous environments (ref. 14), ranging from no oxygen to the oxygen levels present in Earth's atmosphere: i.e., anaerobic (99 percent N₂, 1 percent CO₂), microaerophilic (98 percent N₂, 1 percent CO₂, 1 percent O₂), and

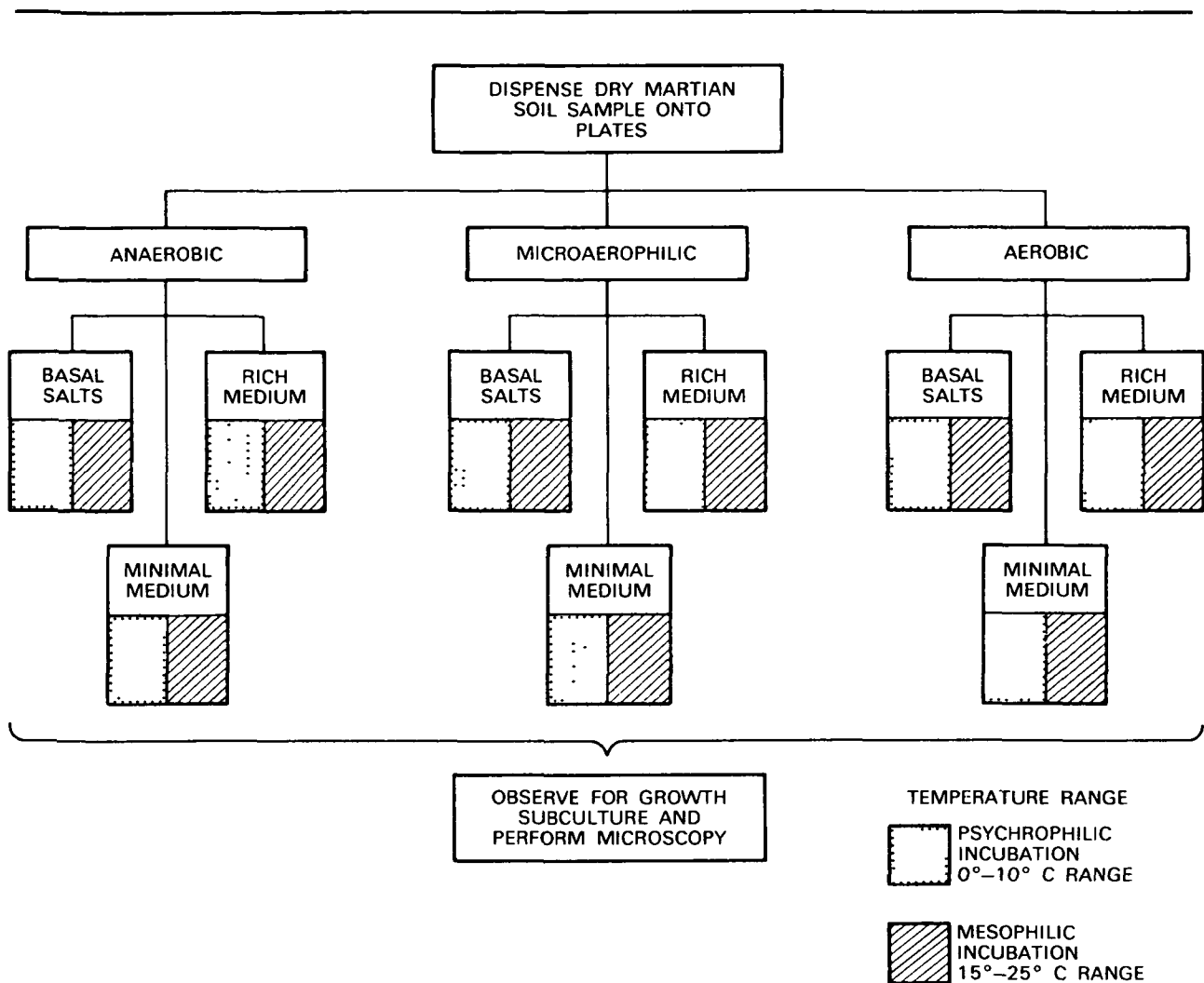


Figure 4-15.—The various environmental conditions under which the Martian soil samples are incubated on plates.

aerobic (78 percent N₂, 1 percent CO₂, 21 percent O₂). The relative humidity in the chambers should be sufficient to prevent drying of the medium. The suggested combinations of media, temperature, and gas environments are shown in figure 4-15.

The sealed chamber (figure 4-14) can be removed from the incubator every 24 to 48 hours and the plates examined for evidence of growth. A stereomicroscope with photographic capabilities can be used to examine the duplicate plates by rotating the chamber 180 degrees. Any evidence of growth, such as the appearance of colonies, would dictate subculturing onto the appropriate duplicate medium and the preparation of slides for light and SEM microscopy. Incubation times of 40 to 50 days are suggested, with each temperature

range starting at the lowest temperature and raised 1° C every 5 days.

The extra pair of culture plates is placed in the chamber for sterility control and for use in the subculture protocol.

Rationale. Any viable organisms contained in the Martian sample are exposed to various environmental conditions that can be found both on Mars and on Earth. The range of conditions may provide the Martian organisms with an environment suitable for growth/reproduction. The soil is not separated from the media because any organisms present may need components from both the soluble and particulate fractions.

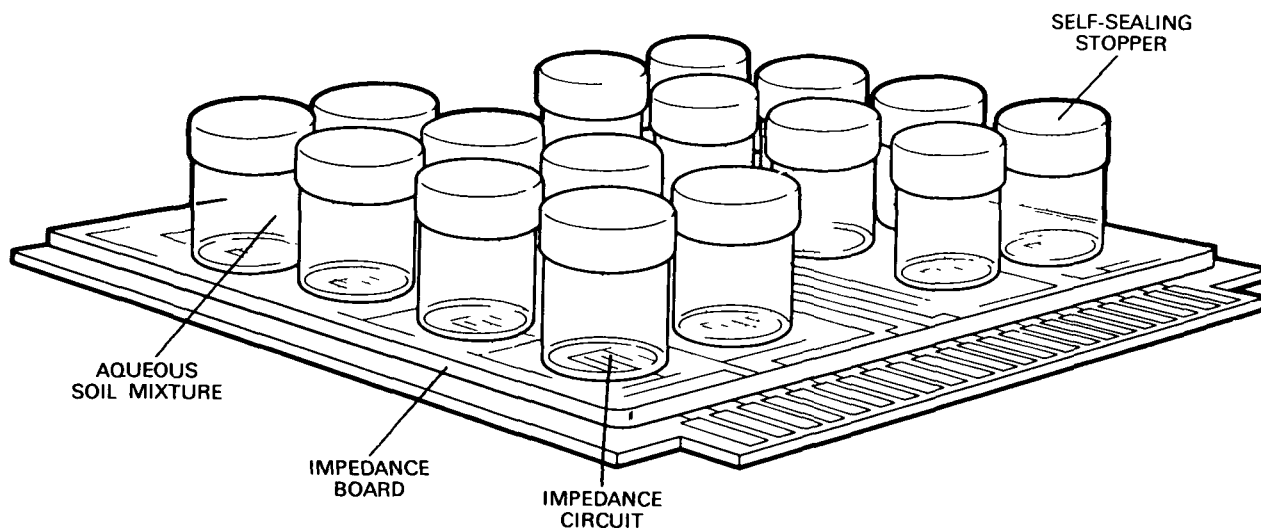


Figure 4-16.—Chambers in which soil samples are continuously monitored for changes in impedance.

Design Requirements. The following are needed for this experiment: a method of dispersing soil samples onto agar plates; stereomicroscope, incubators with two adjustable temperature ranges (0° to 10° C and 15° to 25° C); sterile inoculating loops; 72 50×12 mm agar plates with tight lids; and 6 plastic chambers ($170 \times 110 \times 30$ mm) to hold the petri dishes.

Microbial Growth Experiment: Impedance Measurements

Objective: To detect metabolism by measuring the increases of ionic compounds in Martian soil suspensions.

Method: This experiment, like the previous one, exposes soil suspensions to three different media, three gaseous environments, and two incubation temperature ranges. Procedural differences include wetting the sample with aqueous materials (refs. 20, 68, 69), providing a varied range of nutrients, and recording impedance changes automatically (ref. 70). The required media, gaseous environments, and temperatures are as follows:

1. *Native aqueous system*—A 1.2 g sample of Martian soil is added to 5 ml of sterile, triple-distilled water to make a soil suspension. (The pH, electrical conductivity, and soil composition have been obtained from the chemical analyses.)

Buffering the sample by adding salts of nutrients during incubation is desirable.

2. *Minimal medium*—A medium such as Thornton's salt medium (ref. 20) or a simulated Martian soil medium with minimal organic nutrients is added to 1.2 g of Martian soil.
3. *Rich medium*—A relatively nonionic medium such as phytone or another plant peptone is added to 1.2 g of Martian soil. This medium should also include D-amino acids. In each system, salts or nutrients could be added during incubation.

The three media types will be incubated at 0° to 10° C or 15° to 25° C, and will be exposed to either an aerobic, microaerophilic, or anaerobic atmosphere, thus producing 18 different environments.

Each experimental impedance cell (figure 4-16) is designed to be completely filled by 1 ml of the sample (containing 0.2 g Martian soil) injected through a flexible cover that prevents gas diffusion. During the 30- to 40-day incubation period, temperatures within each range will be increased by 1° C every 5 days. The impedance within each cell is automatically monitored, and if it is different from controls, a sample will be withdrawn, cultured on the appropriate medium and environment, and examined microscopically. Even if no impedance changes are noted, the samples will be microscopically examined for any evidence of growth (ref. 68).

Rationale The use of an impedance system has several advantages: It is an automated system, it requires little crew involvement, it provides continuous readings, and it is sensitive to impedance changes. Such changes are indications that nutrients were converted to lower molecular weight end products that leached out of the organism and altered the electrolyte balance in the medium. Thus, an increase in ion concentration may indicate the activity of viable microorganisms (ref. 71).

Design Requirements: An impedance system such as the one shown in figure 4-16 is required. The 16-chamber unit uses 30 watts and has dimensions of 22 × 22 × 10 cm. The circuit board chambers can be modified for the zero-g laboratory and the system interfaced with a computer. Also needed are devices to prepare the soil-medium suspensions, and to add and remove samples from the chamber.

Growth of Organisms on Membrane Filters

Objective: To determine whether any soil particles collected on membrane filters contain organisms that can be detected by culturing.

Method. Any particulate materials collected on membrane filters used for filtering Martian soils will be cultured on a basal salt solid medium. The culturing plates will be sealed in clear chambers (figure 4-14), maintained at low-temperature (0° to 4° C), in anaerobic conditions, and examined at approximately 5- to 7-day intervals.

Challenge Culture Protocol

A major concern of an MSR mission is the prospect of introducing into the biosphere an agent which is potentially harmful to humans, other animals, plants, or microorganisms essential to the function of biogeochemical cycles (ref. 4). To investigate completely the possibility of such an occurrence would require the exposure of each of the hundreds of thousands of Earth's species to the Martian soil under controlled conditions (ref. 72)—clearly an impossible task in any laboratory facility. However, as was discussed in Chapter 2 (see "Characteristics of Potential Martian Life Forms"), it is reasonable to assume that because Martian organisms have not evolved in the presence of terrestrial organisms, they would not demonstrate a host specificity as is seen with Earth pathogens; if they were pathogenic, then they could attack a variety of

different hosts (ref. 73) and would be detected by use of representative terrestrial organisms as hosts.

The question then arises as to what constitutes a representative organism. In a comprehensive study conducted for the Lunar Receiving Laboratory (the "Baylor Protocol") (ref. 74), 110 species of plants and animals were proposed. This number was reduced by about 50 percent in the actual lunar quarantine (ref. 75), and it has been suggested that it could be lowered even further without reducing the credibility of the results (refs. 1, 72).

In the choice of species for such a challenge, a number of biological constraints are imposed. The organism must grow reliably under laboratory conditions, be a sensitive indicator of pathogenicity, and be well researched so that any change caused by exposure to the sample can be easily recognized.

The small size of the orbiting facility places additional constraints on species selection: Large organisms are unacceptable, as are any test systems that require complex support facilities or a large number of maintenance personnel. For example, the germ-free mice used in the Lunar Receiving Laboratory required five full-time technicians for support, and occupied an area approximately equivalent to that of the proposed orbiting laboratory. An additional problem is that, even using moderately small organisms, the inclusion of enough replicate individuals to provide a statistically significant sample size would result in overwhelming the available space.

The zero-g environment imposes still another constraint. It is necessary to understand not only the normal biology of the challenge species, but the zero-g biology as well. Organisms with minimal reaction to zero g would be preferred to facilitate accurate interpretation of the effects of Martian soil exposure. Most of the organisms challenged in the Lunar Receiving Laboratory would be unsuitable because of anticipated abnormal reactions to zero g that would confuse interpretation of results.

The challenge system selected for this protocol represents a major departure from the system used at the LRL. In the protocol developed for the OQF, whole organisms are replaced by cell cultures. Although the use of cell cultures in the quarantine facility will require a great deal of additional research, because the number of flight-tested species is quite limited, cell culture challenge systems provide several advantages in an orbiting facility.

1. *Sensitivity*—The use of cell cultures permits the application of small quantities of soil while still providing significant concentrations. In challenges of whole organisms, large amounts of soil are necessary because of the dilution provided by the large number of cells in the organism. Also, many of the defense mechanisms that protect whole organisms against pathogens are absent in cell cultures.
2. *Maintenance*—Large numbers of cell cultures can be maintained in a small space. Also, maintenance can, to a great extent, be mechanized. Cell culture systems of similar types were maintained in Skylab for 59 days without any intervention by crew members (refs. 76, 77).
3. *Inoculation*—It is possible to inoculate all of the cultures through their perfusion feeding systems without opening any containers. This reduces the chance of contaminating the culture with extraneous terrestrial organisms. Soil can be mixed with the culture medium and added directly to the cultures. This can be accomplished without the use of hypodermic needles, thus reducing the danger of a crew member's being accidentally injected. (Accidental self-injection is one of the most common causes of laboratory-acquired infections [ref. 78].)
4. *Observation*—With the use of a video camera-equipped microscope, the cultures can be monitored from the ground. This permits careful examination of all the cultures by specialists in the cytology of the challenge cell species. Because the chambers are small, all the cells can be examined rather than just certain sample areas. In addition, the cells can be observed directly without the extensive sectioning and histological preparation required of whole animal and plant tissues.
5. *Growth response*—Whole plants and animals exhibit a wide range of aberrations in zero *g*. Cell cultures have shown little or no aberrations in zero *g* (ref. 79).

The probability of detecting replicating, toxic, or pathogenic responses by means of the challenge culture protocol is presented in table 4-6 (Appendix A). Figure 4-17 presents an overview of the challenge culture protocol steps.

The laboratory is designed to accommodate 10 culture maintenance systems, thus permitting selection of tissues from organisms representing major

taxonomic groups: i.e., procaryotic cells, green plants, fungi, vertebrates, and invertebrate species. Prior to the quarantine, it is most important that the various responses of the challenge species to disease and zero *g* be fully understood.

The following challenge protocol for a mammalian cell line presents the general procedure recommended for the challenge system. Other species would be handled similarly, except that media and environmental conditions must be determined individually for each cell line.

Mammalian Cell Challenge Cultures

Objective: To determine whether Martian soil contains biologically active agents capable of producing diseases in, or reproducing within, cells maintained in culture.

Method The cell cultures used in this experiment should be chosen because they are representative of various life forms, their cultures are stable, they are sensitive to disease, and their reaction to zero *g* is minimal. Human embryonic lung tissue (WI38) has been flown in Skylab 3 (ref. 76), and other commonly grown mammalian cell lines (i.e., African green monkey kidney [GMK] or human embryonic kidney [HEK]) may be flown prior to MSR.

The cells will be maintained on appropriate media in 1.0 ml transparent chambers similar to those used in the Woodland Wanderer 9 system of Skylab 3 (ref. 76). The culture chambers are shown emplaced in the cabinet for the OQF system in figure 4-18. There will be three sets of six chambers for each species. One control set will be exposed to sterilized terrestrial soil, a second control set will be treated with Martian soil that has been dry-heat and (or) radiation sterilized (refs. 11, 80), while the experimental set of six chambers will be exposed to unsterilized Martian soil.

Six hundred milligrams of soil will be mixed with 1.2 ml of the culture medium, and 0.2 ml of the soil-medium mixture will be added to each culture. Prior to the mission all cell lines will be tested for sensitivity to particulate matter and, if unaffected, the culture will receive the mixture of soil and culture media directly. If the cell line will not tolerate particulates, the media mixture will be filtered and the liquid phase added to the cultures.

If filtering is required for a particular species, then the filters will be sequentially incubated at 10° C and 35° C in petri dishes with the same medium solidified

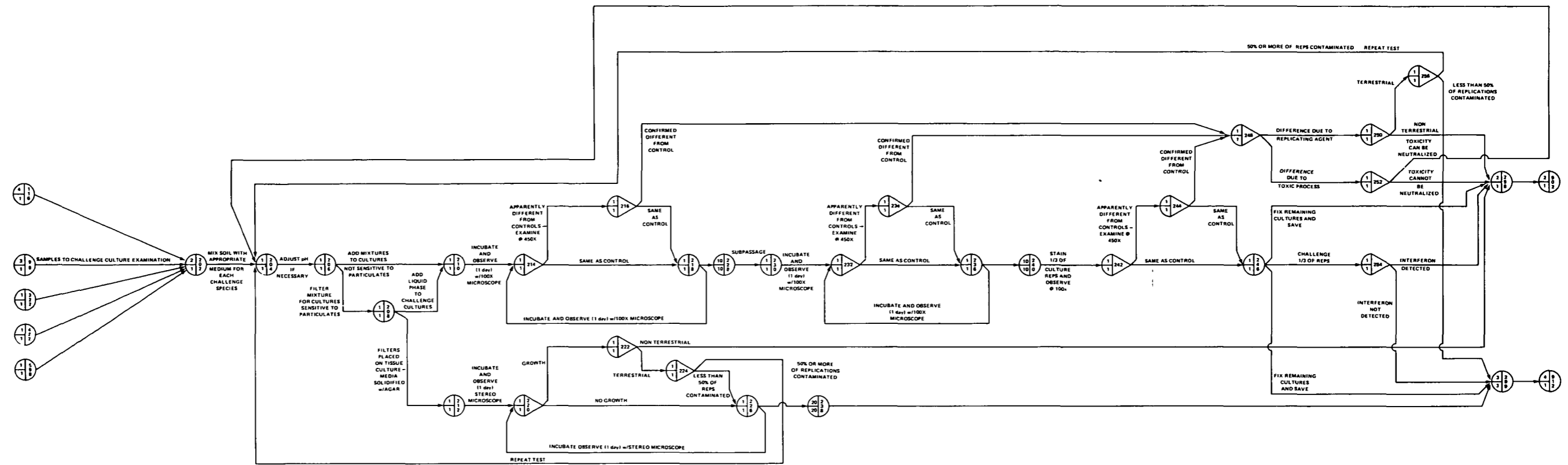


Figure 4-17.—The challenge culture protocol.

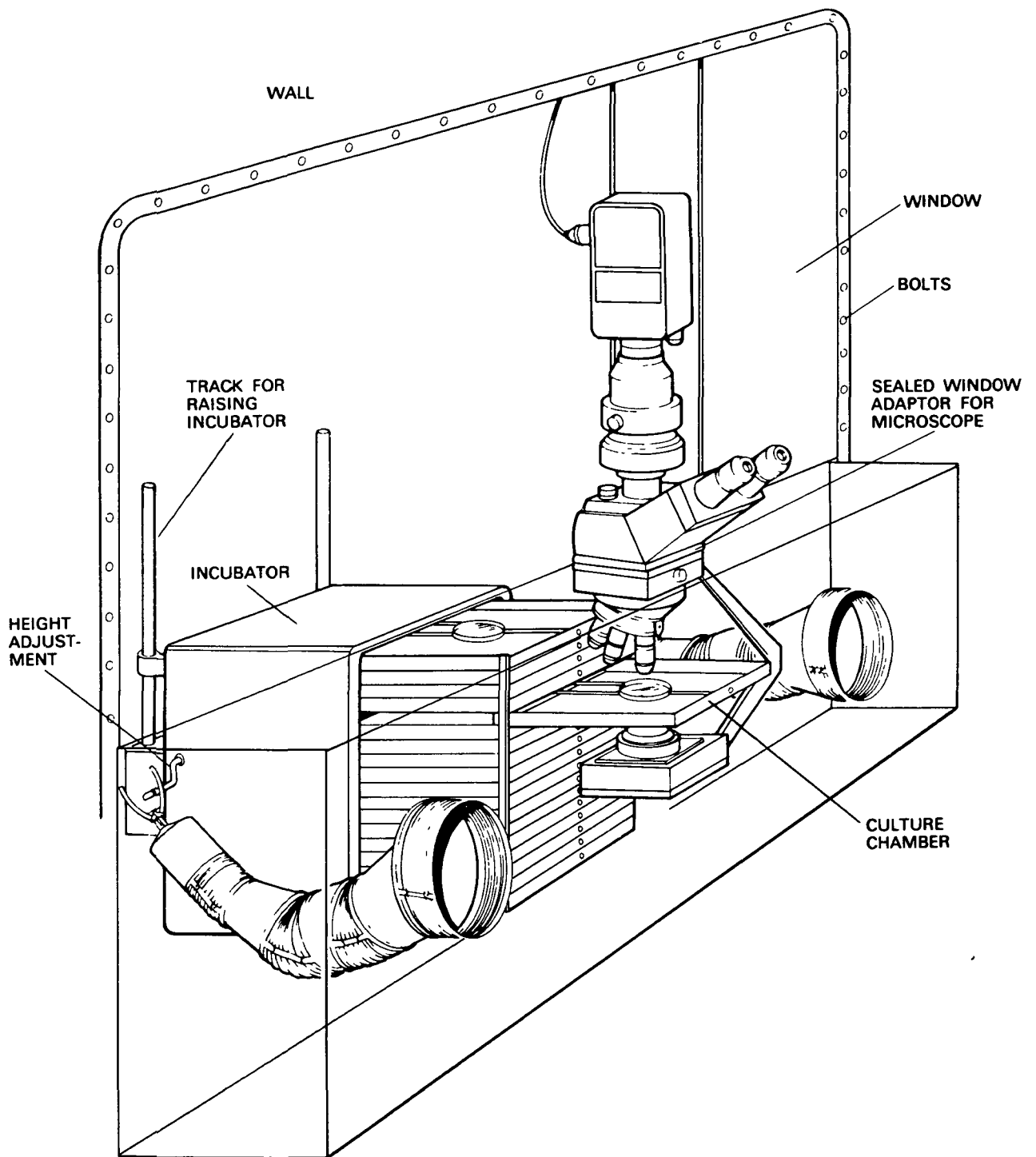


Figure 4-18.—The system for microscopically monitoring the challenge cultures.

with agar. (See "Growth of Organisms on Membrane Filters," page 71)

Cultures will be incubated at their optimal temperatures and observed microscopically (100×) for 10 days, after which the tissues will be subcultured if there are no observable differences between experimental and control cultures. These subcultures likewise will be incubated and observed for 10 days. If no effects are observed, one third of the replicates will be fixed and stained for detailed microscopic examination, and another third will be challenged with a known terrestrial virus to check for interferon production (ref. 73). If these tests are negative, all remaining cultures will be fixed for later study on Earth.

If at any time treated cultures appear different from controls, tests will be conducted to determine whether the difference is due to a replicating agent or toxin. If a nonreplicating toxin is found, attempts will be made to neutralize it so that the challenge can be rerun.

In the event that half or more of the treated cultures of one species are contaminated with terrestrial organisms, that species culture will be rerun.

Design Requirements. The Woodland Wanderer 9 system (refs. 76, 77) must be modified so that 18 culture chambers can be individually observed microscopically (figure 4-18) in zero *g*. The microscope should have 100× and 400× magnification, bright-field and phase contrast optics, and a video camera. A system must be developed to inoculate cultures and to remove cells for subculture. Additional research will be needed to develop and select tissue culture strains that are representative of a diversity of life forms, yet are compatible with the OQF conditions.

Second-Order Testing Sequence

An outline of the second-order testing sequence, shown in figure 4-19, has been developed to indicate possible activities that would follow the detection of nonterrestrial life forms during execution of the planned primary protocol. Development of detailed methods for the second-order protocol is deferred in this study because it would be more appropriate to develop such a plan in response to actual data received from the primary protocol testing. Note that in the event that the sample does not pose a threat to Earth, the sample will be sent to Earth where it will remain under controlled conditions to ensure that it is not environmentally degraded. Curatorial accounting

procedures will be established to protect the soil from loss or negligence while subsamples are loaned to scientific investigators around the world.

Appendix A—GERT Used in Protocol Planning

EXAMPLE OF THE USE OF GERT SYMBOLOGY

This section describes the GERT symbology summarized in figure 4-1, using the chemical analysis protocol shown in figure 4-8 as an example to illustrate the application of this method. The initiation of the chemical analysis of solids is signaled by node 102. Before these tests can begin, three of the four activities leading into node 102 (shown in figure 4-7) must be completed: Gas analysis from the sample container must be complete, the soil must be observed, the soil must be processed into subsamples, and the filter through which the sample's gases passed must be analyzed. Because the last activity has three outcomes, two of which do not indicate Martian life forms (i.e., no life found or only terrestrial contaminants observed), only one outcome would connect to node 102. When three activities are finished, then the activities emanating from node 102 would be initiated: organic carbon analysis, aqueous extraction; elemental analysis of solids, and pH, Eh, and conductance measurements (figure 4-8) may all be initiated in parallel with one another. This is indicated in the figure by the fact that the output side of GERT node 102 is circular. It is a deterministic node—all activities leading from that node must be accomplished. A node with a probabilistic output side (i.e., a pointed side) is illustrated at node 106 to account for the two mutually exclusive outcomes of the organic carbon analysis: complex organics either are or are not observed. Each outcome leading from node 106 (the completion of organic carbon analysis) has a specific probability of occurrence, as described in the following section.

Node 116 indicates the completion of the chemical analysis. It is a deterministic node because the information resulting from chemical analysis is a prerequisite for initiating the other major quarantine tests. Once chemical analysis is complete, this information is forwarded to microbiological (node 402), challenge culture (node 202), metabolic (node 502), and microscopic (node 302) testing for use in preparing these experiments.

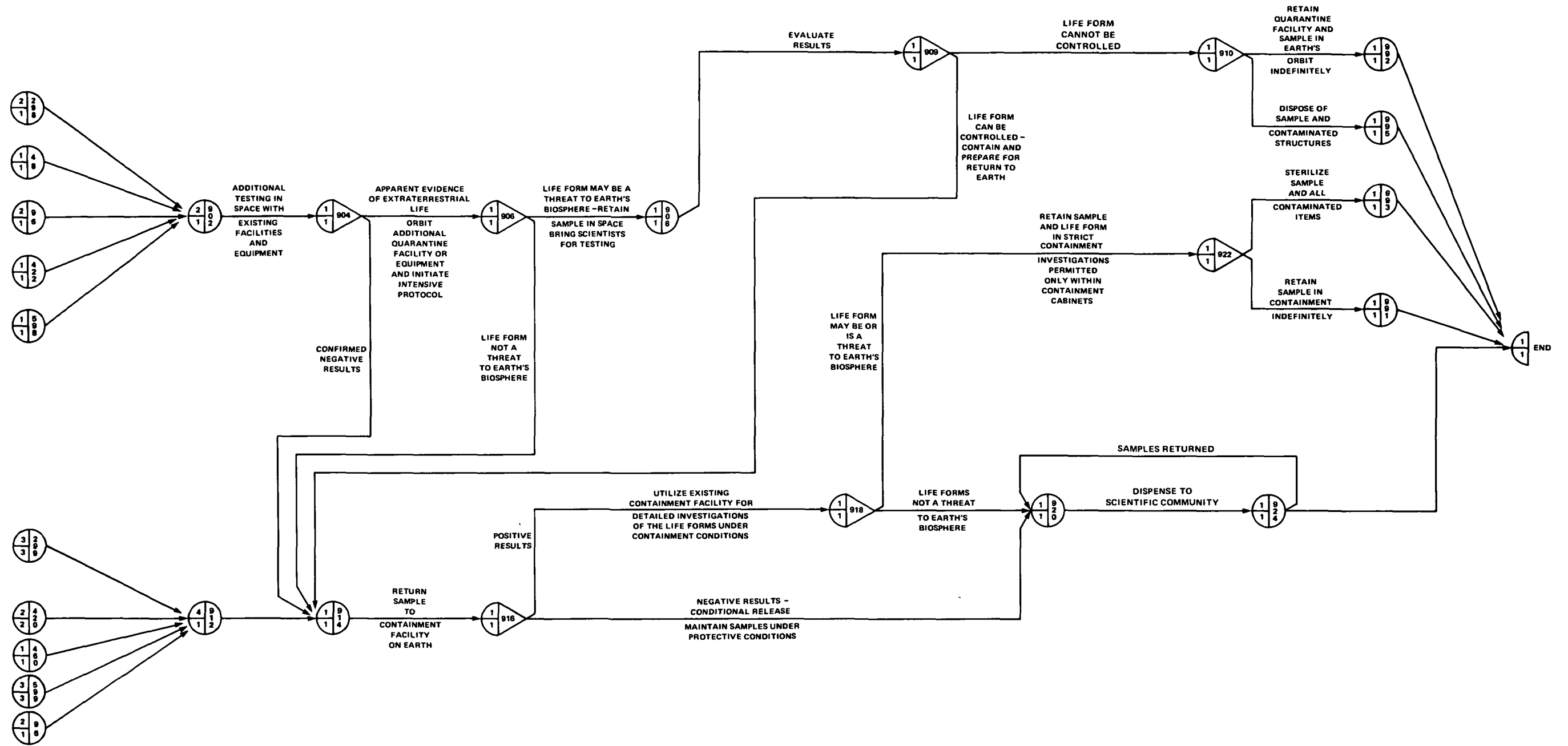


Figure 4-19.—The second-order testing protocol.

Note in figure 4-2 that there are basically two outcomes from each of the major protocols outside of chemical analysis. either there is some evidence of extraterrestrial life or there is not. In addition, all of the experiments in the quarantine facility lead to one of these two results, as indicated by connection to node 902 (positive result) and node 912 (negative result). There are four activities/outcomes leading into node 912, all of which must be accomplished before node 912 is activated, resulting in a recommendation that the Martian sample be certified safe for transport to Earth and further analysis. Node 902 is activated if at least one quarantine test yielded evidence of extraterrestrial life, as indicated by the five activity/event lines leading to the node. Realization of node 902 initiates second-order testing on the discovered life form to determine its characteristics, and whether it is pathogenic to life forms or harmful to processes in the Earth's biosphere.

OUTCOME PROBABILITIES FOR GERT NETWORKS

To calculate the probability of a certain outcome using the GERT network, it is first necessary to assign probabilities to each possible outcome for the probabilistic nodes. This is difficult because the success of each test depends upon the number of organisms

present in the soil, the sample size, the sensitivity of the particular tests being performed, and the ability of those tests to permit recognition of alien organisms. Tables 4-3 to 4-6 present the outcome probabilities of each of the major protocols. The combined probabilities of all the protocols are given in table 4-7.

For purposes of illustration, the challenge culture portion of the protocol is used here to demonstrate the calculation of outcome probabilities (table 4-6), i.e., that if there is life in the sample, it will be detected by this particular step. There are four probabilistic nodes in the challenge culture experiments (figure 4-17). The first probabilistic node (node 214) is reached after the introduction of Martian soil into challenge cultures. Assuming that there are a certain number of organisms in the soil, there is a specific probability that the challenge culture will behave the same as the control cultures (node 218) and another probability that the challenge cultures will behave differently from the control (node 216). It is estimated that if there is only one microorganism per gram of the Martian soil, the probability that the test will not detect it (resulting in the experimental culture behaving the same as the control) is 0.95; the probability that the experimental culture will differ from the control is therefore 0.05 (i.e., the test ends at node 216). However, node 216 is also a probabilistic node and has two possible outcomes if activated. Either the effect noted would be due to a toxic characteristic of the Martian soil

TABLE 4-3.—MICROSCOPY PROTOCOL DETECTION CAPABILITY ANALYSIS

Start Node	End Node	Activity/Outcome Description	Conditional Probabilities With		
			1 org/g	1000 org/g	100 000 org/g
Soil					
306	308	Detection in field at 450×	3×10^{-7}	3×10^{-4}	3×10^{-2}
306	312	No detection at 450×	$1-(3 \times 10^{-7})$	$1-(3 \times 10^{-4})$	$1-(3 \times 10^{-2})$
308	310	Detection at 1000×	0.5	0.75	0.90
308	312	No detection at 1000×	0.5	0.25	0.10
310	314	Life structure confirmed w/SEM	1	1	1
310	318	Life structure not confirmed w/SEM	0	0	0
Supernatant					
328	330	Detection in field at 450×	3×10^{-7}	3×10^{-4}	3×10^{-2}
328	334	No detection at 450×	$1-(3 \times 10^{-7})$	$1-(3 \times 10^{-4})$	$1-(3 \times 10^{-2})$
330	332	Detection at 1000×	0.5	0.75	0.90
330	336	No detection at 1000×	0.5	0.25	0.10
332	336	Life structure confirmed w/SEM	1	1	1
332	338	Life structure not confirmed w/SEM	0	0	0
Summary					
	322	Life structures identified	0.001	0.367	1
	342	Life structures not identified	0.999	0.633	0

TABLE 4-4.—METABOLIC PROTOCOL DETECTION CAPABILITY ANALYSIS

Start Node	End Node	Activity/Outcome Description	Conditional Probabilities With		
			1 org/g	1000 org/g	100 000 org/g
Dry Sample Gas Exchange Measurement					
506	508	Gas change	0	1	1
506	510	No gas change	1	0	0
508	598	Indicates life	0.865	1	1
508	510	Nonbiotic source	0.135	0	0
514	598	Evidence of photosynthesis	0	1	1
514	516	No evidence of photosynthesis	1	0	0
520	598	Evidence of photosynthesis	0	1	1
520	599	No evidence of photosynthesis	1	0	0
Labeled Gas Test					
524	526	Labeled gas released	0	1	1
524	528	Labeled gas not released	1	0	0
526	598	Kinetics indicates life	0.865	1	1
526	528	Nonbiotic source	0.135	0	0
532	598	Kinetics indicates life	0	1	1
532	599	Nonbiotic source	1	0	0
GC/MS					
538	540	Organic levels changed	0.04	1	1
538	554	Organic levels unchanged	0.96	0	0
540	598	Organics indicate life	0.90	1	1
540	554	Nonbiotic change	0.10	0	0
Autoradiography					
546	548	Label diffuse	0	0	0
546	560	Label concentrated	0	1	1
546	554	No label	1	0	0
548	554	Nonbiotic	0	0	0
548	560	Possibly biotic	1	1	1
552	598	Appearance indicates life	0	1	1
552	554	Nonbiotic	1	0	0
Summary					
	598	Extraterrestrial life detected	0.036	1	1
	599	Extraterrestrial life not detected	0.964	0	0

(resulting in ending at node 218—no life forms) or it would be due to a replicating organism (end node 248). The probability that, with one organism per gram of soil, the positive results could be reconfirmed is assumed to be only 0.45. It is possible at this point to calculate joint probabilities using Baye's theorem:

$$P(A \cap B) = P(A/B) P(B) = P(B/A) P(A)$$

where:

- A = Outcome: challenge culture different from control culture;
- B = Outcome: difference confirmed;

- B/A = Outcome: difference confirmed given that challenge culture is different from control culture;
- A ∩ B = Outcome: difference confirmed and challenge culture is different from control culture;
- P(A) = Probability that the challenge culture is different from control culture = .05;
- P(B/A) = Probability that the difference is confirmed given that the challenge culture is different from control culture = .45;

TABLE 4-5 —MICROBIOLOGICAL PROTOCOL DETECTION CAPABILITY ANALYSIS

Start Node	End Node	Activity/Outcome Description	Conditional Probabilities With		
			1 org/g	1000 org/g	100 000 org/g
Plates					
408	416	Growth	0.18	1	1
408	420	No growth	0.82	0	0
416	420	Terrestrial	0.0001	0.0001	0.0001
416	422	Nonterrestrial	0.9999	0.9999	0.9999
Impedance					
414	418	Growth	0.33	1	1
414	420	No growth	0.67	0	0
418	420	Terrestrial	0.0001	0.0001	0.0001
418	422	Nonterrestrial	0.9999	0.9999	0.9999
Summary					
	422	Extraterrestrial life indicated	0.45	1	1
	420	No extraterrestrial life indicated	0.55	0	0

TABLE 4-6 —CHALLENGE CULTURE PROTOCOL DETECTION CAPABILITY ANALYSIS

Start Node	End Node	Activity/Outcome Description	Conditional Probabilities With		
			1 org/g	1000 org/g	100 000 org/g
214	216	Different from control	0.05	0.75	1
214	218	Same as control	0.95	0.25	0
216	248	Confirmed different from control	0.45	0.95	1
216	218	Same as control	0.55	0.05	0
232	234	Different from control	0.02	0.95	1
232	236	Same as control	0.98	0.05	0
234	248	Confirmed different from control	0.45	0.95	1
234	236	Same as control	0.55	0.05	0
242	244	Different from control	0.01	0.95	1
242	246	Same as control	0.99	0.05	0
244	248	Different from control	0.01	0.95	1
244	246	Same as control	0.99	0.05	0.25
248	250	Replicating agent	0.75	0.50	0.25
248	252	Toxic process	0.25	0.50	0.75
250	256	Terrestrial	0.0001	0.0001	0.0001
250	298	Nonterrestrial	0.9999	0.9999	0.9999
256	204	High-level forward contamination	0.50	0.50	0.50
256	299	Low-level forward contamination	0.50	0.50	0.50
252	204	Toxicity neutralized	0.50	0.50	0.50
252	298	Toxicity cannot be neutralized	0.50	0.50	0.50
254	298	Interferon detected	0.25	0.50	0.50
254	299	Interferon not detected	0.75	0.50	0.50
220	222	Growth	0.05	0.95	0.95
220	226	No growth	0.95	0.05	0.05
222	224	Terrestrial	0.0001	0.0001	0.0001
222	298	Nonterrestrial	0.9999	0.9999	0.9999
224	204	High-level forward contamination	0.50	0.50	0.50
224	226	Low-level forward contamination	0.50	0.50	0.50
Summary					
	298	Extraterrestrial life detected	0.47	1	1
	299	Extraterrestrial life not detected	0.53	0	0

TABLE 4-7.—COMBINED PROTOCOLS DETECTION CAPABILITY ANALYSIS

Start Node	End Node	Activity/Outcome Description	Conditional Probabilities With		
			1 org/g	1000 org/g	100 000 org/g
502	598	Metabolic protocol—life	0.036	1	1
502	912	Metabolic protocol—no life	0.964	0	0
302	322	Microscopy protocol—life	0.001	0.367	1
302	390	Microscopy protocol—no life	0.999	0.633	0
408	422	Microbiological protocol—life	0.45	1	1
408	912	Microbiological protocol—no life	0.55	0	0
202	902	Challenge culture protocol—life	0.47	1	1
202	912	Challenge culture protocol—no life	0.53	0	0
Summary					
	902	Initiate second-order testing	0.719	1	1
	912	Return sample to Earth	0.281	0	0

$P(A \cap B)$ = Probability that challenge culture is different from control culture and the difference is confirmed = $(.05)(.45) = .0225$.

This process of calculating joint probabilities, using the estimated chance of success for each aspect of the testing program, continues sequentially throughout the challenge culture protocol, ending at the two outcomes (node 298 and node 299). If a sample of Martian soil with one microorganism per gram were exposed to a variety of challenge cultures, the probability of not detecting the organism (node 299) is 0.53, so that the chance of successful detection is 0.47. As the microorganism population increases, the probability of detection at each node would have to be adjusted to reflect an increased probability of detecting life. The calculations illustrated in table 4-6 reflect the initial testing of Martian soil, and even retesting (if any toxins can be neutralized). They do not, however, reflect testing initiated from other protocols such as microscopy or metabolism.

PROJECTING RESOURCE REQUIREMENTS

Another advantage of the GERT network is that it permits projecting the requirements for resources such as the Martian soil, experimentation time, power, etc. Using the chart, it is possible to predict how many times each section of the protocol would have to be repeated to have a certain probability of success. Thus, if one wishes to set an arbitrary attainment level of 0.95 probability for detection, then by inspecting a set of probability distributions produced by the GERT

computer simulation program, the number of replicate experiments needed can be determined. With this information, it is possible to realistically calculate the quantity of resources needed to attain that degree of success.

REFERENCES

1. Bagby, J. R. *Back Contamination: Lessons Learned During the Apollo Lunar Quarantine Program*. Colorado State University, Fort Collins, July 1, 1975, 51 pp.
2. Michaelsen, G. S., and Mahoney, T. A. *Personnel Management Techniques Necessary to Maximize Bio-Barrier Integrity at a Martian Receiving Laboratory, Annual Report, July 1, 1974-June 30, 1975*. Minnesota University, Minneapolis, June 30, 1975, 13 pp. (NASA-CR-142963; Grant NGL-24-005-160)
3. Duke, M. B., and Reynolds, M. A. Lunar sample quarantine procedures: Interaction with non-quarantine experiments. In *Life Sciences and Space Research XII*, Proceedings of the Open Meeting of the Working Group on Space Biology of the 16th Plenary Meeting of COSPAR, Constance, F.R.G., May 23-June 5, 1973 (ed. by P. H. A. Sneath). Akademie-Verlag, Berlin, 1974, pp. 203-208.
4. Alexander, M. Quarantine for samples from Mars. In *Theory and Experiment in Exobiology, Volume 2* (ed. by A. E. Schwartz). Wolters-Noordhoff Publishers, Groningen, The Netherlands, 1972, pp. 121-146.

-
5. Michaelsen, G. S. Safety of containment systems: State-of-the-art—Biobarrier technology. Paper presented at the AIBS Planetary Quarantine Panel, Cocoa Beach, Florida, June 11, 1974, 13 pp.
 6. Levinthal, E. C., Jones, K. L., Fox, P., and Sagan, C. Lander imaging as a detector of life on Mars. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4468–4478.
 7. Horowitz, N. H., Hobby, G. L., and Hubbard, J. S. Viking on Mars: The carbon assimilation experiments. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4659–4662.
 8. Oyama, V. I., and Berdahl, B. J. The Viking gas exchange experiment results from Chryse and Utopia surface samples. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4669–4676.
 9. Levin, G., and Straat, P. Recent results from the Viking Labeled Release experiment on Mars. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4663–4667.
 10. Klein, H. P. The Viking biological investigation: General aspects. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4677–4680.
 11. Shih, K. L., and Souza, K. A. Degradation of biochemical activity in soil sterilized by dry heat and gamma radiation. *Origins of Life*, Vol. 9, 1978, pp. 51–63.
 12. Biemann, K., Oro, J., Toulmin, P., 3rd, Orgel, L. E., Nier, A. O., Anderson, D. M., Simmonds, P. G., Flory, D., Diaz, A. V., Rushneck, D. R., Biller, J. E., and Lafleur, A. L. The search for organic substances and inorganic volatile compounds in the surface of Mars. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4641–4658.
 13. Seiff, A., and Kirk, D. B. Structure of the atmosphere of Mars in summer at mid-latitudes. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4364–4378.
 14. Owen, T., Biemann, K., Rushneck, D. R., Biller, J. E., Howarth, D. W., and Lafleur, A. L. The composition of the atmosphere at the surface of Mars. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4635–4639.
 15. Clark, B. C., 3rd, Baird, A. K., Rose, H. J., Jr., Toulmin, P., 3rd, Christian, R. P., Kelliher, W. C., Castro, A. J., Rowe, C. D., Keil, K., and Huss, G. R. The Viking X ray fluorescence experiment: Analytical methods and early results. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4577–4594.
 16. Baird, A. K., Castro, A. J., Clark, B. C., Toulmin, P., 3rd, Rose, H. J., Jr., Keil, K., and Gording, J. L. The Viking X ray fluorescence experiment: Sampling strategies and laboratory simulation. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4595–4624.
 17. Toulmin, P., 3rd, Baird, A. K., Clark, B. C., Keil, K., Rose, H. J., Jr., Christian, R. P., Evans, P. H., and Kelliher, W. C. Geochemical and mineralogical interpretation of the Viking inorganic chemical results. *Journal of Geophysical Research*, Vol. 82, 1977, pp. 4625–4634.
 18. Pritsker, A. A. B. *Modeling and Analysis Using Q-GERT Networks*. Halsted Press, New York, 1977, 420 pp.
 19. Moore, L. J., and Clayton, E. R. *GERT Modeling and Simulation: Fundamentals and Applications*. Petrocelli/Charter, New York, 1976, 227 pp.
 20. Cameron, R. E., King, J., and David, C. N. Soil microbial ecology of Wheeler Valley, Antarctica. *Soil Science*, Vol. 109, 1970, pp. 110–120.
 21. Laitinen, H. A., and Harris, W. E. *Chemical Analysis: An Advanced Text and Reference, 2nd edition*. McGraw-Hill Book Co., New York, 1975, pp. 565–582.
 22. Willard, H. H., Merritt, L. L., Jr., and Dean, J. A. *Instrumental Methods of Analysis, 5th edition*. D. Van Nostrand Co., New York, 1974, 860 pp.
 23. Jackson, M. L. *Soil Chemical Analysis*. Prentice-Hall, Englewood Cliffs, New Jersey, 1958, 498 pp.
 24. Richards, L. A. (ed.). *Diagnosis and Improvement of Saline and Alkali Soils*. U.S. Government Printing Office, Washington, D.C., February 1954, 160 pp. (U.S. Department of Agriculture Handbook No. 60)
 25. Economou, T. E., and Turkevich, A. L. An alpha particle instrument with alpha, proton, and X ray modes for planetary chemical analyses. *Nuclear Instruments and Methods*, Vol. 134, 1976, pp. 391–400.
-

26. Lawless, J. G. Amino acids in the Murchison meteorite. *Geochimica et Cosmochimica Acta*, Vol. 37, 1973, pp. 2207-2212.
27. Lawless, J. G., Kvenvolden, K. A., Peterson, E., Ponnampereuma, C., and Jarosewich, E. Evidence for amino-acids of extraterrestrial origin in the Orgueil meteorite. *Nature*, Vol. 236, 1972, pp. 66-67.
28. Lawless, J. G., Kvenvolden, K. A., Peterson, E., Ponnampereuma, C., and Moore, C. Amino acids indigenous to the Murray meteorite. *Science*, Vol. 173, 1971, pp. 626-627.
29. Lawless, J. G., Folsome, C. E., and Kvenvolden, K. A. Organic matter in meteorites. *Scientific American*, Vol. 226, No. 6, June 1972, pp. 38-46.
30. Kvenvolden, K. A. Criteria for distinguishing biogenic and abiogenic amino acids: Preliminary considerations. *Space Life Sciences*, Vol. 4, 1973, pp. 60-68.
31. Soffen, G. A., and Sloan, R. K. Life detection by visual imaging. In *The Search for Extraterrestrial Life*, Proceedings of the 12th Annual Meeting of the American Astronautical Society, Anaheim, California, May 23-25, 1966 (ed. by J. S. Hanrahan). Scholarly Publications, Sun Valley, California, 1967, pp. 253-270. (Advances in the Astronautical Sciences, Volume 22)
32. Imshenetskiy, A. A. Exobiology: Methods and problems. In *Inhabited Space, Part One* (ed. by P. B. Konstantinov and V. D. Pekelis). Nauka Press, Moscow, 1972, pp. 177-189. (English translation: NASA-TT-F-819)
33. Todd, R. L., and Kerr, T. J. Scanning electron microscopy of microbial cells on membrane filters. *Applied Microbiology*, Vol. 23, 1972, pp. 1160-1162.
34. Gray, T. R. G. Stereoscan electron microscopy of soil microorganisms. *Science*, Vol. 155, 1967, pp. 1668-1670.
35. Casida, L. E., Jr. Microorganisms in unamended soil as observed by various forms of microscopy and staining. *Applied Microbiology*, Vol. 21, 1971, pp. 1040-1045.
36. Aaronson, S. *Experimental Microbial Ecology*. Academic Press, New York, 1970, 236 pp.
37. Norris, J. R., and Swain, H. Staining bacteria. In *Methods in Microbiology, Volume 5A* (ed. by J. R. Norris and D. W. Ribbons). Academic Press, New York, 1971, pp. 105-134.
38. Pital, A., Janowitz, S. L., Hudak, C. E., and Lewis, E. E. Direct fluorescent labeling of microorganisms as a possible life-detection technique. *Applied Microbiology*, Vol. 14, 1966, pp. 119-123.
39. Bohlool, B. B., and Schmidt, E. L. Nonspecific staining: Its control in immunofluorescence examination of soil. *Science*, Vol. 162, 1968, pp. 1012-1014.
40. Babiuk, L. A., and Paul, E. A. The use of fluorescein isothiocyanate in the determination of the bacterial biomass of grassland soil. *Canadian Journal of Microbiology*, Vol. 16, 1970, pp. 57-62.
41. McElroy, L. J., and Casida, L. E., Jr. An evaluation of Rhodamine-labeled lysozyme as a fluorescent stain for *in situ* soil bacteria. *Canadian Journal of Microbiology*, Vol. 18, 1972, pp. 933-936.
42. Mayfield, C. I. A fluorescence-staining method for microscopically counting viable microorganisms in soil. *Canadian Journal of Microbiology*, Vol. 23, 1977, pp. 75-83.
43. Bulla, L. A., Jr., St. Julian, G., Hesseltine, C. W., and Baker, F. L. Scanning electron microscopy. In *Methods in Microbiology, Volume 8* (ed. by J. R. Norris and D. W. Ribbons). Academic Press, New York, 1973, pp. 2-33.
44. Casida, L. E., Jr. Observation of microorganisms in soil and other natural habitats. *Applied Microbiology*, Vol. 18, 1969, pp. 1065-1071.
45. Millar, W. N., and Casida, L. E., Jr. Microorganisms in soil as observed by staining with Rhodamine-labeled lysozyme. *Canadian Journal of Microbiology*, Vol. 16, 1970, pp. 305-307.
46. Casida, L. E., Jr. Infrared color photography: Selective demonstration of bacteria. *Science*, Vol. 159, 1968, pp. 199-200.
47. Casida, L. E., Jr. Infrared color photomicrography of soil microorganisms. *Canadian Journal of Microbiology*, Vol. 21, 1975, pp. 1892-1893.
48. Casida, L. E., Jr. Continuously variable amplitude contrast microscopy for the detection and study of microorganisms in soil. *Applied and Environmental Microbiology*, Vol. 31, 1976, pp. 605-608.
49. Hagen, C. A., Hawrylewicz, E. J., Anderson, B. T., Tolkacz, V. K., and Cephus, M. J. Use of the scanning electron microscope for viewing bacteria in soil. *Applied Microbiology*, Vol. 16, 1968, pp. 932-934.

50. Balkwill, D. L., and Casida, L. E., Jr. Microflora of soil as viewed by freeze-etching. *Journal of Bacteriology*, Vol. 114, 1973, pp. 1319-1327.
51. Todd, R. L., Cromack, K., Jr., and Knutson, R. M. Scanning electron microscopy in the study of terrestrial microbial ecology. In *Modern Methods in the Study of Microbial Ecology, Proceedings of a Symposium, Agricultural College, Uppsala, Sweden, June 19-23, 1972* (ed. by T. Rosswall). Statens naturvetenskapliga forskningsrad, Stockholm, 1973, pp. 109-118. (Bulletins from the Ecological Research Committee No. 17)
52. Heywood, V. H. The characteristics of the scanning electron microscope and their importance in biological studies. In *Scanning Electron Microscopy: Systematics and Evolutionary Applications* (ed. by V. H. Heywood). Academic Press, New York, 1971, pp. 1-16.
53. Oyama, V. I., Merek, E. L., and Silverman, M. P. A search for viable organisms in a lunar sample. In *Proceedings of the Apollo 11 Lunar Science Conference, Houston, Texas, January 5-8, 1970, Volume 2* (ed. by A. A. Levinson). Pergamon Press, New York, pp. 1921-1927. (*Geochimica et Cosmochimica Acta*, Supplement 1)
54. Merek, E. L. Imaging and life detection. *BioScience*, Vol. 23, 1973, pp. 153-159.
55. Fehrmann, R. C., and Weaver, R. W. Scanning electron microscopy of *Rhizobium* spp. adhering to fine silt particles. *Soil Science Society of America Journal*, Vol. 42, 1978, pp. 279-281.
56. Larsson, K., Weibull, C., and Cronberg, G. Comparison of light and electron microscopic determinations of the number of bacteria and algae in lake water. *Applied and Environmental Microbiology*, Vol. 35, 1978, pp. 397-404.
57. Clough, K. S., and Sutton, J. C. Direct observation of fungal aggregates in sand dune soil. *Canadian Journal of Microbiology*, Vol. 24, 1978, pp. 333-335.
58. Brockett, R. M., Brady, J., Day, J. L., Ferguson, J. K., and Walsh, J. M. Slide staining device for use during space flight. *Applied and Environmental Microbiology*, Vol. 33, 1977, pp. 203-205.
59. Govindjee, and Papageorgiou, G. Chlorophyll fluorescence and photosynthesis: Fluorescence transients. In *Photophysiology: Current Topics in Photobiology and Photochemistry, Volume VI* (ed. by A. C. Giese). Academic Press, New York, 1971, pp. 1-46.
60. Oyama, V. I., Berdahl, B. J., Carle, G. C., Lehwalt, M. E., and Ginoza, H. S. The search for life on Mars: Viking 1976 gas changes as indicators of biological activity. *Origins of Life*, Vol. 7, 1976, pp. 313-333.
61. Merek, E. L., and Oyama, V. I. Integration of experiments for the detection of biological activity in extraterrestrial exploration. In *Life Sciences and Space Research VIII, Proceedings of the Open Meeting of Working Group V at the 20th Plenary Meeting of COSPAR, Prague, May 11-24, 1969 and The Symposium on Biological Rhythms, Prague, May 13, 1969 and The Symposium on Nutrition of Man in Space, Prague, May 14, 1969* (ed. by W. Vishniac and F. G. Favorite). North-Holland Publishing Co., Amsterdam, 1970, pp. 108-115.
62. Fliermans, C. B., and Schmidt, E. L. Autoradiography and immunofluorescence combined for autecological study of single cell activity with *Nitrobacter* as a model system. *Applied Microbiology*, Vol. 30, 1975, pp. 676-684.
63. Waid, J. S., Preston, K. J., and Harris, P. J. A method to detect metabolically-active microorganisms in leaf litter habitats. *Soil Biology & Biochemistry*, Vol. 3, 1971, pp. 235-241.
64. Ramsay, A. J. The use of autoradiography to determine the proportion of bacteria metabolizing in an aquatic habitat. *Journal of General Microbiology*, Vol. 80, 1974, pp. 363-373.
65. Stotzky, G. Relevance of soil microbiology to search for life on other planets. *Advances in Applied Microbiology*, Vol. 10, 1968, pp. 17-54.
66. Eglinton, G., and Tonkin, S. An automatically-returned Martian sample by 1985? *Origins of Life*, Vol. 5, 1974, pp. 463-482.
67. Averner, M. M., and MacElroy, R. D. *On the Habitability of Mars: An Approach to Planetary Ecosynthesis*. NASA, Washington, D.C., 1976, 105 pp. (NASA SP-414)
68. Taylor, G. R., Ellis, W., Johnson, P. H., Kropp, K., and Groves, T. Microbial assay of lunar samples. In *Proceedings of the Second Lunar Science Conference, Houston, Texas, January 11-14, 1971, Volume 2* (ed. by A. A. Levinson). The MIT Press, Cambridge, Massachusetts, 1971, pp. 1939-1948. (*Geochimica et Cosmochimica Acta*, Supplement 2)

-
69. Taylor, G. R., and Wooley, B. C. Evaluations of lunar samples for the presence of viable organisms. In *Proceedings of the Fourth Lunar Conference, Houston, Texas, March 5-8, 1973, Volume 2*. Pergamon Press, New York, 1973, pp. 2267-2274. (*Geochimica et Cosmochimica Acta*, Supplement 4)
70. Cady, P., and Dufour, S. W. Automated detection of microorganism metabolism and growth by impedance measurements. In *Abstracts of the Annual Meeting of the American Society for Microbiology 1974*, Chicago, Illinois, May 12-17, 1974. American Society for Microbiology, Washington, D.C., abstr. E43.
71. Silverman, M. P., and Munoz, E. F. Microbial metabolism and dynamic changes in the electrical conductivity of soil solutions: A method for detecting extraterrestrial life. *Applied Microbiology*, Vol. 28, 1974, pp. 960-967.
72. Wooley, B. C. Containment and biological evaluation procedures for returned Mars samples. In *Life Sciences and Space Research, Volume XV*, Proceedings of the Open Meeting of the Working Group on Space Biology of the 19th Plenary Meeting of COSPAR, Philadelphia, Pennsylvania, June 8-19, 1976 (ed. by R. Holmquist and A. C. Stickland). Pergamon Press, New York, 1977, pp. 3-7.
73. Jukes, T. J. Evolution and back-contamination. In *Life Sciences and Space Research, Volume XV*, Proceedings of the Open Meeting of the Working Group on Space Biology of the 19th Plenary Meeting of COSPAR, Philadelphia, Pennsylvania, June 8-19, 1976 (ed. by R. Holmquist and A. C. Stickland). Pergamon Press, New York, 1977, pp. 9-14.
74. Baylor University College of Medicine. *Comprehensive Biological Protocol for the Lunar Sample Receiving Laboratory, Manned Spacecraft Center, National Aeronautics and Space Administration, Houston, Texas*. Houston, Texas, June 16, 1967, 572 pp. (NASA-CR-92209, MSC-DA-68-1)
75. Manned Spacecraft Center. *Summary of Lunar Quarantine Biotest Protocols—Revision B*. Houston, Texas, November 13, 1969. (MSC-00013)
76. Montgomery, P. O'B., Cook, J. E., Reynolds, R. C., Paul, J. S., Hayflick, L., Stock, D., Schultz, W. W., Kimsey, B., Thuroff, R. G., Rogers, T., and Campbell, D. The response of single human cells to zero gravity. *In Vitro*, Vol. 14, 1978, pp. 165-173.
77. Thuroff, R. G. *Development and Characteristics of the Hardware for Skylab Experiment S015*. Lyndon B. Johnson Space Center, NASA, Houston, Texas, September 1975, 44 pp. (NASA-TM-X-58164; JSC-09728)
78. Wedum, A. G. Bacteriological safety. *American Journal of Public Health*, Vol. 43, 1953, pp. 1428-1437.
79. McDonnell Douglas Astronautics Co. *Manned Orbital Systems Concepts Study. Books 1 and 2*. Huntington Beach, California, September 30, 1975. (NASA-CR-144062 and 144063, MDC-G5919)
80. Winans, L., Pflug, I. J., and Foster, T. L. Dry-heat resistance of selected psychrophiles. *Applied and Environmental Microbiology*, Vol. 34, 1977, pp. 150-154.
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Chapter 5

The Laboratory Module

Of the five modules comprising the Orbiting Quarantine Facility (see Chapter 3), the most important in terms of the objectives of this study is the Laboratory Module. This module must provide not only an extensive research capability to permit execution of the protocol, but also the flexibility to accommodate second-order testing if nonterrestrial life is discovered in the sample. All experiments done in the Laboratory Module must be performed within biocontainment barriers that protect the sample and the researchers from cross contamination, i.e., they must prevent escape of soil-associated organisms while protecting the sample from contamination by terrestrial organisms (ref. 1).

GENERAL DESIGN CONSIDERATIONS

The attainment of these goals—extensive research capability, flexibility, and safety—was the primary consideration in design proposals for the Laboratory Module, although several other factors were also considered. The use of the basic Spacelab-type module imposed a series of physical constraints including the location of equipment attachment points and cargo mass and volume. The exteriors of the biocontainment

cabinets were shaped to conform to the slightly crouched or slumped body position assumed by persons in zero *g*, thus increasing crew comfort and reducing fatigue (ref. 2). The interior of the cabinets must be capable of maintaining the wide range of environmental conditions required by the protocol (see table 5-1). Finally, the design of the laboratory was made flexible to permit the laboratory to be easily adapted to general life sciences research after the completion of the primary MSR task (see Chapter 8).

CONTAINMENT CONSIDERATIONS

For the quarantine to be successful, the laboratory personnel must be protected from exposure to the sample (back contamination) and the sample isolated from terrestrial organisms (forward contamination). The design and configuration of the laboratory reflects the accomplishment of these two objectives. The high-hazard containment facility at the Center for Disease Control (CDC) served as a terrestrial model during planning. That facility was developed to handle Class IV pathogens (see page 21), and it has proved highly effective in this regard.

TABLE 5-1.—ENVIRONMENTAL CONDITIONS REQUIRED WITHIN THE CONTAINMENT CABINETS

Area	Environment		
	Atmosphere	Temperature	Pressure
General laboratory	Earth	21°–22° C	1 atmosphere (14.7 psi)
Initial sample inspection, processing, and storage	Mars	–40° C	0.006 atmosphere (0.09 psi)
Biological safety cabinets, class III ¹	Nitrogen ²	21°–22° C	0.995 atmosphere (14.63 psi)

¹ See ref. 1.

² Special areas are (a) aerobic (21 percent O₂, 79 percent N₂, 1 percent CO₂), (b) anaerobic (99 percent N₂, 1 percent CO₂), and (c) microaerophilic (1 percent O₂, 98 percent N₂, 1 percent CO₂).

Back Contamination

The extraterrestrial quarantine facility provides three separate barriers to prevent escape of organisms into the Earth's biosphere. The primary barrier is formed by the sealed walls of biological containment cabinets (Class III type), within which the sample is retained (figure 5-1). Nothing is permitted to enter the cabinetry, including all water, air, and supply materials, without first being sterilized. The cabinet atmosphere is maintained at a slightly lower pressure than in the laboratory, so that any barrier punctures would result in air flowing into the cabinet, thus preventing the escape of quarantined material. Air that is free of microbes is continually passed over the external face of the cabinet, so that chance organisms escaping the cabinets would be swept away from the workers and trapped in filters.

The rubber gloves that are usually used for manipulating objects inside cabinetry are the least reliable aspect of a containment system (ref. 3) because they are easily burned, torn, punctured, or cut. In lieu of rubber gloves, mechanical hand manipulators constructed from continuous welded stainless steel will be used throughout the cabinet line (figure 5-1). Even though a single sheet of steel is used, normal arm motions are possible due to a unique rotary restraint linkage and steel bellows. To provide additional protection against leaks, the manipulators will contain a rubber lining. A variety of interchangeable end-effectors will be available in the cabinet to permit accomplishing different tasks. The effector is mechanically sealed at the end of the arm, yet provides the wrist motion, grasp, and force control to permit the operator to handle samples and laboratory equipment. (See Appendix A for additional details.) Extensive studies (refs. 3, 4, 5) on using remote handling devices for biological analytical techniques suggest that their use is feasible for this purpose. It is assumed that by the mid-1980s, such manipulators will be perfected and available for biological analysis of highly pathogenic organisms.

The secondary barrier (the Laboratory Module itself) restricts or prevents, by use of physical and procedural barriers modeled after those used at the CDC, further passage of material that may have escaped from the cabinets. First, all equipment, materials, and consumables leaving the laboratory are sterilized and packaged in leak-proof containers. Any personnel leaving the laboratory pass through a decontamination area before entering the adjacent

module. The air within the Laboratory Module is continuously filtered to remove any free-floating contaminants. In addition, the atmospheric pressure in the laboratory is slightly less than that of the other modules, ensuring the containment of organisms within the secondary barrier. Therefore, the probability is low that any material which escapes the primary barrier will also pass through the secondary barrier to an adjacent module.

The third barrier protecting the Earth is one that is not available to terrestrial facilities: the envelope of space. In the event of a failure in both the primary and secondary barriers, the Earth's biosphere is still protected. The exposed crew is retained in isolation while quarantine personnel on Earth evaluate the situation and devise plans to deal with the emergency. Any particle released from the facility would remain in orbit for extensive periods of time under exposure to high fluxes of ultraviolet and cosmic radiation and extreme temperatures before eventual entry to the Earth's atmosphere.

Forward Contamination

A series of procedures and barriers have also been incorporated into the system's design to minimize the chance of contaminating the sample with terrestrial organisms. These include constructing physical barriers around the sample, reducing the number of microorganisms within the system, and adopting procedures that minimize the quantity of sample contaminated if a breach occurs.

To begin with, physical barriers designed to prevent back contamination also reduce the chance of forward contamination; the sample will always be within containment cabinets into which nothing can be placed without prior sterilization. While rubber gloves under negative pressure can contaminate the sample with water and oxygen, the stainless steel hand manipulators recommended for use in the OQF do not carry that risk. In addition, the Martian material not involved in the quarantine is retained in a leak-tight container which is sealed and physically isolated from the cabinetry where experiments are performed. Thus, any leaks would jeopardize only the protocol sample—not the entire sample. However, the protocol sample is also physically protected because only small quantities will be exposed within the cabinet, or "glove box," at any one time. The remainder of this sample will be retained in sealed containers or test chambers, where it is less susceptible to contamination. While these

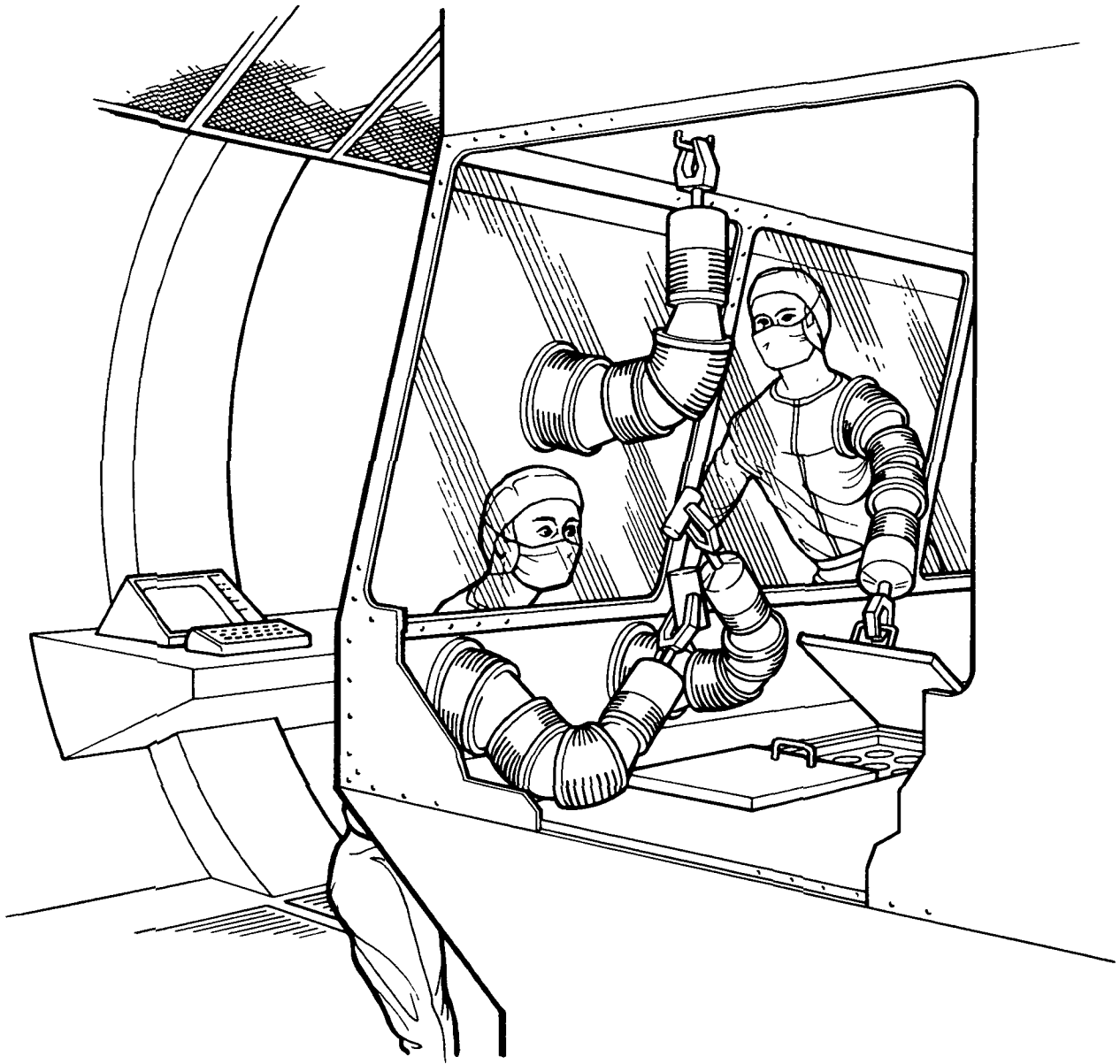


Figure 5-1.—A section of the biocontainment cabinet line within which the protocol will be executed.
Note that the interior is accessed only with stainless steel “gloves.”

precautions should be sufficient to protect the Martian material from forward contamination, an additional physical barrier could be added by constructing the cabinets with double walls. A partial vacuum maintained between the walls would ensure that if leaks developed in either wall, contaminants would be swept between the two walls and not into the cabinet proper. Although this system could not be used in the high-vacuum sample receipt and inspection section,

the pristine MSR material could be protected by an additional container while being stored.

To reduce the number of microbes in the quarantine facility, components and assemblies will undergo dry heat or gas sterilization prior to being assembled under clean-room conditions. Before the completed laboratory is placed in orbit, it will be filled with formaldehyde gas to kill microbes that are exposed on surfaces (ref. 6). After a contact period of 16 to 18

hours, the vapors will be vented from the laboratory and replaced with sterile, filtered air. Additional decontamination treatments of the cabinetry system will be performed in space.

To maintain low levels of terrestrial contaminants once the laboratory is in use, the air will be continually recirculated through a series of high efficiency particle accumulator (HEPA) filters to trap airborne particles and bacteria. The cleaned air will be directed from the ceiling across the face of the biocontainment cabinets, exiting through the floor. Bacteria dislodged from or expelled by laboratory personnel will thus be swept away from the sample area and eventually trapped by the HEPA filter system. Also, by this means any air leaking into the cabinets would have low levels of contamination. Similar systems are routinely used in manufacturing and biological facilities to prevent contamination of materials (refs. 7, 8).

To estimate the maximum number of particles per liter of air expected in the quarantine laboratory, the following formula can be used (ref. 7).

$$N = \frac{G}{\alpha KV} [1 - \exp(-\alpha Kt)]$$

where

- N = number of particles per liter present at any given time (t) in seconds;
- V = volume of clean room in liters (6.52×10^4);
- K = number of complete changes of room air volume per second (0.036, based on a flow rate of 236 liters/sec through each of 10 filters);
- G = total number of particles per second entering the clean room (500, based on one worker without face mask expelling 250 bacterial aerosols/sec) (ref. 7),
- t = time, in seconds;
- α = efficiency of the filter (99.97 percent).

If we assume continuous operation (worst case), a value of $N = 0.21$ particles/liter (6 particles/cubic foot) is obtained, which is well under the 3.5 particles/liter (100 particles/cubic foot) required of a Class 100 "clean room" facility. As a further improvement, laboratory personnel will be outfitted with high-efficiency contagion masks (ref. 8).

LABORATORY LAYOUT

Options Considered

Two configurations were considered for positioning the glove boxes within the laboratory (figure 5-2):

1. Extending the cabinets longitudinally down the center of the module, anchored to the floor and ceiling;
2. Adopting a configuration similar to that used in Spacelab, with glove boxes located on either side of the center aisle (ref. 9).

A comparison of the two arrangements and their relative advantages, summarized in table 5-2, resulted in the selection of the first configuration.

Configuration Chosen

The key structure in the laboratory is the centrally located containment cabinet system (figures 5-3 and 5-4). At the lower left of the cabinetry, there is an area dedicated to sample receipt (the airlock) and to the initial inspection, handling, and processing of the Martian material. A major concern is that contamination on the surface of the sample canister (dust particles, propellant residue, micrometeorites, etc.) could be introduced with the sample into the initial inspection and processing area. Levin and Hall (ref. 10) have proposed a scheme whereby in-flight incineration of the MSR canister's outer covering would remove the contaminants, although such considerations for the mission are only speculative at this time. If the MSR canister was returned "dirty," the sample airlock could be adapted to sterilize and cleanse it of surface contaminants before opening. The sample is moved to the initial processing and storage area, which is maintained at a Mars-like environment with atmospheric pressure of 0.09 psi and temperature of -40° C. Because of the low pressure in this area, all handling and processing of the sample must be done with mechanical manipulators. After a gas sample is taken, the MSR canister is opened, gas sampling of the subsample container(s) is performed, and 100 g of material is removed for the quarantine testing; the remaining 900 g of material is repackaged in a leakproof container and kept in the Mars-like environment until completion of the protocol. The quarantine sample then undergoes visual inspection with a stereomicroscope and is sieved, ground, and packaged for the various protocols. (See figure 4-4.) (The details of

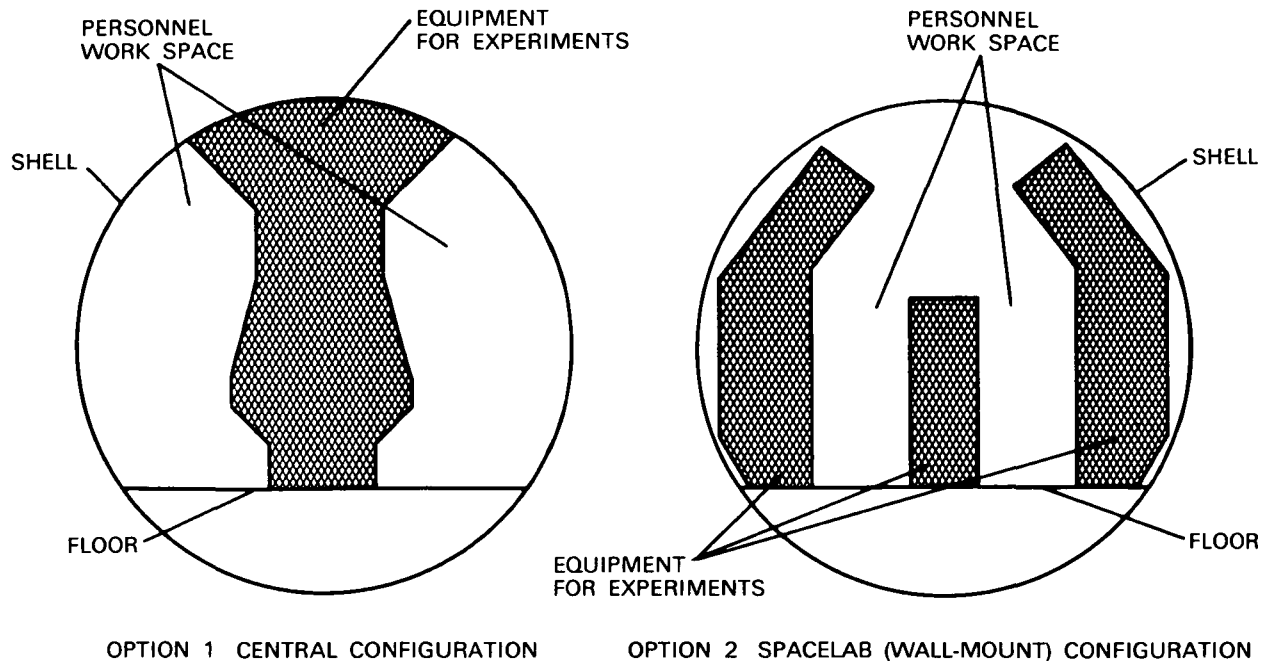


Figure 5-2.—Cross sections of two options for the location of biocontainment chambers in the Laboratory Module.

TABLE 5-2.—A COMPARISON OF TWO LABORATORY LAYOUT OPTIONS

	<i>Central Configuration</i>	<i>Wall-mount Configuration</i>
Volume available	20 m ³	18 m ³
Assurance of containment	Compact arrangement of sample work space and single line of sample transport reduce risk of breach of containment	Double line sample transport system presents higher risk of breach of containment.
Sample transport	Central arrangement facilitates transport of materials between experiment stations.	Transport of materials from one point to another, or across aisle, presents a major difficulty.
Design requirement	A new design needs to be developed for use in the OQF.	Existing rack designs for conventional Spacelab missions possibly could be modified for use.

the equipment designed to perform these tasks in zero *g* without handling the sample are described in Appendix B of this chapter.) For experiments requiring a pristine sample (i.e., metabolic tests) or oxygen-free material (i.e., anaerobic culturing) the sample will be sealed in an airtight chamber to protect it while it is being moved through the cabinet line.

The protocol samples are brought through the airlock into the cabinets where the protocol experiments are conducted. Contained within the cabinetry is the equipment required for the quarantine protocol. Equipment such as the freezer, refrigerator, incubators, and centrifuge are housed in the lower part of the containment cabinet (figures 5-1 and 5-5), and are

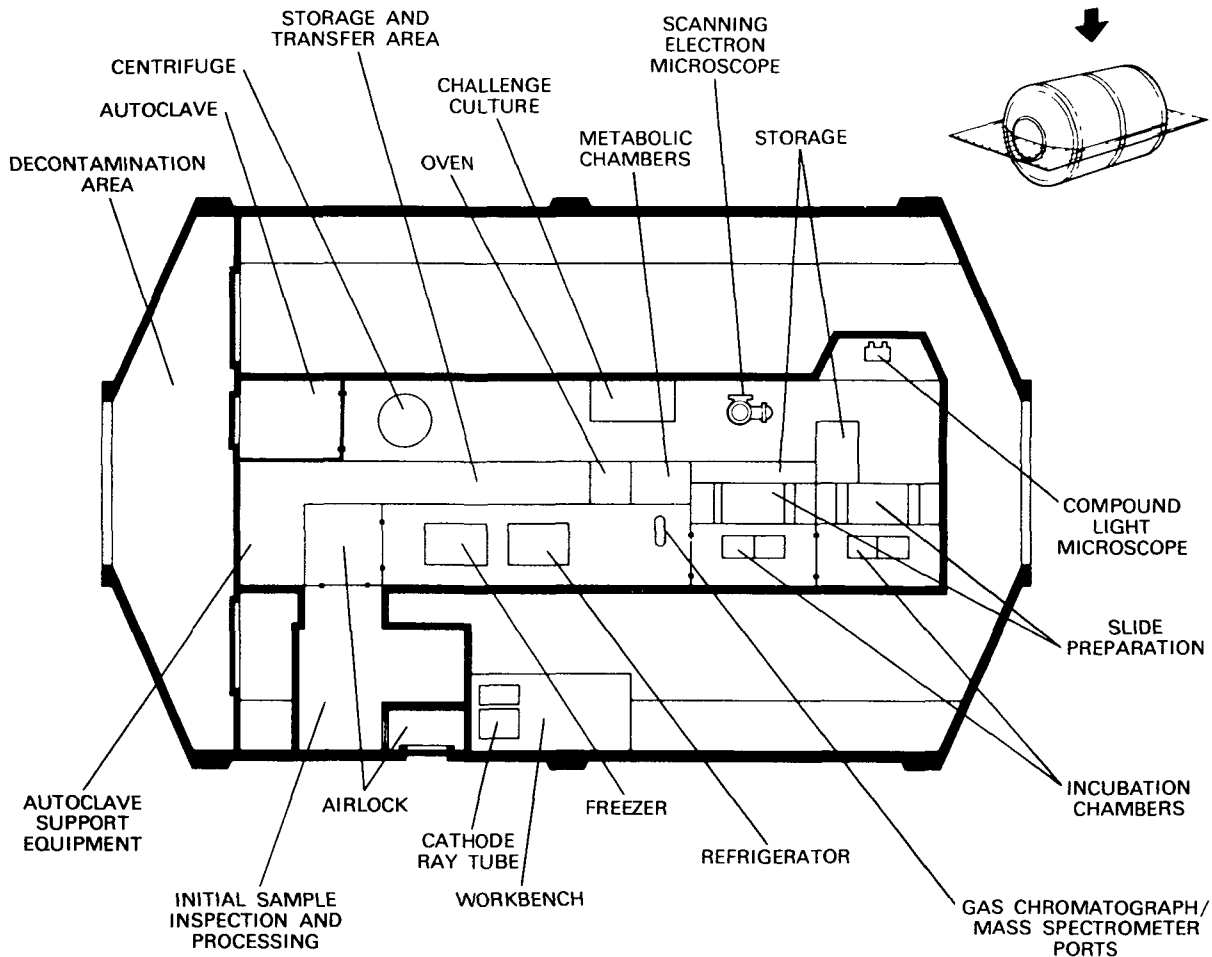


Figure 5-3.—A longitudinal view of the Laboratory Module.

accessible through a door in the work platform, so that the work surface is unbroken.

The gas chromatograph/mass spectrometer and scanning electron microscope also have their major components housed beneath the cabinetry. By locating the major mechanical components of these systems outside the primary barrier, repairs are facilitated. To facilitate viewing of slides with the light microscope, an overhead TV screen will be used, as shown in figure 5-4.

In the cabinet's center, there is a section that is accessible from either side for storing equipment and (or) transferring materials across the cabinet (figures 5-4 and 5-5). Two areas (located at the lower right side of figure 5-3) are separated from the rest of the cabinetry to permit maintaining the two controlled environments required in the microbiological section of the protocol, once the sample has passed through the airtight doors, these chambers are purged of the

aerobic atmosphere, and the anaerobic or microaerophilic atmosphere is introduced for the culture experiments.

To resupply the cabinet system without contaminating the sample, a double-door autoclave/heat/gas sterilizer is located on the left end of the cabinets (figure 5-3). Supplies are brought into the decontamination area, placed in the sterilizer, sterilized by the appropriate means, and then passed into the cabinet line through the inner door. Expendables exit in the reverse manner and are placed in the waste storage area beneath the module, such sterilized materials do not constitute a contamination hazard to the crew.

Another feature noted in the floor plan (figure 5-3) is the decontamination area located at the left end of the module. In addition to providing access to the laboratory from the Docking Module, the decontamination area is a major feature in establishing the Laboratory Module as a secondary barrier against

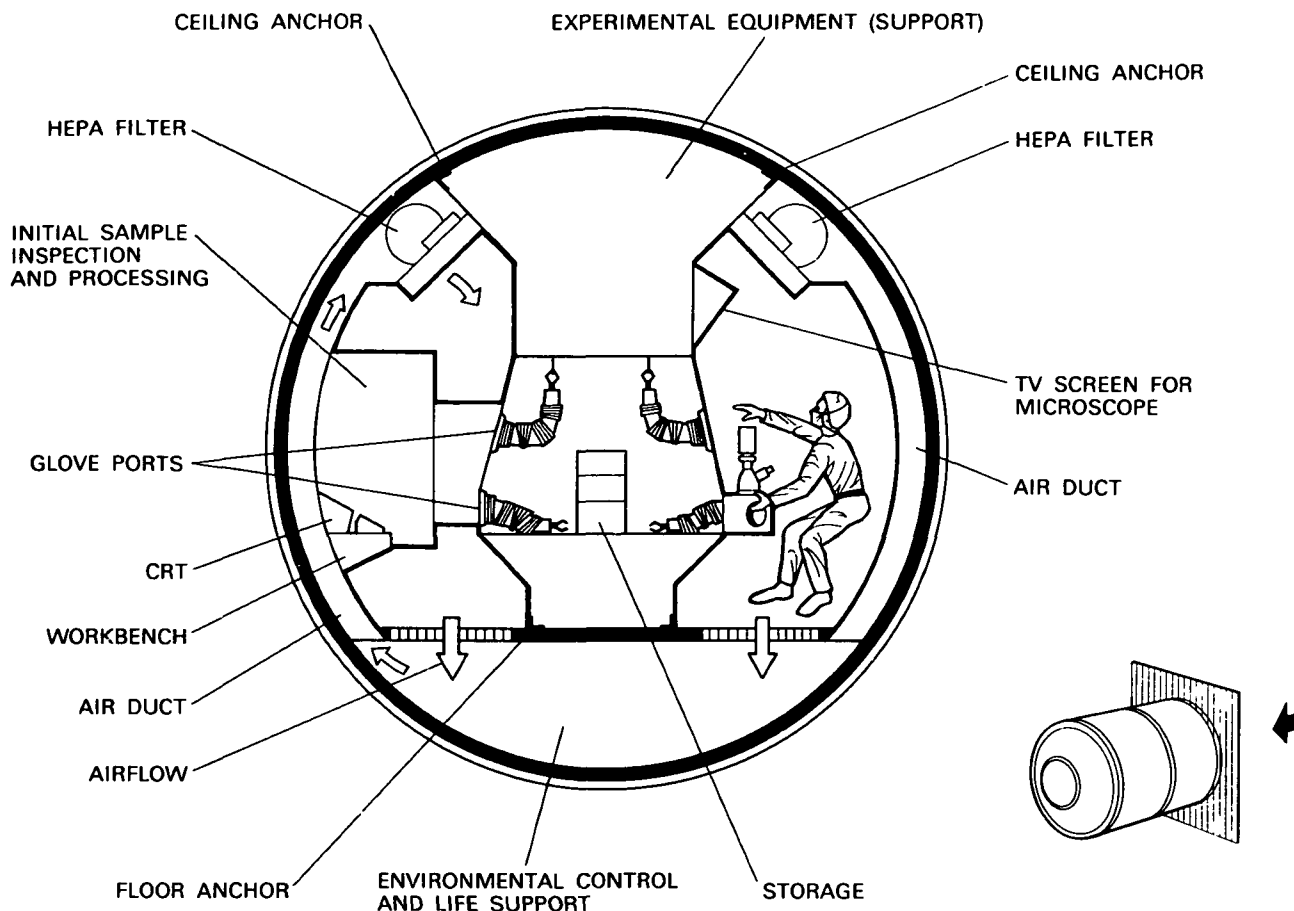


Figure 5-4.—A cross-sectional view of the Laboratory Module.

back contamination (see "Containment Assurance Procedures," page 95).

Work space, communications equipment, and data terminals are located around the perimeter of the cabinet system.

LABORATORY EQUIPMENT

Rationale for Equipment Location

The position of each piece of equipment within the cabinetry, as shown in figure 5-3, was selected after considering the size of the equipment, its frequency of use, environmental requirements, support equipment requirements, material handling, and maximum utilization of available space. For example, the microscopy area is designated to be at an extreme corner of the cabinet system because lengthy microscopy studies are anticipated. Consequently, laboratory personnel en-

gaged in these studies will not be disturbed by concurrent activities in the laboratory. On the other hand, the GC/MS is centrally located because it is required for a number of experiments.

Required Equipment

The list of laboratory equipment for the OQF (table 5-3) has been compiled based on the needs of the protocol experiments. The equipment listed is in various stages of development, ranging from space-ready hardware to items only in a conceptual stage; additional comments on projected development time and specifications can be found in references 9 and 11 through 15. Specialized equipment must also be designed and developed to carry out the many manipulations required by the individual experiments (table 5-4) in a zero-g environment. Although these tasks are easily performed on Earth, basic research will

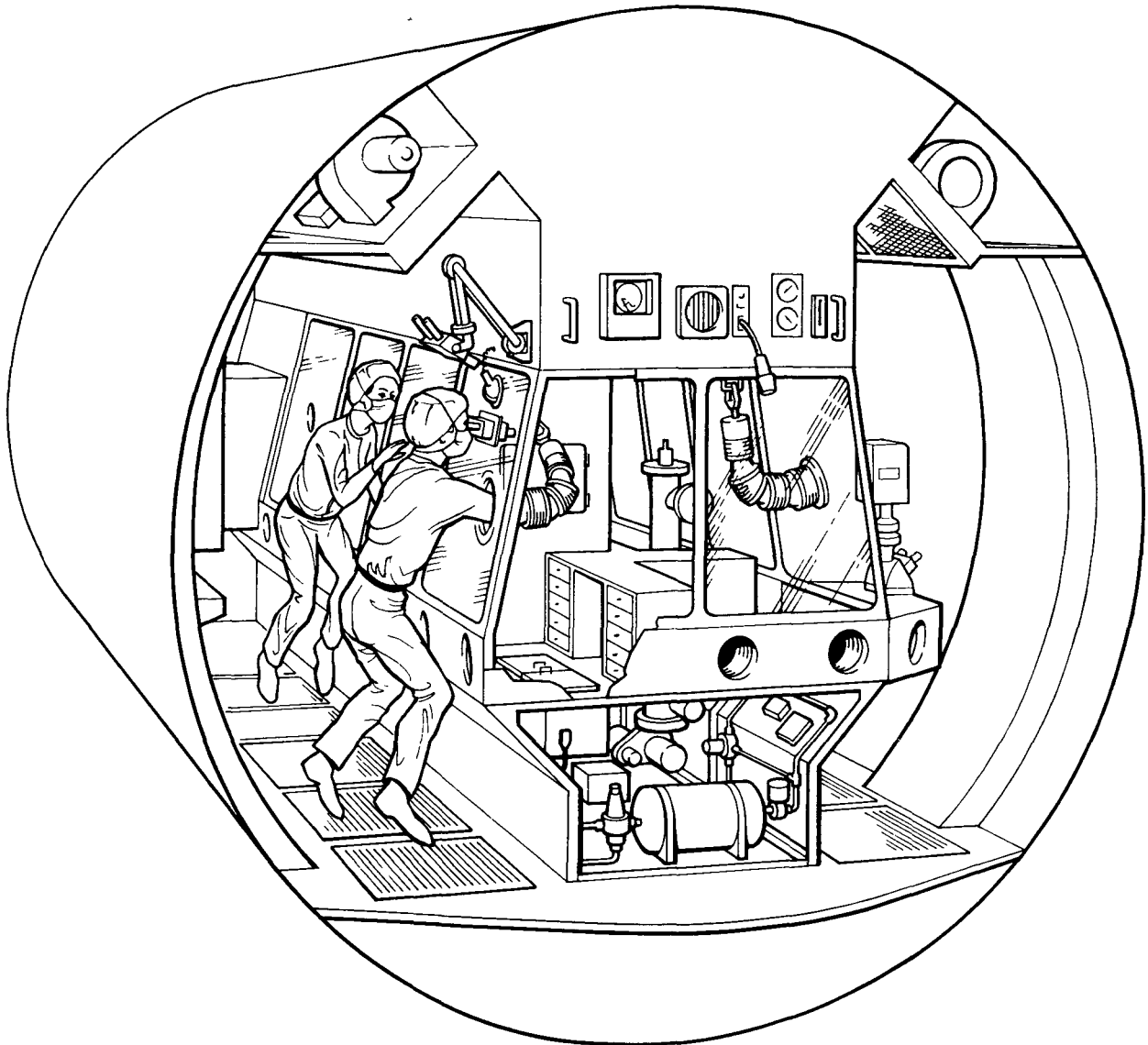


Figure 5-5.—Laboratory personnel viewing slides with a light microscope.

be needed to determine how best to perform them in the absence of gravity.

ENVIRONMENTAL CONTROL

The environmental control and life support (ECLS) system in the Laboratory Module is almost identical to that in the Habitation Module, except that the laboratory's ECLS system is self-contained, using filtered, recirculated air throughout the module. Air is decontaminated by passage through a series of HEPA

filters (ref. 7) which remove 99.97 percent of particles $0.3 \mu\text{m}$ or larger. The air exiting the filter is distributed in a laminar flow field across the face of the cabinets so that any contaminants leaking from the cabinet will be swept down and away from the personnel (this also protects the sample because the air pulled through any leak will be sterile). The air then passes through ductwork back to any of 10 HEPA filters arranged in banks of five on each side of the glove box (figure 5-4).

This ECLS system will meet the standards of a Class 100 (refs. 15, 16) clean atmosphere because: it will not exceed 3.5 particles per liter of air; it is a

TABLE 5-3.—EQUIPMENT LIST FOR THE OQF LABORATORY

<i>Item/Specifications</i>	<i>Power (W)</i>	<i>Weight (kg)</i>	<i>Volume (cm³)</i>	<i>Ref No.</i>
1 Alpha particle instrument	2	1.8	81.0×10 ⁰	12
2. Autoclave	300	11.0	34.7×10 ³	1, 9
3. Autoradiograph	0	1.0	1.0×10 ³	—
4. Camera, roll film	0	2.0	2.0×10 ³	11, 13
5 Camera, video (color)	70	7.0	6.2×10 ³	13
6. Centrifuge	2×10 ³	100.0	5.0×10 ⁵	9, 11
7. Dry heat sterilizer, drying oven	50	2.3	8.5×10 ³	9, 11
8 Electroanalytical apparatus, conductance bridge	10	9.1	28.3×10 ³	9, 11
9 Freezer, freeze dryer	300	15.0	61.0×10 ³	9, 11
10. Gas bottles	0	68.0	141.6×10 ³	9, 11
11. Gas chromatograph/mass spectrometer	50 ^a	10.0 ^a	27.0×10 ³ ^a	14
12. Impedance bridge	1	1.0	1.0×10 ³	—
13. Incubator	60	10.0	20.0×10 ³	9, 11
14 Kits, microbiology	0	1.0 ^a	1.0×10 ³	—
15. Liquid nitrogen dewar	0	50.0	56.6×10 ³	9, 11
16. Mass measurement device, micro	1	2.0	1.0×10 ³	9, 11
17. Micromanipulator	10	2.0	14.0×10 ³	4
18. Microscope, compound, phase contrast, UV	25	5.0	14.0×10 ³	9, 11
19. Microscope, scanning electron	500	70.0	5.0×10 ⁵ ^a	9, 11
20. Microscope, stereoscopic	30	12.0	22.0×10 ³	9, 11
21. Mixer/shaker	10	2.2	8.5×10 ³	9, 11
22. Plate scanner, counter	20	9.0	28.3×10 ³	9, 11
23. Refrigerator	50	10.0	25.0×10 ³	11, 13
24. Scintillation counter	10	4.5	5.6×10 ³	11, 13
25. Spectrophotometer, UV, visible	10	2.3	28.0×10 ³	11, 13
26. Tissue culture chamber and maintenance system	10	15.0	16.0×10 ³	9, 11
27. Ultrasonic cleaner	30	10.0	28.3×10 ³	11, 13
28. Vacuum cleaner	10	1.0	2.0×10 ³	—
29. Vacuum dessicator	0	4.0	56.0×10 ³	11, 13
30. Vacuum evaporator	0	4.0 ^a	50.0×10 ³ ^a	—
31. Vacuum filter	0	4.0 ^a	50.0×10 ³ ^a	—

^a Estimated

closed system; particles 0.5 μm and larger are removed from the air, and it maintains the required temperature, humidity, and pressure. The Class 100 standard is currently used in medical, research, and industrial applications requiring strict control of contaminants.

Thermal control of the Laboratory Module is maintained by using a system that employs both gaseous and liquid coolants for removing heat produced by equipment and laboratory personnel (figure 5-6). To remove heat from inside the cabinets without breaching containment, the equipment contacts a surface (a cold plate) that is cooled from the cabinet's exterior by chilled liquid. The laboratory personnel and equipment located outside the primary containment are cooled by air that is recirculated through an air-liquid heat exchanger. The liquid from the heat exchanger and the cold plates is pumped to the Power

Module, where the heat is radiated to space. (See Chapter 6.)

CONTAINMENT ASSURANCE PROCEDURES

To reduce the possibility that microbes released from the experiment cabinets are inadvertently carried to other modules by crew members, decontamination procedures similar to those used at CDC have been adopted. These procedures also help reduce the terrestrial microbial load in the Laboratory Module, thus lowering the chance of forward contamination.

Before entering the laboratory, personnel will disrobe and store their clothes in the Habitation Module. After passing through the pressurized Docking Module into the decontamination area of the

TABLE 5-4.—MANIPULATIONS REQUIRED FOR PROTOCOL EXPERIMENTS

Manipulation	Experiment												
	Gas Sampling	Radioactive Decay	Measure pH, Eh	Elemental Analysis	Aqueous Extraction	Organic Mass Spectroscopy	Amino Acid Analysis	Microscopic Examination	Gas Exchange—Dry Phase	CO ₂ Fixation—Dry and Moist Phase	Metabolism of Organic Compounds	Microbiological Experiments	Challenge Cultures
Agitate					X		X						
Dispense		X	X	X	X	X		X	X	X	X	X	X
Disperse								X	X		X	X	
Dry								X					
Filter	X		X		X		X	X				X	X
Hold In volume		X	X		X	X							X
Hold on surface			X	X				X	X	X	X		
Mix			X		X		X	X			X	X	X
Wash					X		X	X					
Weigh		X	X	X	X	X	X		X		X	X	X
Heat/cool						X/	X/	X/	X/X	X/X	X/X	X/X	X/X
Pulverize				X	X				X	X	X	X	X
Transfer		X						X				X	
Evaporate					X		X	X					
Notes.							1	2	3	4	5	6	

¹Mix with HCl

²Fixation, staining, etc., some at Mars conditions (see tables 4-1 and 4-2).

³Mars conditions, gas sampling, soil subsampling, layered emulsion (autoradiography)

⁴Radioactive CO₂, Mars conditions, gas sampling, soil subsample, layered emulsion (autoradiography).

⁵Mars conditions, gas sample, autoradiography

⁶Various conditions required.

laboratory (figures 5-3 and 5-7), they close the Docking Module's airtight door. The workers are then subjected to high-velocity, sterile air, which dislodges loose particulate matter and sweeps it to HEPA filters. Each person then uses a moist, disposable towelette impregnated with disinfectant to wipe the more heavily contaminated areas of the body (i.e., the hands, face, and neck) before dressing in protective laboratory clothing (including a head cap) obtained from the moist-heat sterilizer. To further contain bodily bacterial flora, the worker dons surgical rubber gloves and a high-efficiency face mask before opening the airtight door to the laboratory. To exit the

laboratory, the person removes all garments in the decontamination area, places them in the moist-heat sterilizer, disinfects the exposed portions of his or her body, and remains in the air shower for a set period of time. When the decontamination area is not occupied, ultraviolet lamps irradiate the area to kill microbes not trapped within the filters.

Materials destined for the laboratory area are moist-heat sterilized or (if they are heat labile) are given an air shower, wiped with disinfectant, and exposed to ultraviolet light for intervals long enough to decontaminate their surfaces.

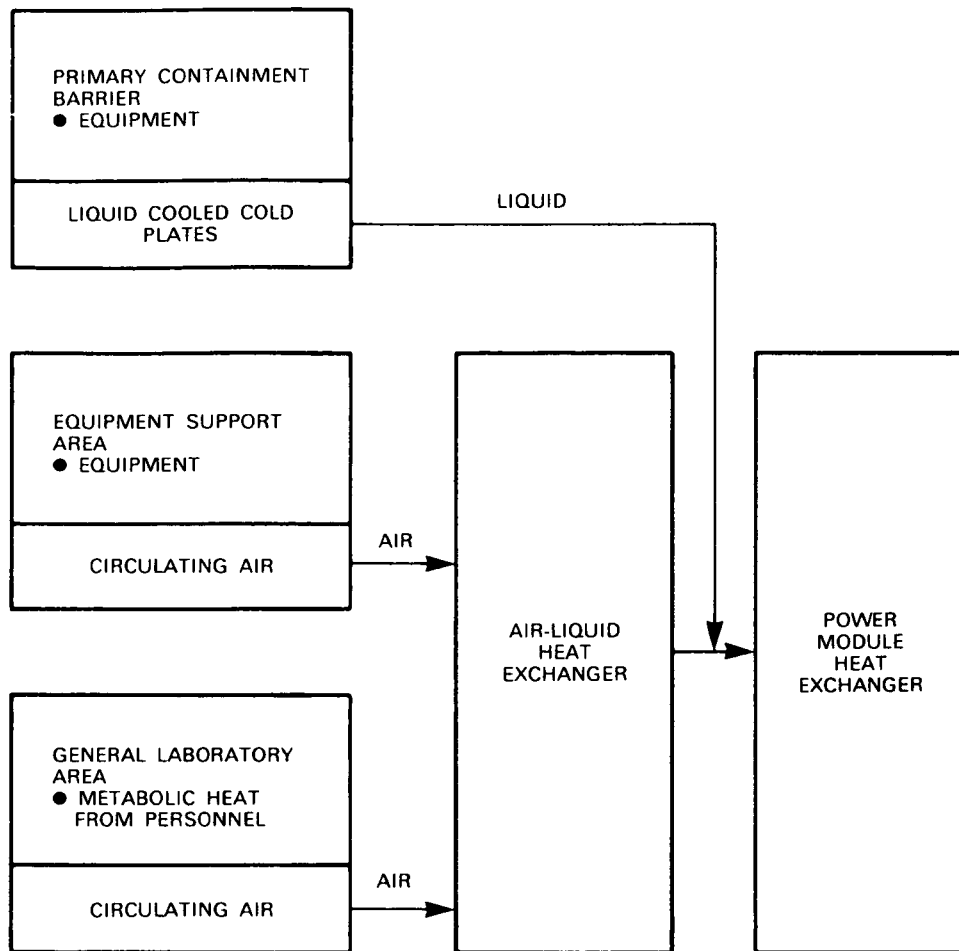


Figure 5-6.—Schematic for removal of heat from the laboratory.

Breach of containment could be caused by such obvious failures as direct puncture of the cabinetry or breakdown of an air filter located between the laboratory and cabinets. However, procedural failures, such as incompletely sterilizing materials being removed from the cabinets or accidentally increasing the cabinet's air pressure above that maintained in the laboratory, will produce the same result.

The remedial procedures followed after containment failure will depend on the type of malfunction and on whether personnel were exposed. For example, a small puncture of a cabinet that maintained negative pressure and did not expose personnel would be sealed with no additional consequence. However, if personnel and (or) the laboratory can be considered to be exposed, the contaminated worker will enter the air shower, undress, and don new laboratory clothing. A protective suit with a self-contained oxygen supply

(such as is used at CDC) is put over the laboratory clothing (figure 5-8), and the suit is pressurized to protect the worker from further back contamination. The worker reenters the laboratory and accomplishes the necessary repairs; he then wipes the protective suit's exterior with disinfectant, enters the air shower, and undresses. The laboratory (except for the containment cabinets) is treated with formaldehyde gas, which, after effectively decontaminating all exposed surfaces, is chemically neutralized to make the laboratory once again functional. If, however, it cannot be established with a high degree of confidence that laboratory decontamination was successful, and (or) that the primary barrier's integrity was reestablished, the protocol can still be completed by crew protected by the pressurized suits. Contingency plans for handling exposed laboratory personnel are described in Chapter 6.

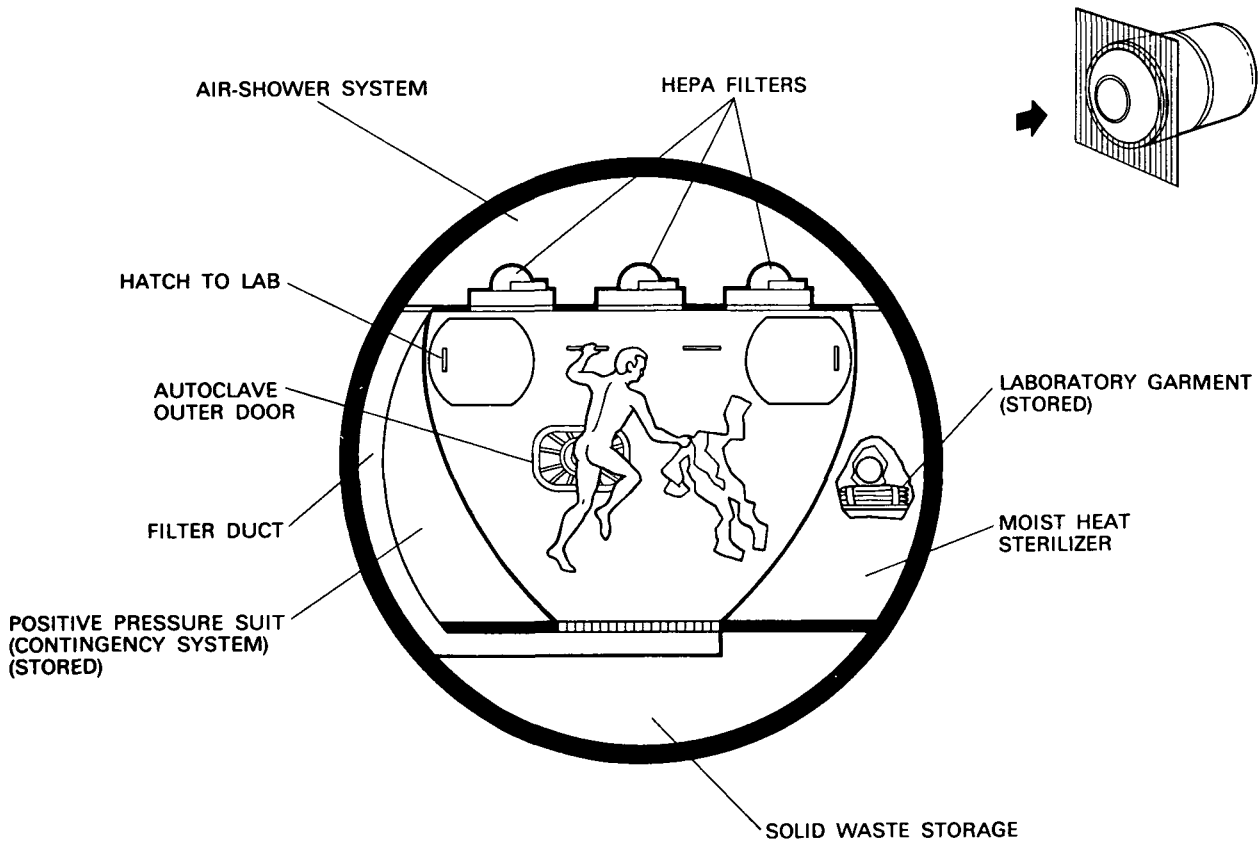


Figure 5-7.—The decontamination area of the Laboratory Module.

Appendix A—Metal Manipulative Arm

Of primary concern in the MSR facility's design is how to perform the quarantine protocol on Martian samples with maximum assurance of complete containment and reliability, yet without sacrificing flexibility and manipulative capabilities. Initially, teleoperators were being considered as the means of handling samples within the cabinets, until it became apparent that this approach was unacceptable because of its cost and the technological risks associated with its development. As a result, a hand-operated metal manipulator (a concept developed by H. C. Vykukal at NASA's Ames Research Center) is being proposed because it appears to provide almost as high a containment assurance as the teleoperators but with greater reliability.

The hermetically sealed, metal bellows manipulative arm shown in figure 5-9 utilizes proved, highly reliable technology. The device incorporates a contin-

uous welded stainless steel structure with flexible metal bellows at the shoulder, elbow, and wrist joints. The external rotary restraint linkage, a recent development at NASA's Ames Research Center, allows for normal human arm motions without the need for rotary seals in the exoskeleton structure. Despite the high pressure difference between the laboratory and that portion of the cabinetry maintained under a simulated Martian atmosphere, no noticeable force is required to flex the various metal bellows joints because the linkage geometry is such that flexing forces needed to bend the arm are balanced.

Metal bellows were first used in the highly successful Ames Hard Space Suit development program, which demonstrated that the technology was feasible. Reliability of such a manipulator was shown in tests that used standard, off-the-shelf industrial metal bellows, rather than units made to NASA's specifications. After welding, the bellows were found to have a leakage rate of 1×10^{-8} SCC/sec of helium, a value too

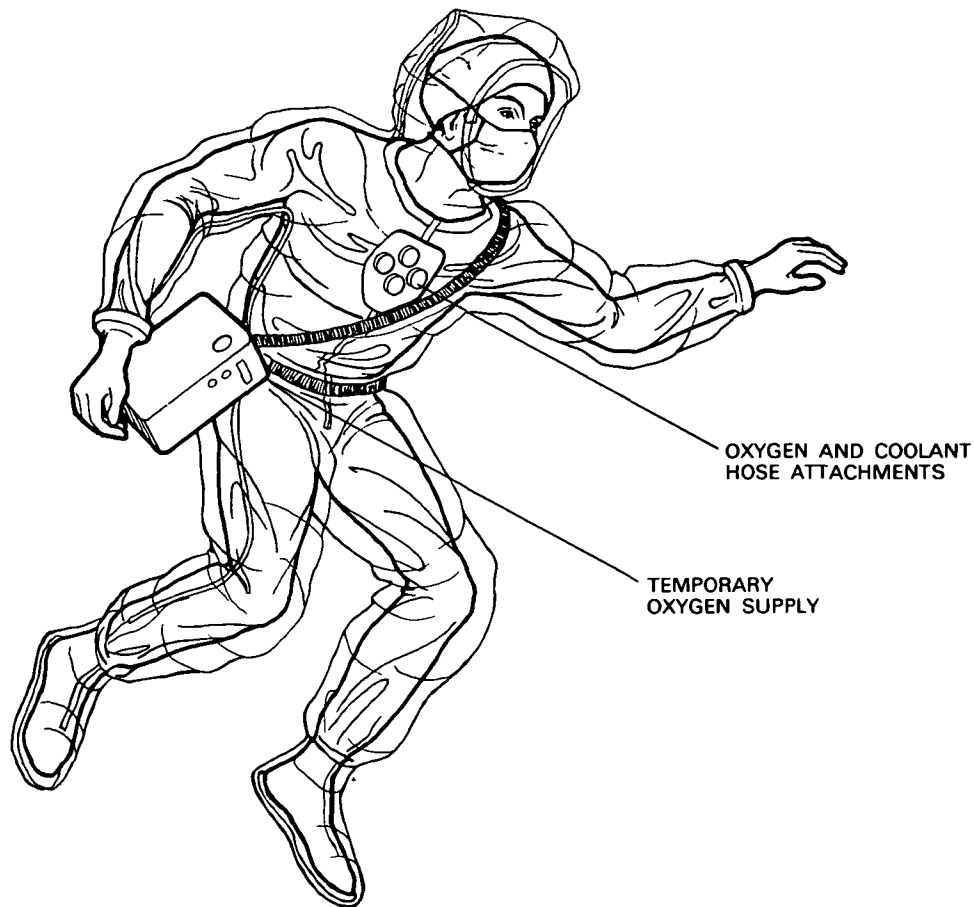


Figure 5-8.—The protective suit to be used during breaches of containment.

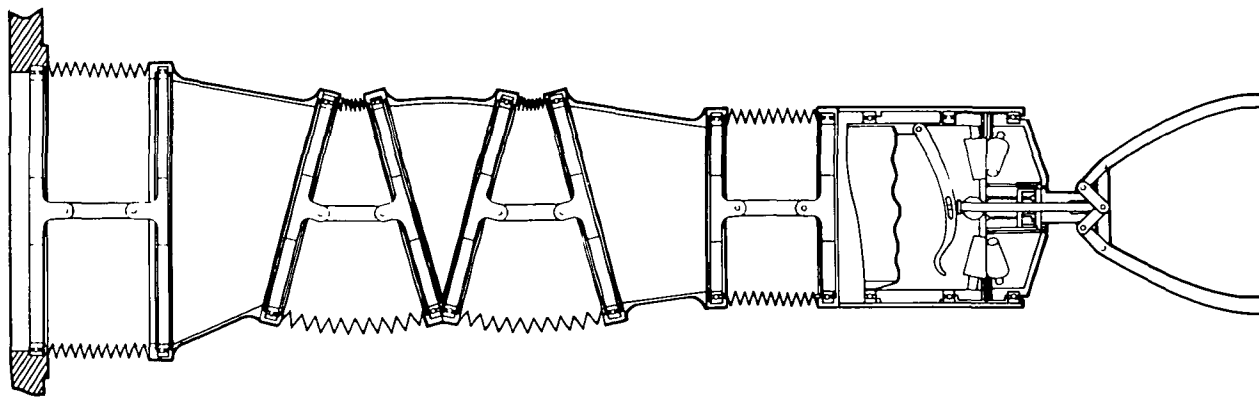


Figure 5-9.—A cutaway view of the hermetically sealed metal bellows manipulative arm proposed for use within the cabinets (courtesy of H. C. Vykukal).

low to be measured by standard leak detectors. A flexural life of over 200 000 cycles with no failure was also demonstrated using a standard industrial metal bellows. The performance of such units undoubtedly

can be improved significantly by additional quality control, better materials selection, and frequent inspection.

The effector located at the end of the arm provides

a positively sealed, mechanical means by which the operator has wrist rotation, grasp, and force control in handling samples and associated laboratory materials. A variety of interchangeable effector configurations would be provided within the work area for selection by the human operator.

APPENDIX B—Sample Receipt and Processing

In planning the MSR mission, NASA is considering many possible configurations for the canister that will be used to return the soil. As has been discussed, these vary from a canister containing loose soil to one that contains 10 individual, hermetically sealed containers (see Chapter 3, figure 3-3). The exact design chosen will weigh mission costs and technological constraints against the information to be gained by having a more complex return system. (It should be noted that with designs using more than one sample container it would be more difficult to get a representative sample for testing because each subsample container would need to be opened and processed.) Whatever design option is selected, the procedures described in this appendix can be easily adapted to it. For purposes of illustration, however, and for the sake of simplicity, the procedures outlined here are based on the use of only one (of 10) subsamples to comprise the quarantine sample for testing.

Because the materials handling system must process the samples in zero *g*, much equipment that would not be needed on Earth must be included in the design. To retrieve the MSR canister from the incoming IUS-TELLE transfer vehicle and bring it into the OQF, a collapsible structure located in the airlock, similar to the one designed for Spacelab (ref. 9), is used (figure 5-10). After the craft is guided into position by the docking cone, a trigger mechanism and clamp acquire the sample canister and draw it into the canister housing by means of a linear actuator. The docking cone and transfer vehicle are then jettisoned, the retractor structure is collapsed, and the outside airlock door is closed. If the MSR canister has not been sterilized en route from Mars, it can be decontaminated and cleaned in the airlock as described earlier. Before the inner airlock is opened, the atmosphere within the airlock is brought to a Mars-like environment. (See table 5-1.)

The canister housing is then rotated about the canister's midpoint (figure 5-11) so that the bottom of the sample canister faces into the initial processing area to permit gas sampling. The linear actuator pushes the container against a needle (figure 5-11) and the gas passes into a previously evacuated container, from which it goes to the GC/MS for analysis. Puncturing the container was considered preferable to using a valve; a valve would probably leak during the year-long voyage from Mars.

To open the MSR canister (figure 5-11) a mechanism similar to a can opener is used to remove the sample canister's bottom. Once this is done, the 10 individual quarantine sample vessels within the MSR canister are exposed to a simulated Martian environment maintained in the processing area of the glove box. The quarantine sample vessels are slightly tapered to facilitate sample removal, and an easily dislodged end plug holds the sample in the vessel after it has been removed from the MSR canister (figure 5-12). Gas sampling of the selected quarantine vessel is similar to that performed on the MSR canister, in that a needle is pushed through the thin labyrinth seal, and after the gas flows into the evacuated container, it is twisted so the needle seals itself and breaks. The gas sampling container is then taken to the GC/MS for analysis. A clamp is tightened on the quarantine vessel and it is unscrewed from the MSR canister, using a manipulator, and transferred to a sample container unit in the processing area. After the vessel is removed from the canister, the remaining subsample containers, still in the canister, are stored in a leakproof structure to ensure their pristine status. (In the case of a composite quarantine sample, the mixing of material from each subsample takes place immediately after gas sampling, and the 10 original subsample vessels are then resealed and stored.)

The absence of gravity in the OQF presents serious problems in processing the Martian material. It is necessary to provide forces on individual sample particles both to move them about and to hold them in a fixed position (as for microscopic examination). Since an artificial gravity for the OQF was dismissed early in the design process due to its cost and extensive developmental needs (see "Hardware Considerations," page 21), substitute forces must be provided within the material-handling equipment contained in the cabinetry.

The required forces could be provided as *body forces*, developed within the mass of the particles themselves. In addition to gravity, body forces are

SAMPLE CANISTER ACQUISITION

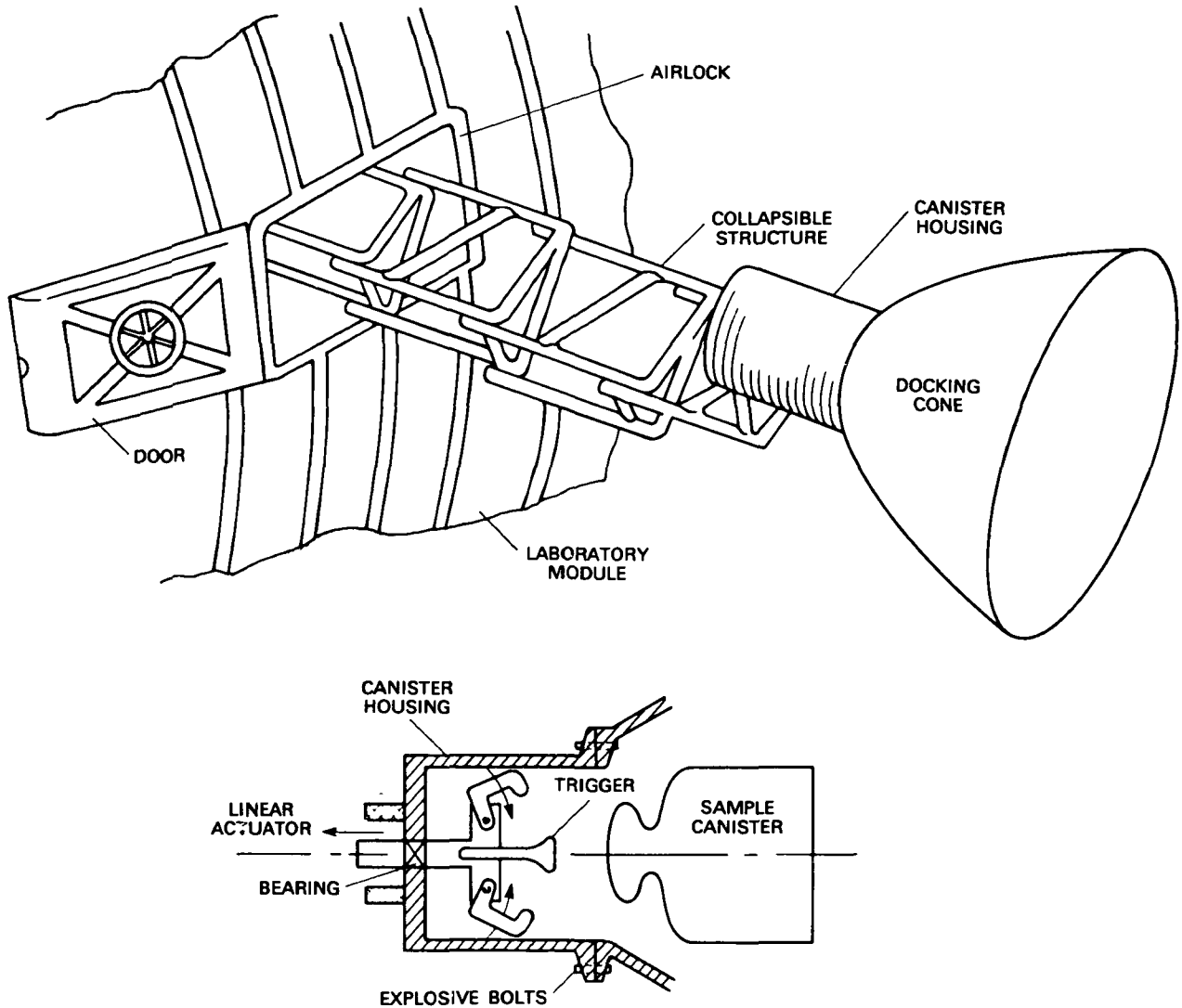


Figure 5-10.—Acquisition of the sample canister by the Laboratory Module.

produced by magnetic, electrostatic, and centrifugal rotational fields. Alternatively, *surface forces* could be generated by actually pushing the particles with moving objects such as hand- or motor-driven mechanisms, magnetic vibrators, remote magnetic actuation, piezo-electric actuation, etc. It is also possible to generate surface forces by discharging pressurized, simulated Martian gas to a gas sink, resulting in sample movement.

Of these possibilities, use of centrifugal force to move and hold the sample was selected for prime

consideration because this method seems to be technically possible, although developmental effort would be necessary. One feasible design for such a system is shown in figure 5-13. The central processing unit consists of a sample container unit whose interior design facilitates the various operations to be performed upon the quarantine sample. A centrifugal drum (figure 5-13) enclosing a simulated Martian atmosphere has rotating arms *a* (supported by bearing *b* in the drum enclosure) that spin the sample container unit and the quarantine vessel (which is

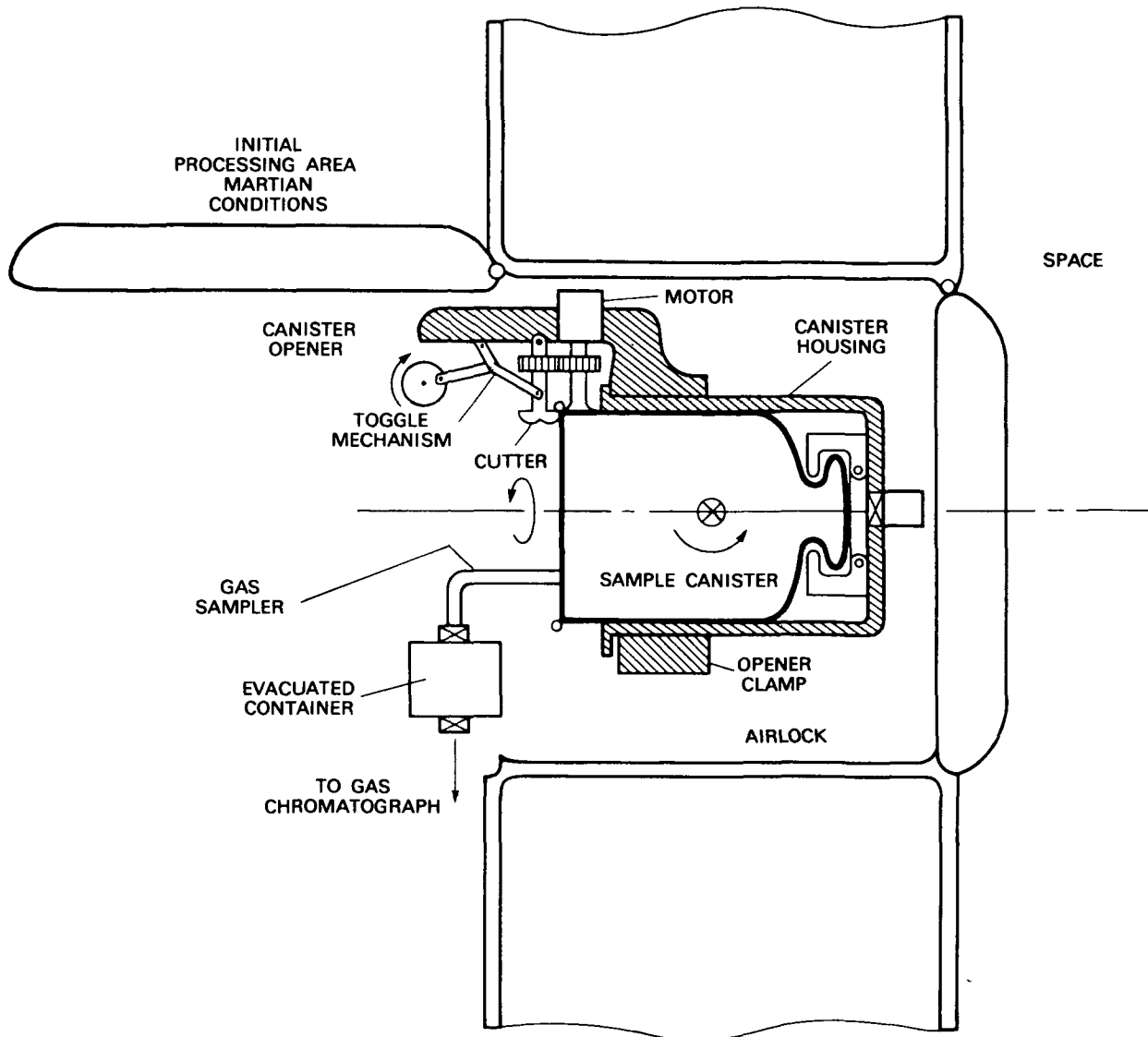


Figure 5-11.—The mechanism for acquiring a gas sample from the sample canister and for opening the canister within the containment cabinetry.

screwed into it), thereby developing centrifugal forces on the soil particles. The material is forced out of the vessel and against interior surface A so that a TV camera, movably mounted on arm c, can continuously observe the sample particles (the TV camera is powered through slip rings located at bearing b). Rotation of the processing unit on bearing c causes centrifugal forces to distribute the particles over various internal surfaces to permit sieving, mixing, dispensing, or grinding of the materials.

Figure 5-14 shows a detailed cross-section of the sample container unit, in which all handling and

processing operations necessary to prepare the protocol sample can be performed via the following sequence:

1. The unit is initially rotated on bearing c to orient the centrifugal forces in direction A. The loosely fitting plug is forced out of the vessel by the increased weight of the sample behind it, although a short internal chain prevents the plug from moving with the sample material to the opposite wall. To facilitate emptying the vessel, the pulverizing probe p may be used to agitate

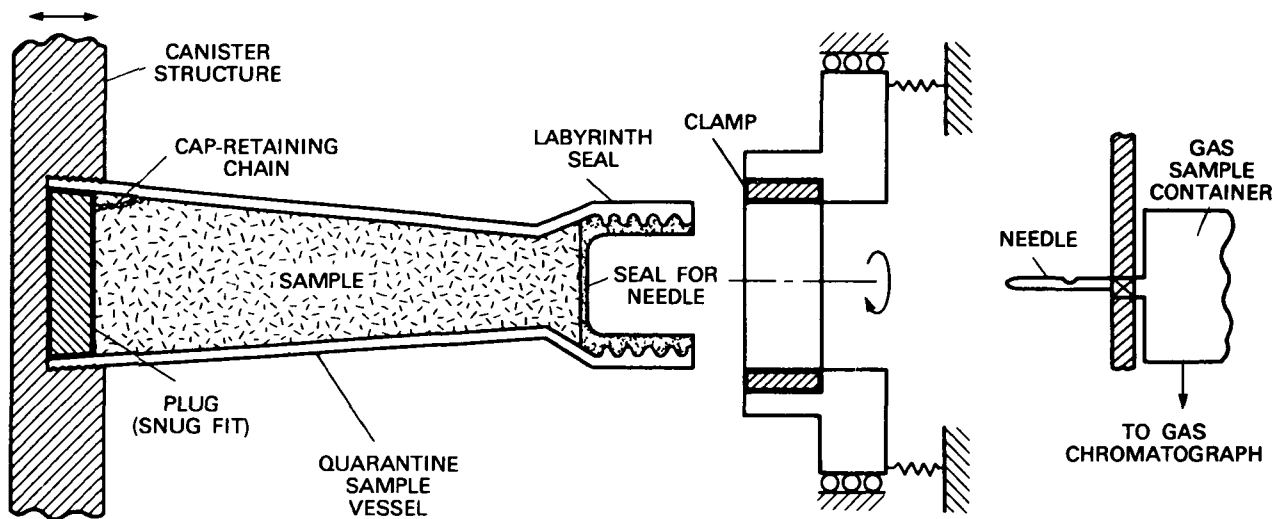
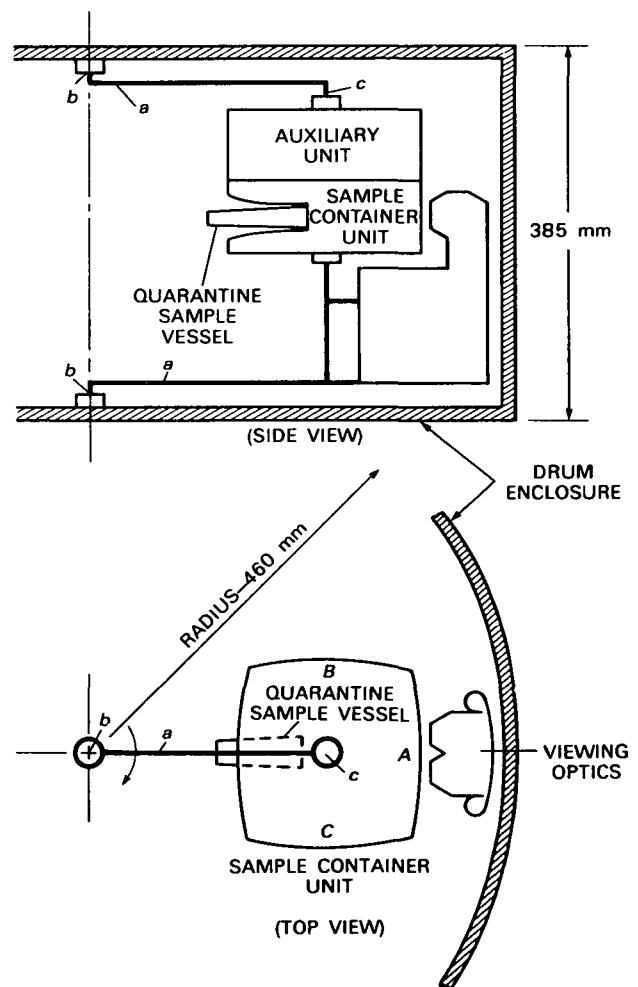


Figure 5-12.—The mechanism for acquiring a gas sample from a quarantine sample vessel and for removing the vessel from the sample canister.

Figure 5-13.—The centrifugal device employed to sieve, separate, grind, and visually inspect the quarantine sample.

- the sample vessel, or the unit can be rotated faster to increase centrifugal forces.
2. Particles less than $100\ \mu\text{m}$ in diameter are separated by orienting the processing unit to direct the centrifugal forces toward a $100\text{-}\mu\text{m}$ screen (figure 5-14). Small oscillation about point c would agitate the sample across the screen so that all small particles pass to the compartment below.
 3. Realignment of the processing unit to orient the forces in direction C will cause sample particles larger than $100\ \mu\text{m}$ to spread along the interior of glass plate g , while retaining the particles that passed through the screen in recess d . Microscopic examination of the larger particles is accomplished using the stereomicroscope TV assembly (figure 5-14), which is moved to observe the entire surface of the glass plate.
 4. To grasp and manipulate selected particles on the glass plate, a micromanipulator housed in the auxiliary unit "above" the sample container unit (figure 5-13) is inserted into the processing unit and removes sample material for storage in the auxiliary unit.
 5. Clockwise movement of the processing unit (as viewed from figure 5-14) toward D results in



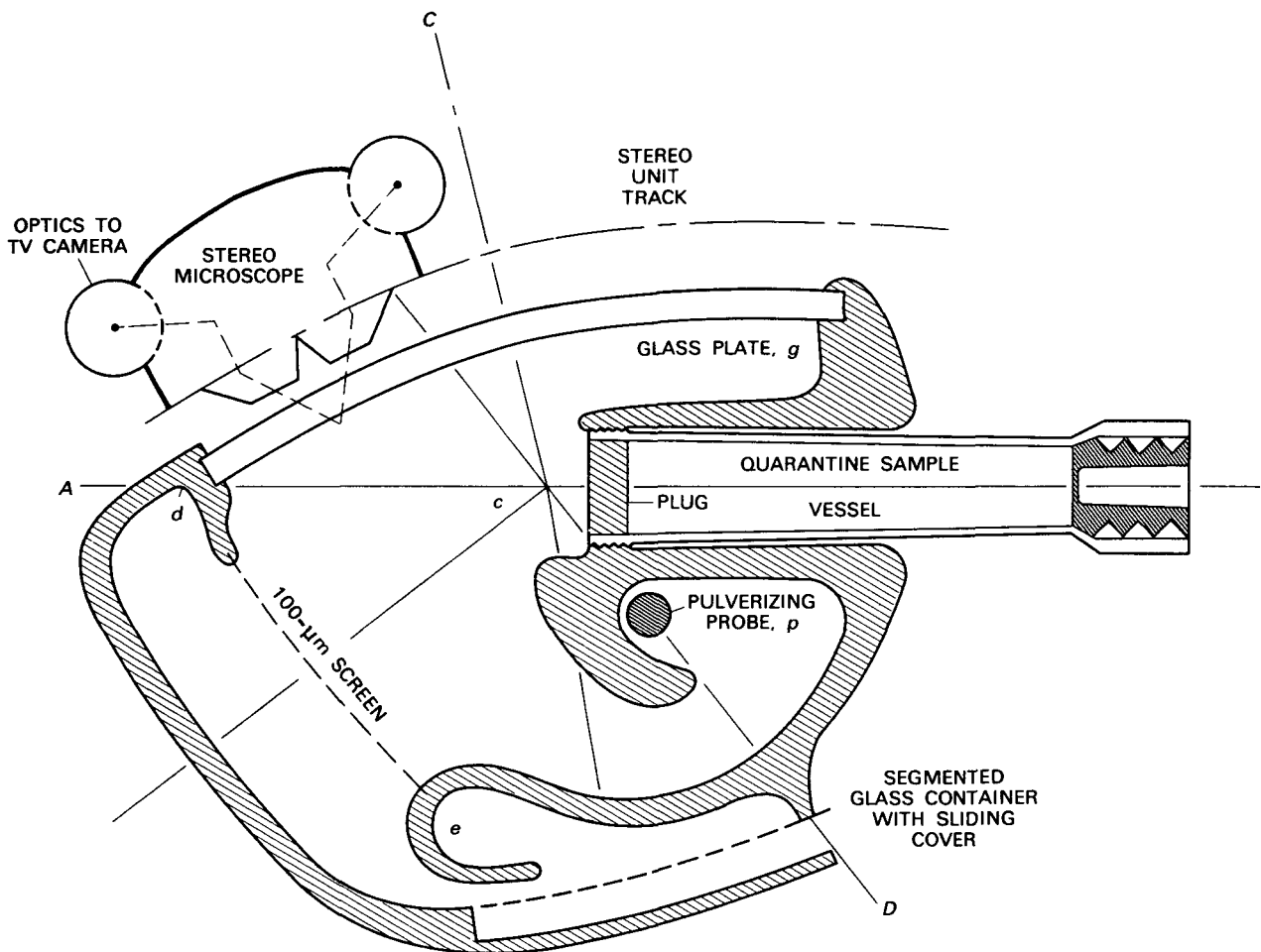


Figure 5-14.—A cross-sectional view of the sample processing unit.

centrifugal force urging all larger particles toward the pulverizing probe *p*. Actuation of this probe at suitable frequencies grinds larger particles. The particles below the screen are retained in a pocket *e*.

6. After pulverizing, counterclockwise rotation returns the pulverized particles to the 100- μ m screen, where oscillations between directions *A* and *D* serve to increase the passage of particles through the screen and permit mixing of the sample in the lower compartment.
7. Orientation of the processing unit so that forces are toward the sample vessel results in the screened quarantine material moving into containers that, after being removed from the processor, are used to distribute the homogeneous sample to the various protocol experiment stations.

The above discussion illustrates the technological design challenges to be encountered in developing a system for processing the MSR material under zero-*g* conditions. Considerable development of equipment unique to this mission is required to perform operations considered routine in laboratories on Earth.

REFERENCES

1. Runkle, R. S., and Phillips, G. B. *Microbial Contamination Control Facilities*. Van Nostrand Reinhold Co., New York, 1969, p. 91.
2. Jackson, J., Bond, R., and Gunderson, R. Neutral body posture in zero-*g*. *Skylab Experience Bulletin*, No. 17, July 1975, 38 pp (JSC-09551)
3. Michaelsen, G. S., and Mahoney, T. A. *Personnel Management Techniques Necessary to Maximize*

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- Bio-BARRIER Integrity at a Martian Receiving Laboratory. Annual Report, July 1, 1974–June 30, 1975.* Minnesota University, Minneapolis, June 30, 1975, 13 pp. (NASA–CR–142963, Grant NGL–24–005–160)
4. E. Leitz Co. *Leitz Micromanipulator Catalog* Rockleigh, New Jersey, 1978, 8 pp.
 5. Miyakawa, M. The Miyakawa remote-control germfree rearing unit. *Annals of the New York Academy of Sciences*, Vol. 78, 1959, pp. 37–46.
 6. Sweet, H. C. Surface decontamination in an autoclave chamber with formaldehyde gas. *Applied Microbiology*, Vol. 22, 1971, pp. 250–251.
 7. Agnew, B. *The Laminar Flow Clean Room Handbook, 3rd edition.* Agnew-Higgins, Garden Grove, California, 1968, 233 pp.
 8. Guyton, H. G., and Decker, H. M. Respiratory protection provided by five new contagion masks. *Applied Microbiology*, Vol. 11, 1963, pp. 66–68.
 9. General Dynamics/Corvaar Division. *Definition of Life Sciences Laboratories for Shuttle/Spacelab. Volume 5: Life Sciences Laboratory System Requirements Data Book. Book 3 Preliminary Equipment Item Specification Catalog.* San Diego, California, December 1975, 319 pp. (NASA–CR–144124; CASD–NAS–75–054–Vol–5–Bk–3)
 10. Levin, G. V., and Hall, J. M. Quarantine concepts for a Mars return sample mission. In *Life Sciences and Space Research, Volume XV, Proceedings of the Open Meeting of the Working Group on Space Biology of the 19th Plenary Meeting of COSPAR, Philadelphia, Pennsylvania, June 8–19, 1976* (ed. by R. Holmquist and A. C. Stickland). Pergamon Press, New York, 1977, pp. 15–19.
 11. Kail, L. T. *Requirements Study for a Biotechnology Laboratory for Manned Earth Orbiting Missions. Volume 1: Results, Recommendations and Requirements.* McDonnell Douglas Co., Huntington Beach, California, August 1969, 169 pp. (NASA–CR–1408)
 12. Economou, T. E., and Turkevich, A. L. An alpha particle instrument with alpha, proton, and X-ray modes for planetary chemical analyses. *Nuclear Instruments and Methods*, Vol. 134, 1976, pp. 391–400
 13. Throff, R. G. *Development and Characteristics of the Hardware for Skylab Experiment S015.* Lyndon B. Johnson Space Center, NASA, Houston, Texas, September 1975, 44 pp. (NASA–TM–X–58164, JSC–09728)
 14. Finnigan Instruments. *Finnigan Handbook. 4000 Series GC/MS System.* Sunnyvale, California, 1978, 140 pp.
 15. Austin, P. *Design and Operation of Clean Rooms, Revised edition.* Business News Publishing Co., Detroit, Michigan, 1970, 452 pp.
 16. General Services Administration. *Federal Standard Clean Room and Work Station Requirements, Controlled Environment.* Washington, D.C., April 24, 1973, 35 pp. (Fed. Std. No. 209B)
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Chapter 6

Support Systems of the Orbiting Quarantine Facility

The preceding chapters have outlined the general design of the OQF, described the mission rationale and experimental protocols, and defined the hardware required for the protocols. This chapter describes the physical support systems, the personnel management structure, and the contingency systems necessary to permit the OQF to function as an integrated system.

The interactions between the subsystems within the preassembled modules are illustrated in figure 6-1. The Power Module generates and distributes electrical power throughout each of the four modules, stabilizes the OQF's attitude, and dissipates heat generated throughout the system. The Habitation Module is a multifunctional structure designed to monitor and control all aspects of the system's activities. Through its command console it processes incoming and outgoing data and controls communications with the ground and within the OQF; its life support equipment provides air regeneration, water purification, and waste treatment; and the habitation area provides the crew with living quarters and medical facilities. The Logistics Module stores the supplies needed for 30 days of operation and provides storage for waste materials generated during the mission. Monthly supply of the facility is accomplished by exchanging the Logistics Module with a new unit transported to the OQF by the orbiter portion of the Space Shuttle. The Laboratory Module contains the equipment necessary for executing the protocol, as well as an independent life support system. Its design and functions were described in Chapter 5.

All of the physical support systems have backup components that are designed to operate during a malfunction of the primary component. Contingency plans have been formulated to deal with emergencies such as fire, crew illness, a break in the sample containment that exposes the crew to potentially hazardous material, and equipment failures. A management scheme has been developed that specifies the

personnel requirements, management procedures, and work schedules.

MODULES

General Structural Aspects

The component modules of the OQF utilize a common primary structural design, although the internal arrangement, furnishings, and equipment within each differ. A primary constraint on module design is imposed by orbiter limitations on payload size and mass, and weight distribution (ref. 1). Because these requirements and subsequent designs have been well detailed for the orbiter (refs. 1, 2), only a brief overview will be made here.

Modules will be designed for a minimum functional lifespan of 15 years in orbit. Each module will be fabricated from a series of section rings, constructed of waffled 2.5-cm thick aluminum panels that are longitudinally welded together and formed into rings (figure 6-2). Each section is thoroughly insulated on the inner surface and is provided with an overhead viewing window. The conical end caps are formed from chemically milled and machined panels that have a 1.3-m wide portal with sealable hatch and small docking viewports. Assembly of the end caps and section rings is accomplished with bolted flanges and airtight seals; the resulting module is suitable for orbiter transport and can be docked with other units in space, where it is pressurized to approximate Earth atmospheric conditions.

Within the shell, internal furnishings which are essential to the module's particular mission are bolted or bonded in place to resist impact loads of 136 kg (300 lb). The floor is an aluminum-beam frame supporting honeycomb sandwich panels having a capacity of 500 kg/m² (102 lb/ft²). The area below the floor is used for storage and to house the ECLS

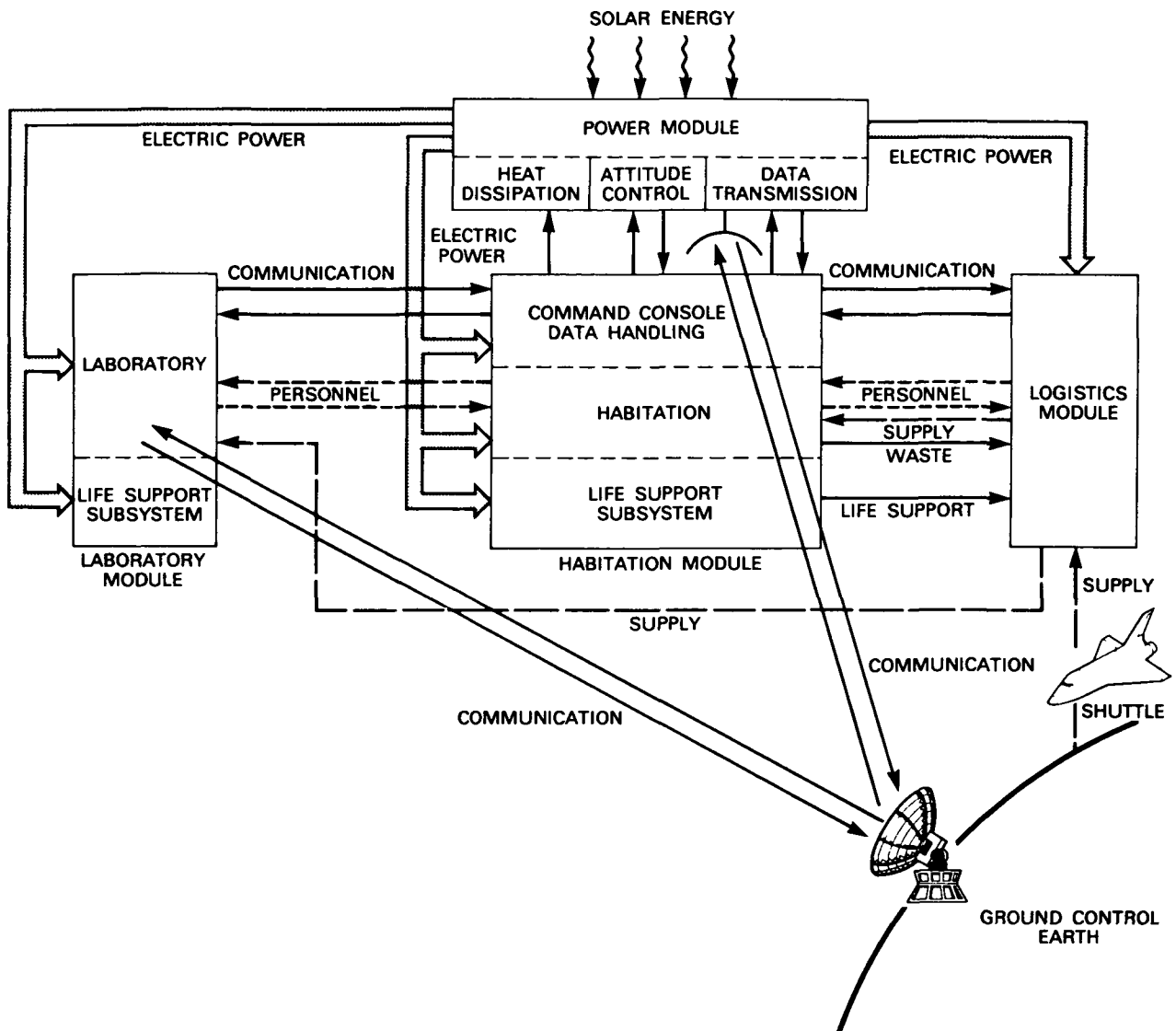


Figure 6-1.—An overview of the support network that allows the OQF to function as a system.

system. An integral component of the modules is an electronic network that permits communication throughout the entire system or with the ground from anywhere in the craft.

Power Module

In designing the OQF, it has been assumed that power modules capable of providing substantial quantities of electricity while maintaining a stable orbit and exercising system-wide thermal control would be available in the 1980s (ref. 3).

As conceived by McDonnell Douglas (ref. 4), the Power Module is transported to orbit by the orbiter with its solar cell arrays folded as illustrated in figure 6-3. Deployment of the panels to their full 631 m² (6790 ft²) of surface area exposes 636 480 solar cells, permitting the generation of 25 to 35 kw of electricity (ref. 3). The power is stored in batteries to provide energy for general applications, the scientific instruments, life support, and emergency use. Power is channeled through the system by the command console, so that the console remotely controls energy distribution.

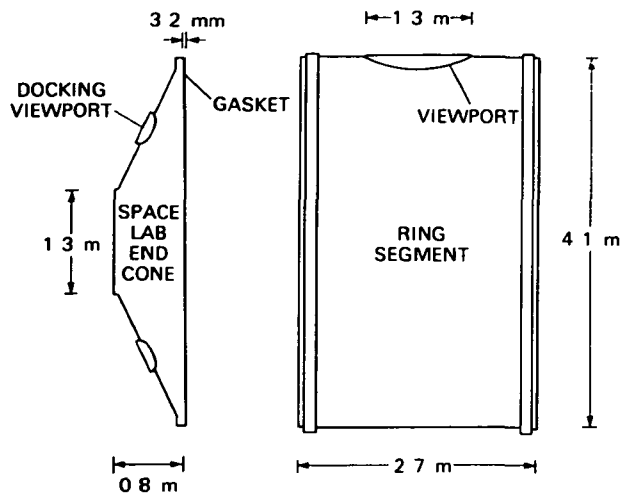


Figure 6-2.—A generalized view of a section ring and an end cap (adapted from ref. 13).

In addition to providing electricity, the Power Module will stabilize and reorient the entire facility in response to both internal and ground commands. The Power Module provides uninterrupted electrical power, despite any orbital or attitude changes, by redirecting the orientation of the solar arrays. The specifications for a system that meets these requirements have been developed by McDonnell Douglas (ref. 5) and have been adapted for the OQF.

Heat produced throughout the system is dissipated by the thermal control system located in the Power Module. A system similar to one designed by McDonnell Douglas is diagrammed in figure 6-4, cold fluid (1.7°C), continually cools the storage batteries to increase their efficiency, then enters the various modules to cool equipment (by means of cold plates) and air (by means of heat exchangers). Control valves can shunt all or part of the resulting hot fluid to

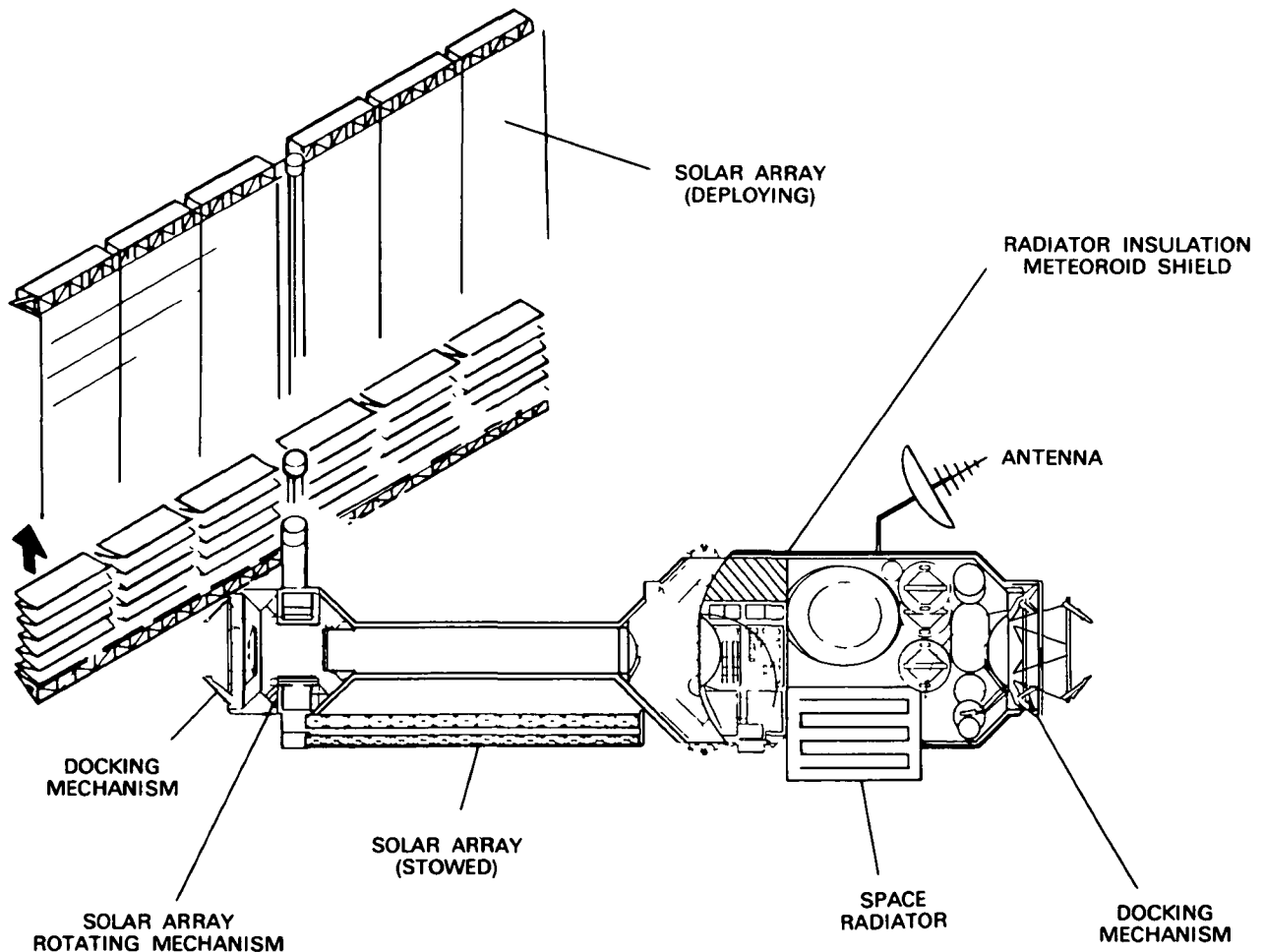


Figure 6-3.—One concept of a power module (adapted from ref. 4).

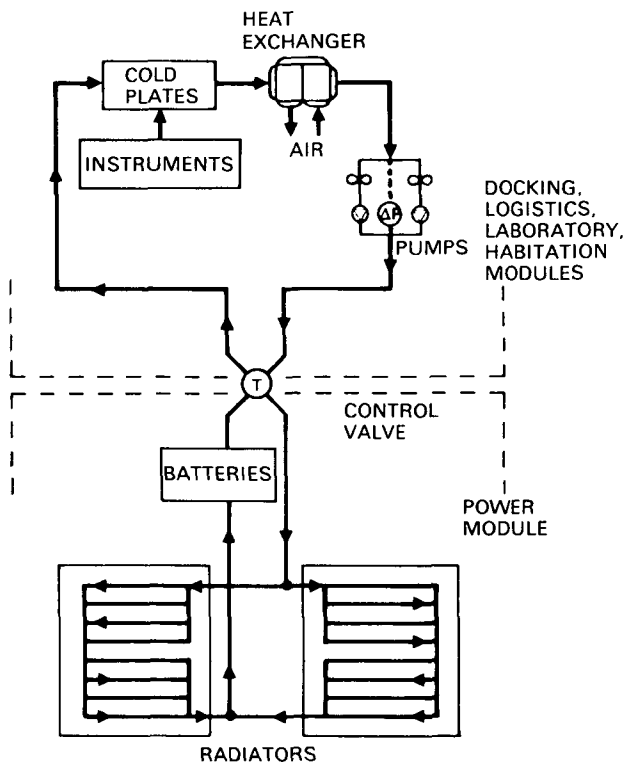


Figure 6-4.—The thermal control system proposed for the OQF (adapted from ref. 5)

radiators located on the Power Module to adjust temperature within the facility (see refs. 1 and 5 through 7 for additional information). Finally, the module is responsible for transmitting and receiving data and communications between the OQF and the ground by means of a directional antenna.

Habitation Module

The Habitation Module provides five crew members with the support equipment, furnishings, and supplies necessary for efficient and safe working conditions. The structure adopted (figure 6-5) is based on designs for Spacelab (ref. 1) and studies by McDonnell Douglas (ref. 6) and Grumman (ref. 8). The unit is constructed of four ring sections and two end caps with overall dimensions of 12.4 × 4.1 m. Approximately one half of the module's 139 m³ volume is allocated for equipment and nonhabitable uses (ref. 6).

Each crew member has private quarters (although dual occupancy may be required during crew rota-

tion), with a storage locker, sleeping bag, and fold-down desk as shown in figure 6-6. The size of these areas was determined by the free volume (ref. 9) recommended for each crewman (5 to 6 m³, or 176 to 212 ft³). A food service/recreation area has a galley and dining area that can also be used for passive recreation such as watching television or playing computer and board games. During food preparation, the tables will be stowed flush with the floor to increase space and permit unhindered access to the small food storage area across the aisle. An area for active recreation provides space for exercise on a treadmill, ergometer, and a universal exercise machine modified for use in zero g. Personal hygiene accommodations include a toilet, a shower, and a grooming station similar to those on Skylab and the orbiter (ref. 10). A waste management system provides a closed water loop for regenerating 5 kg of potable water per crew member per day (refs. 4, 6). A small workshop contains equipment (ref. 11) that will permit routine maintenance as well as emergency repair of hardware in zero g. A medical facility is located at one end of this module so that there is direct access to the Laboratory Module in the event of a laboratory emergency requiring an isolation procedure. The command console permits system monitoring and communication, both throughout the OQF and with the ground, guidance control, power distribution, and data handling (figure 6-7). Throughout the module, additional storage is provided in overhead cabinets and those regions beneath the floor not occupied by the ECLS system. The ECLS system (refs. 11, 12, 13) is designed to maintain the craft's atmosphere at conditions approximating those at sea level (i.e., 1 atmosphere of pressure, with 21 percent O₂ and 79 percent N₂), regeneration is accomplished according to the techniques developed during earlier manned missions (ref. 7).

Logistics Module

The Logistics Module is made from a single ring section and two end caps, and contains numerous storage compartments radiating out from the central access aisle (figure 6-8). The rectangular compartments permit greater organization of and easier access to the stowed materials within this very limited maneuvering space. Space between the outer ends of the compartments contains permanently stowed items (e.g., gas canisters, emergency power systems, refriger-

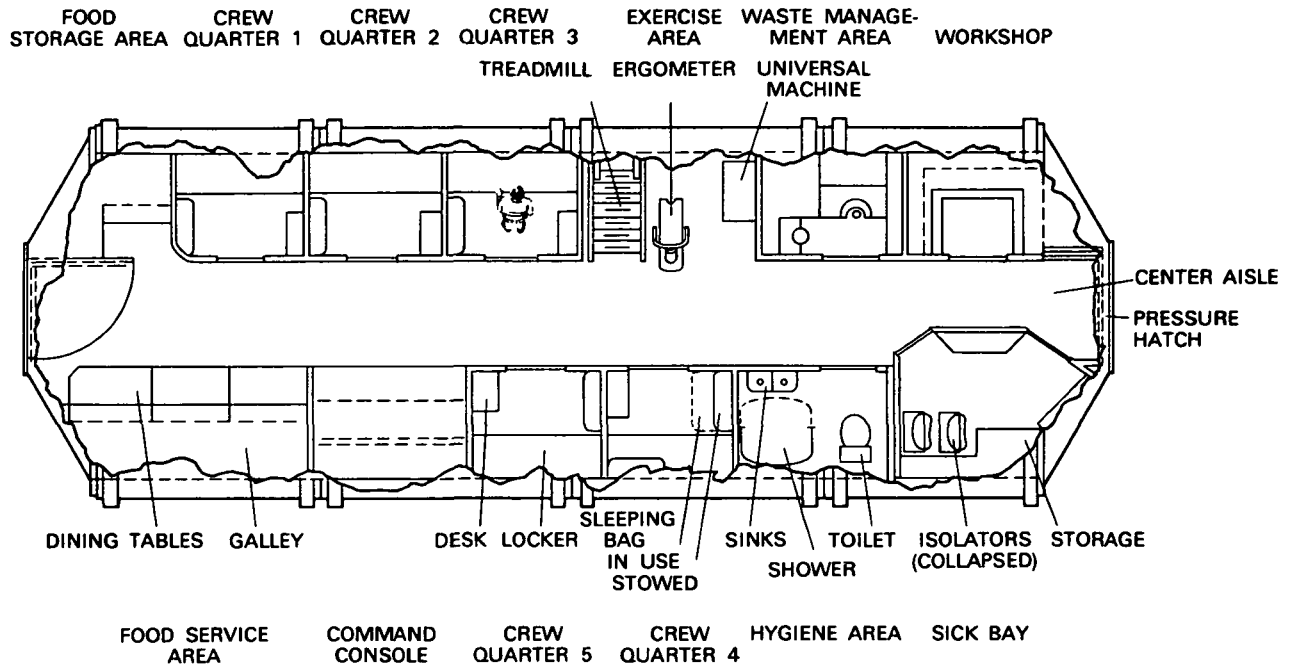


Figure 6-5.—An overhead view of the Habitation Module.

ation equipment, and back-up life support equipment).

Within the compartments, all of the supplies required to support a 30-day mission are stored. Relocation of supplies to the other modules is noted on the command console so that inventory control can be maintained. Waste materials from the Habitation Module are stored in the emptied compartments. Waste generated within the Laboratory Module, however, is retained in that unit to avoid the risk of contamination.

Docking Module

To link the component modules of the OQF in the configuration pictured in figure 3-10, a separate module will be used to provide a common interface. Owing to the general applicability of a docking module to other space missions, it has been assumed that a unit capable of connecting four to six modules will be available in the 1980s and that its structure will be heavily based on existing hardware.

All modules (and the orbiter) are equipped with an international docking mechanism (ref. 12) that can be mated with other international docking mechanisms when one is in the active position and the other is passive (figure 6-9). The modules are brought together

(using the orbiter remote manipulator system to ensure a slow closing velocity) until the latches engage; then the guide ring is retracted and additional latches are set in place to ensure formation of an airtight seal. Disengagement of the docking mechanism permits rapid separation of the modules for their return to Earth.

CONTINGENCY PLANNING

The final design of the OQF will have redundant systems to handle possible equipment and system malfunctions. In this study, particular attention has been paid to the following major emergencies: a failure of the life support system, loss of air pressure, fire, crew illness, and exposure of personnel to potentially hazardous material from the Martian sample.

The life support systems are run by electricity from the Power Module, which in turn has built-in redundant backup circuits. This assures a stable power supply for the life support systems. Normally, the ECLS system for the Laboratory Module functions independently of the atmospheric regeneration system in the remainder of the OQF. However, if the ECLS system within the Habitation Module failed, the

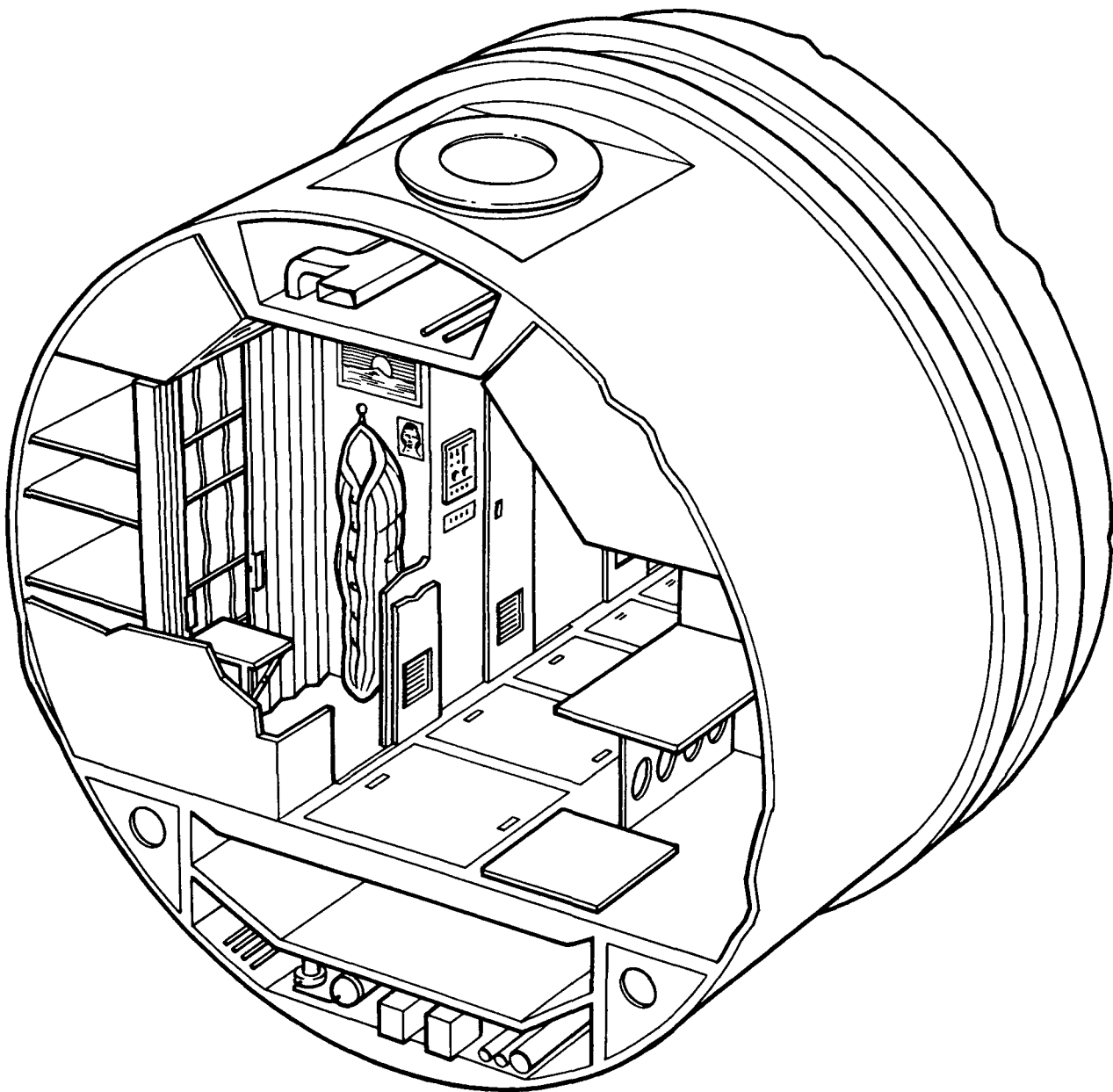


Figure 6-6.—A cutaway view of the Habitation Module showing a crew member's cabin and galley. Note removable floor sections and subfloor. One table is shown in its collapsed position.

Laboratory Module's system could be interconnected to support the entire OQF. In addition, a backup ECLS system in the Logistics Module can be activated in case of a failure in the main systems. The various contingency systems can sustain the crew for twice the maximum time needed to prepare and dispatch a rescue mission from Earth. In the event of a total system breakdown, the pressure suits located through-

out the facility could be linked to bottled air stored in the Logistics Module.

To prevent depressurization of the entire OQF in the event of an air leak, the interconnecting hatches of the leaking module would be sealed. Access from space to the depressurized module could be made through any of the undocked hatches (in the Docking Module or at the far end of the other modules) using

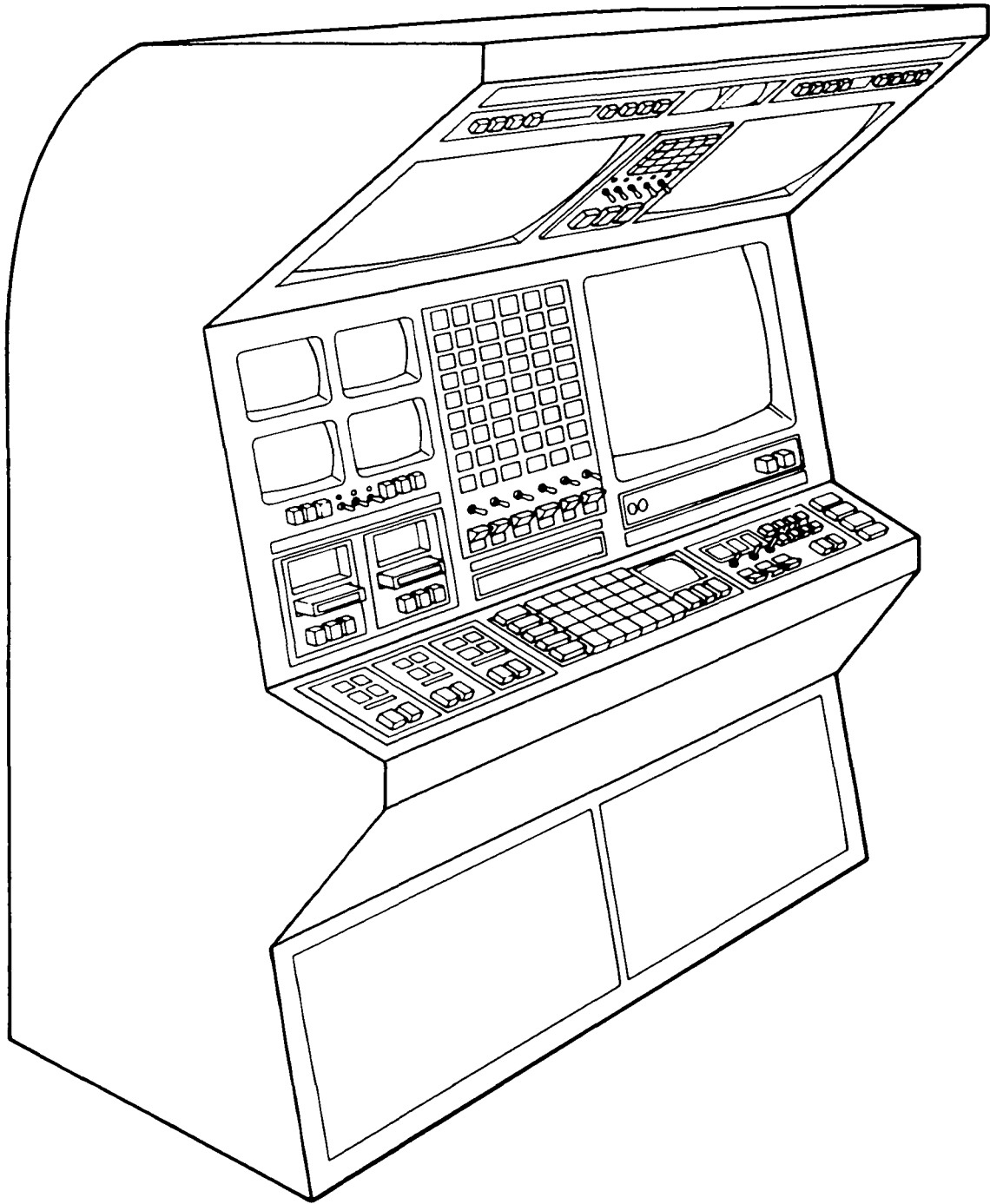


Figure 6-7.—An artist's conception of the command console (adapted from ref. 6).

pressure suits, and repairs could be made. During such crises, personnel movements to the other modules would be unaffected unless the depressurization occurred in the Docking Module, in this circumstance, extravehicular activity would be essential for intermo-

dular movements. If the module is not repairable, a replacement unit could be sent up from Earth.

Fire in a spacecraft, a frightening thought to many, is not a likely possibility in the OQF for several reasons. The OQF maintains a partial pressure of

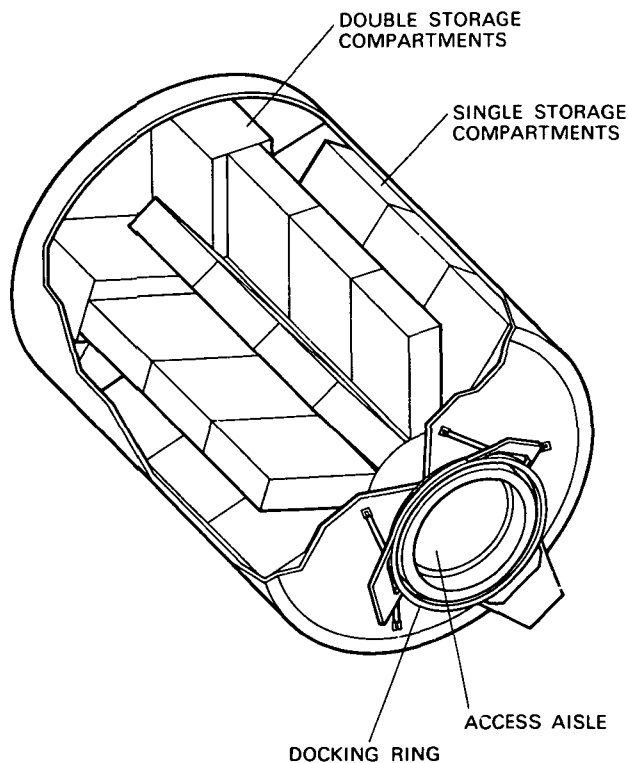


Figure 6-8.—A design conception of the Logistics Module.

oxygen equivalent to 21 percent oxygen at sea level. A gas mixture with this concentration of oxygen is far less flammable than, for example, the 100 percent oxygen system used at the time of the Apollo fire in which three astronauts died. Materials used in the OQF will also meet the rigid flame-suppressive requirements currently employed in manned space missions. Furthermore, because gravity is required to induce the convection currents that bring oxygen-rich air to the fire, flames in areas of the OQF where air is not circulating rapidly would have difficulty obtaining enough oxygen to continue burning in zero g. As an additional precaution, smoke and ionization detectors located within the air ducts will alert the crew in time to put out the fire. In the event of an extensive fire in a module, the crew will institute decompression procedures and then leave the module.

Illness of crew members in the OQF presents a serious problem because an illness may be caused by a terrestrial infection, an organic malfunction, or a Martian pathogen. To minimize terrestrial infections, a strict quarantine of all crew members will be initiated

3 weeks prior to launch. In addition, the interior of the orbiter will be surface-decontaminated immediately before launch, and the crew will be transported to it in protective garments. A prelaunch quarantine will not guarantee health, nor will it reduce significantly the number of pathogens that are carried into space, but it will reduce the chance that the crew will be exposed to a strain of pathogen to which they are not immune. However, during the crew rotation the arriving crew will be exposed to the microbial flora of the previous members, resulting in an increased chance of illness.

If a crew member does become ill after receipt of the Martian sample, he or she will be held in quarantine within the OQF until tests can confirm that the condition is either noninfectious or of terrestrial origin. The patient will be placed in one of two flexible isolators (figure 6-10), which are stored in the sickbay. The air for the isolation unit is exchanged via HEPA filters, which are balanced to maintain a slight negative pressure within the unit. Supplies can be introduced through a decontamination lock in the isolator's side, and manipulations are performed using the attached rubber gloves. If the illness is discovered to be caused by a terrestrial microorganism (or is of nonpathogenic origin), and its treatment is not possible in the OQF, the patient could be returned to Earth for additional treatment. A strict isolation procedure will be required during transport of the patient in the orbiter if the illness appears to be highly contagious.

In the event that the crew member is suspected of having an illness caused by exposure to the Martian soil or has a condition that cannot be diagnosed, the patient will remain in the isolator and be treated within the OQF in consultation with the ground medical personnel and the authorities responsible for making quarantine decisions. If there is a containment failure, decontamination of the laboratory and cleanup of the "spill" (the released contaminated material) will be performed as described in "Containment Assurance Procedures," Chapter 5. A crew member must be isolated if he or she is considered to be contaminated by Martian soil; i.e., if he inhaled and (or) ingested particles or aerosol of Martian soil (or materials that were potentially contaminated with the soil), or the material penetrated into the circulatory system through a skin lesion or through the mucous membranes. After such an exposure, the person takes an air shower and moves into an inflated isolator, which is positioned in the laboratory airlock hatch. The exposed crew member will be confined, monitored, and

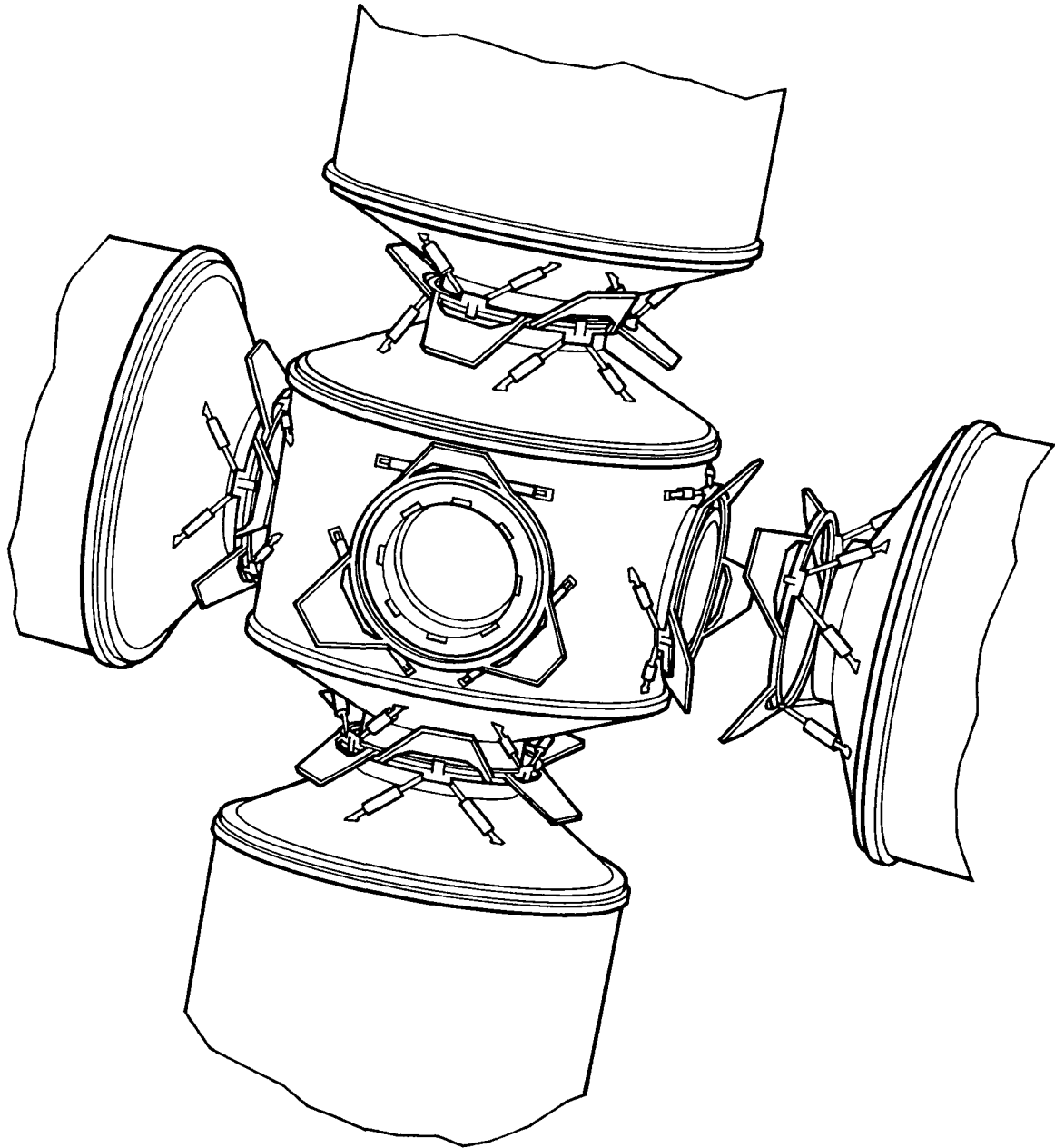


Figure 6-9.—*The Docking Module, at center, with its docking system in the passive position, being mated with a replacement module, on the right. The international docking system on the incoming unit is in the active position (note extension of docking guide ring).*

attended in the isolator for up to 21 days (ref. 14) for any pathological symptoms. If symptoms that cannot be considered as resulting from terrestrial organisms develop, the location and course of treatment will be determined by ground personnel whose responsibility it is to ensure the quarantine's adequacy.

PERSONNEL REQUIREMENTS AND MANAGEMENT

Crew Size and Capabilities

The protocol has been designed to permit as much automation and as many remotely executed tasks as

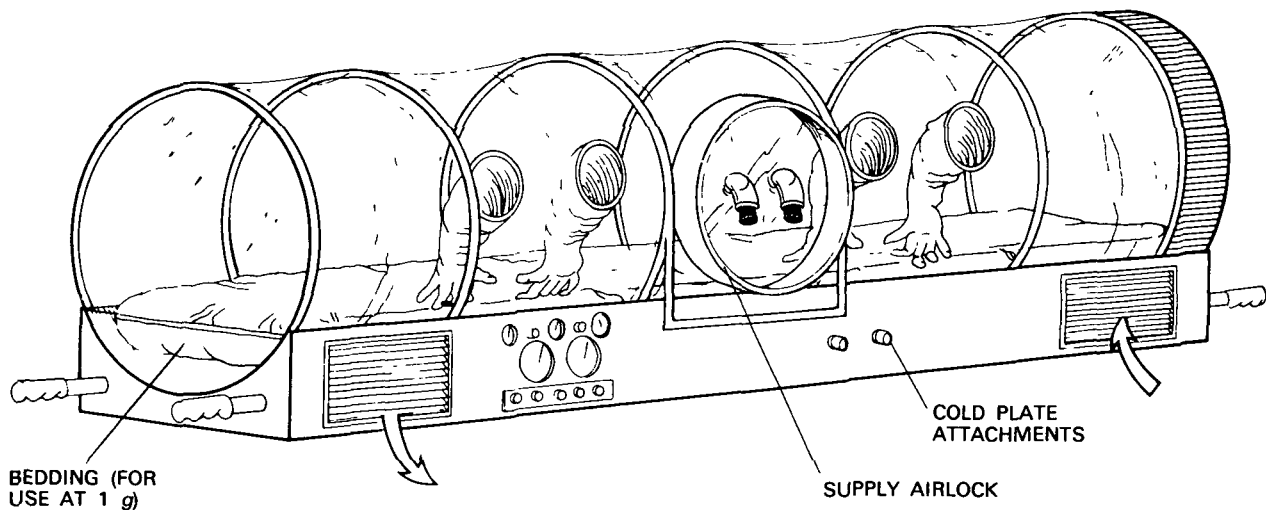


Figure 6-10.—A medical isolator suitable for zero g quarantine and transport of the patient to Earth.

possible, however, man's manipulative and judgmental skills are essential for experiments that require situational decisions. The tasks that must be performed by the crew members can be divided into two major categories:

1. Operation and maintenance of the overall facility:
 - a. Vehicle guidance and control (i.e., rendezvous with MSR, berthing, attitude maintenance);
 - b. Command decisions (i.e., system safety, management, and crew scheduling),
 - c. Systems management (i.e., medical exams, inventory, communications, housekeeping, and repair of equipment).
2. Laboratory work: Execution of the protocol and maintenance of laboratory equipment:
 - a. Experimental operations (i.e., sample handling and specimen preparation);
 - b. Data handling (i.e., recording observations and processing the data);
 - c. Containment decisions (i.e., laboratory safety considerations and quarantine maintenance).

To determine how many crew members would be required to accomplish the mission objectives and perform these tasks, several factors were evaluated. Safety considerations prohibit one person working alone in the laboratory, but more than two persons in the laboratory would find their movements somewhat impeded. The optimal research crew was therefore set at two persons working in the laboratory for 8 hours. A second shift of two workers (increasing the research crew to four) is essential to provide the manpower to complete the protocol, but the possibility of having a

third shift was dismissed, the reduced man-hours in the lab was believed to be offset by the increased performance resulting when the crew's sleep periods coincide and are not interrupted by some of the crew being active. One nonscientist crew member is needed to maintain the entire system, increasing the minimum crew size to five. This number is consistent with that suggested in other studies (ref. 15). In selecting the crew members for the mission, consideration should be given to the type of training, versatility, and backgrounds of scientists to ensure that the crew will be capable of performing a variety of tasks ranging from operating control functions to interpreting laboratory data. One suggested distribution of crew expertise is:

- Commander— An astronaut with engineering training (electrical and (or) mechanical) and proved administrative ability;
- Scientist 1— A medical doctor who is an experienced clinical researcher;
- Scientist 2— A research geobiologist with experience in the geochemical sciences;
- Scientist 3— A biochemist with a research emphasis in the microbiological sciences;
- Scientist 4— A biologist who has had extensive research experience in many phases of the biological sciences, including biostatistics.

Selected crew members will undergo a vigorous 2-year training program. They will be taught the skills needed for general housekeeping of the facility and for

repair and maintenance of the laboratory equipment, as well as how to execute the protocol.

Work Scheduling

Several considerations influenced the scheduling of crew activities during the quarantine mission. The experiences with Skylab (ref. 16) indicate that during any 24-hour crew day, 8 (± 3) hours can be dedicated to experimental work. The remaining 16 hours are allocated as follows: 5.5 (± 1) hours for eating, hygiene, and recreation; 2.5 (± 2.5) hours for system maintenance; and 8 (± 1) hours for sleep (figure 6-11). In general, one crew member, usually the commander, will be engaged in the system maintenance functions, while two crew members are in the Laboratory Module conducting experiments and functions in support of protocol testing. The laboratory work schedule is based on two 4-hour periods for each scientist, staggered so that the laboratory is manned for 16 hours per day (figure 6-12). The normal mode of operation specifies two crew members in the Labora-

tory Module; however, during crew rotation and during periods of maximum activity (such as initiating the experiments), more than two may be present. In the former case, the second shift would obtain briefings on the status of the experiments, while during high activity phases of the protocol, extra persons would be essential to help set up the experiments. During nonwork intervals, the crew members will be

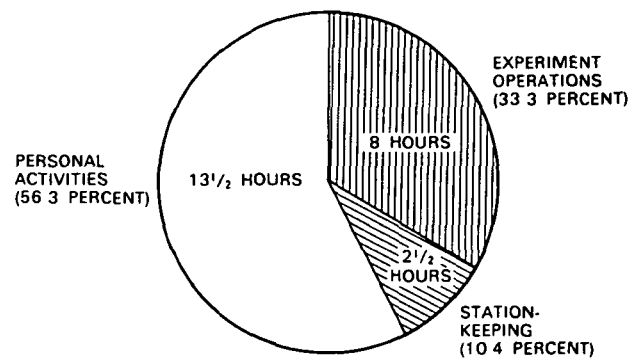
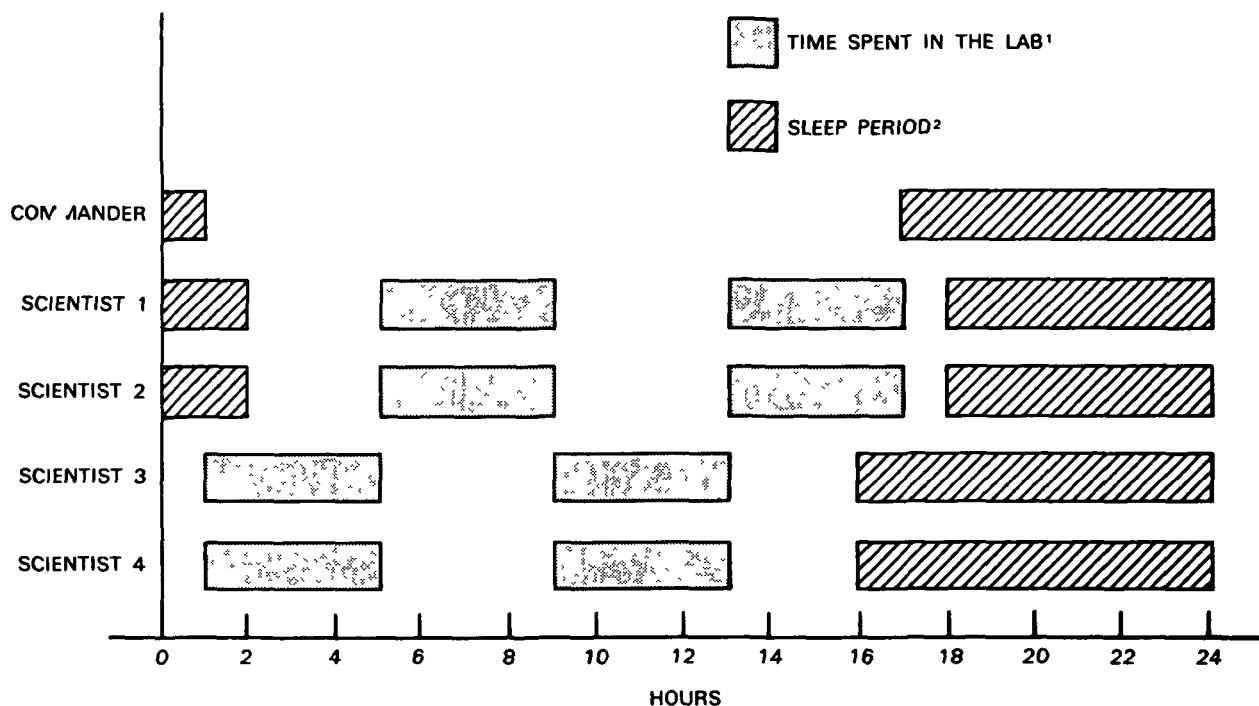


Figure 6-11.—Allocation of a crew member's day.



¹ WHEN NOT WORKING IN LABORATORY, CREW IS REQUIRED TO PERFORM GENERAL MAINTENANCE, LIMITED FLIGHT OPERATIONS, INVENTORY, AND LABORATORY MONITORING

² ALL OPERATIONS MONITORED AND CONTROLLED FROM GROUND STATIONS

Figure 6-12.—A chart of the laboratory work and sleep schedules.

engaged in system maintenance and activities related to personal needs. When the entire crew is sleeping, ground-based specialists and investigators will remotely monitor the experiments and other system maintenance functions.

REFERENCES

1. European Space Agency. *Spacelab Payload Accommodation Handbook*. Paris, France, July 1978, 569 pp. (NASA-TM-79937, ESA-SLP/2104)
2. Lyndon B. Johnson Space Center. *Space Shuttle System Payload Accommodations—Revision B*. Houston, Texas, December 1973. (JSC-07700-Vol-14)
3. Lockheed Missiles and Space Co. *Presentation Material for Program Review* [25 kw Power Module Evolution Study]. Sunnyvale, California, June 1978, 466 pp. (LMSC-D614922)
4. McDonnell Douglas Astronautics Co. *Space Station Program Executive Summary*. Huntington Beach, California, December 1971, 131 pp. (MDC-G2587)
5. McDonnell Douglas Astronautics Co. *Orbital Service Module Systems Analysis Study Mid-Term Review*. Huntington Beach, California, July 1978. (MDC-G7518)
6. McDonnell Douglas Astronautics Co. *Space Station Systems Analysis Study. Part 2 Final Report. Volume 2. Technical Report*. Huntington Beach, California, February 28, 1977, 251 pp. (NASA-CR-151226, MDC-G6715-Pt-2-Vol-2)
7. Roth, E. M. *Space-Cabin Atmospheres. Part IV Engineering Tradeoffs on One- Versus Two-Gas Systems*. NASA, Washington, D.C., 1967, 138 pp. (NASA-SP-118)
8. Grumman Aerospace. *Space Station Systems Analysis Study. Part 3: Final Report Volume 1. Technical Report*. Bethpage, New York, 1977. (NSS-SS-RP-021)
9. Dalton, M. Architectural evaluation for sleeping quarters. *Skylab Experience Bulletin*, No. 3, 1974, 77 pp. (JSC-09537)
10. Hunt, S. R., Jr., and Burt, R. A. Engineering design studies for a shuttle waste management system. Paper presented at the Intersociety Conference on Environmental Systems, San Francisco, California, July 21-24, 1974. (American Society of Mechanical Engineers Paper 75-ENAs-56)
11. McDonnell Douglas Astronautics Co. *Space Station Systems Analysis Study Part 2. Final Report. Volume 3. Appendices. Book 1 Program Requirements Documentation*. Huntington Beach, California, February 28, 1977, 256 pp. (NASA-CR-151227, MDC-G6715-Pt-2-Vol-3-Bk-1)
12. McDonnell Douglas Astronautics Co. *Space Station Systems Analysis Study Part 3 Documentation Volume 3. Appendices Book 1: Supporting Data*. Huntington Beach, California, July 1977, 174 pp. (NASA-CR-151500; MDC-G6922-Pt-3-Vol-3-Bk-1)
13. Vallerani, E. Design features of the Spacelab module structure. Paper presented at the 14th Symposium Spatial Europeen, Toulouse, France, April 23-25, 1975, 23 pp.
14. Manned Spacecraft Center. *Summary of Lunar Quarantine Biotest Protocols—Revision B*. Houston, Texas, November 13, 1969. (MSC-00013)
15. McDonnell Douglas Astronautics Co. *Manned Orbital Systems Concepts Study. Book 3: Configurations for Extended-Duration Missions*. Huntington Beach, California, September 30, 1975, 358 pp. (NASA-CR-144072; MDC-G5919-Bk-3)
16. Johnston, R. S., and Dietlein, L. F. (eds.). *Biomedical Results from Skylab*. NASA, Washington, D.C., 1977, 491 pp. (NASA SP-377)

Chapter 7

Cost Analysis

Editor's Note—Estimated system costs presented in this section should be treated with caution. A detailed and accurate cost analysis was not a prime objective of the design study. Rather, this section is intended to illustrate a *method* by which costs could be estimated for a system as complex as the one described here. As a result, it does not represent the product of a detailed and comprehensive analysis. The figures are based heavily on calculations used for estimating cost for similar concepts. They are also highly dependent upon assumptions made regarding the treatment of the many variables that characterize the system. Costs were estimated in 1978 dollars at the time of the study, and no effort has been made since then to refine the estimates further. This section is included for the sake of completeness, and its value to the overall study lies in the methodology of, and approach to, the cost calculations.

COST CONSIDERATIONS AND GUIDELINES

In the course of this study, an analysis was performed to predict the total cost of the OQF mission. However, several variables were encountered that, depending on the constraint selected, yielded quite different versions of an "accurate" cost estimate. One variable that is impossible to predict is the length of the quarantine mission. On the one hand, if no extraterrestrial organisms are identified by the quarantine protocol, laboratory work on the sample would terminate after 60 days. At the other extreme, it is possible that the quarantine protocol might detect pathogenic extraterrestrial organisms, in which case the quarantine protocol and second-order testing might be extended by as much as several years. This uncertainty was treated in this analysis by accumulating costs for two alternative mission scenarios:

1. *Minimum mission time*—It was assumed in this scenario that the results of the quarantine protocol are negative, with no indications of any extraterrestrial organisms. In this case, after the 60 days required to perform the protocol, the sample would be released to an existing maximum containment facility on Earth for further scientific investigations. Making an optimistic

estimate of the time required for the mission, beginning with the in-flight system check, through the testing of one returned sample (see figure 3-1), the OQF modules would be dedicated to the mission for 2 years.

2. *Maximum mission time*—This scenario assumes that a positive indication of life is encountered, requiring second-order testing to assess the pathogenicity of the life form. In addition, the organisms are considered to be harmful in some manner to the Earth's biosphere, necessitating extensive scientific studies in the OQF. Under this circumstance, it is assumed that the OQF modules would be involved with mission activities for 6½ years.

A second variable that makes a cost estimate difficult is the proportion of the OQF design, development, testing, and engineering (DDT&E) costs to be added to the total mission expense. It would seem reasonable that, because the various OQF modules are of a general design, they will be used for other missions after (and possibly before) they are assembled for quarantine purposes. This would suggest treating DDT&E costs in the same manner as they are treated for the Space Shuttle: i.e., as fixed costs which are not allocated to specific missions (ref. 1). On the other hand, it is possible that the Mars sample quarantine will be the only use of these modules, in which case a more accurate representation of total mission cost would include a substantial portion of the facility's DDT&E costs for each of the OQF modules.

With the assumption that the modules will be used for missions in addition to the Martian sample testing, the proportion of the DDT&E costs assigned to the quarantine mission changes with the length of time needed to complete the protocol. For instance, because all the modules are expected to have a useful life span of 15 years, a mission utilizing these modules for the minimum scenario would be allocated a smaller

share of the production costs than would one using the maximum scenario.

Based on the above considerations, four different estimates of total cost have been generated a 2-year mission duration, determined with and without DDT&E costs, and a 6¹/₂-year mission, also calculated with and without DDT&E costs.

Dangers inherent in any cost estimating effort include neglecting, double-counting, and inaccurately estimating cost elements. A detailed work breakdown structure as shown in figure 7-1 has been employed to address the first two dangers. This figure is based on the Manned Orbital Systems Concept (MOSC) study developed by McDonnell Douglas (ref. 2), modified to reflect a five-man crew, variable mission length, and the quarantine facility as the payload.

The MOSC study by McDonnell Douglas concluded that the optimal way to accommodate a series of extended duration missions (those greater than 30 days) would be to build two manned craft—one placed in a 28.5 degree orbit, and the second in a polar orbit (ref. 3). In addition, these facilities should have a functional life of 8 years, during which period they would accommodate 26 missions. Although two manned orbital systems are a possibility for the quarantine mission, it is questionable that enough additional benefit would be derived from the second system to offset the additional expense. Thus, cost estimates in this report have been modified from those developed in the MOSC study to reflect the design study group's assumption that only one manned orbital system will be built, that the projected life span of its components will be extended to 15 years, and that a smaller crew will be involved. In addition, the costs used by McDonnell Douglas were adjusted from a 1975 to a 1978 fiscal year base with an annual inflation rate of 7.2 percent. Finally, the MOSC cost estimates were modified to eliminate savings resulting from increased efficiency while constructing the second unit (due to learning from the first); the use of common ground support equipment for the two units, and production cost differentials between building one and two units.

Another important consideration for a mission on the scale of the OQF mission is the distribution of funds as a function of time. The estimates of total cost for the mission phases (DDT&E, production, and operations) are of limited value for planning purposes unless distributed over the time periods in which they are incurred. Figure 7-2 illustrates the programmatic

time schedule used in distributing the mission costs for the four conditions described earlier.

MISSION PHASES FOR COST ANALYSIS

The OQF's mission work breakdown structure (figure 7-1) is a task-oriented display of both hardware and major functions required to complete each of three phases of the quarantine mission: (a) DDT&E, (b) production, and (c) operations (see figure 7-3).

The *DDT&E phase* includes costs for items such as: development engineering and development support, major test hardware, captive and ground tests, ground support equipment, tooling and special test equipment, site activation; and simulation of protocol testing.

The *production phase* consists of hardware assembly and functions associated with producing flight-certified hardware. It includes all costs associated with.

1. Fabrication, assembly, and checkout of flight hardware;
2. Ground test factory checkout of flight hardware,
3. Initial stocks of spare components;
4. Maintenance of tooling and special test equipment;
5. Payload experimental and support equipment.

The *operations phase* begins when activities required to support the mission are performed and materials are acquired. It includes costs associated with:

1. *Support operations*—Replacement of spare parts, engineering support, and maintenance of ground support equipment;
 2. *Launch operations*—Receiving flight hardware, prelaunch assembly into orbiter vehicle, test and checkout, servicing, launching, and postlaunch support;
 3. *Mission operations*—Mission control, mission planning and management, flight crew training, simulation aids for crew training, in-flight mission costs, and shuttle support flights;
 4. *Maintenance and refurbishment operations*—Activities required to maintain and restore a previously flown, reusable module to a flight readiness condition.
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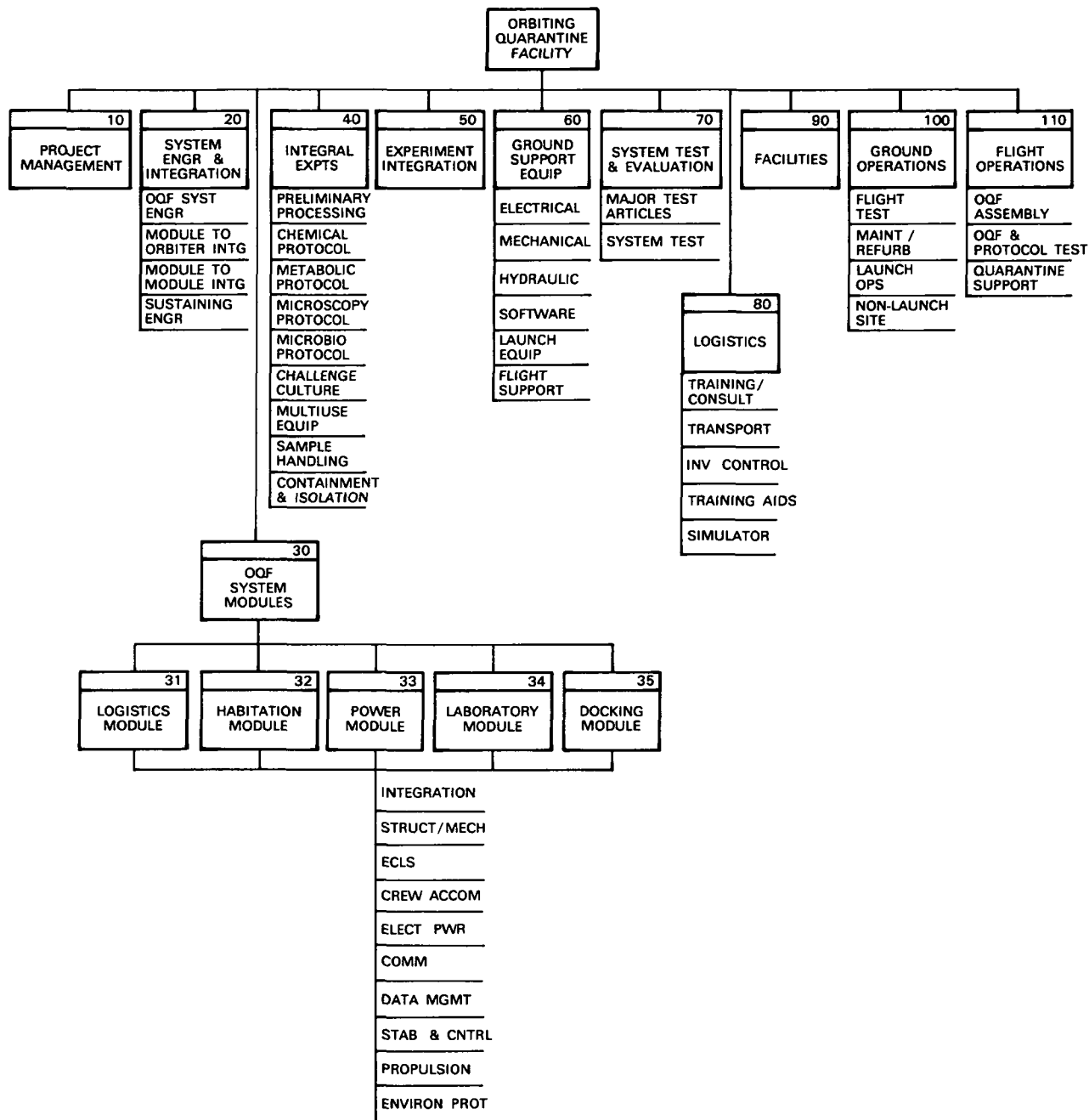


Figure 7-1.—Work breakdown structure for the OQF program.

MISSION COST ESTIMATES

The summary of the DDT&E cost estimate according to the categories used in the work breakdown structure (figure 7-1) is shown in table 7-1. As was discussed previously, it is possible to consider these costs as being expended partly in support of missions

other than the OQF since the modules are of general design. Alternatively, these costs can be assessed wholly to the quarantine mission.

The total costs required for production of the system, according to the work breakdown structure in figure 7-1, are given in table 7-2. Because the minimum mission scenario would demand use of the

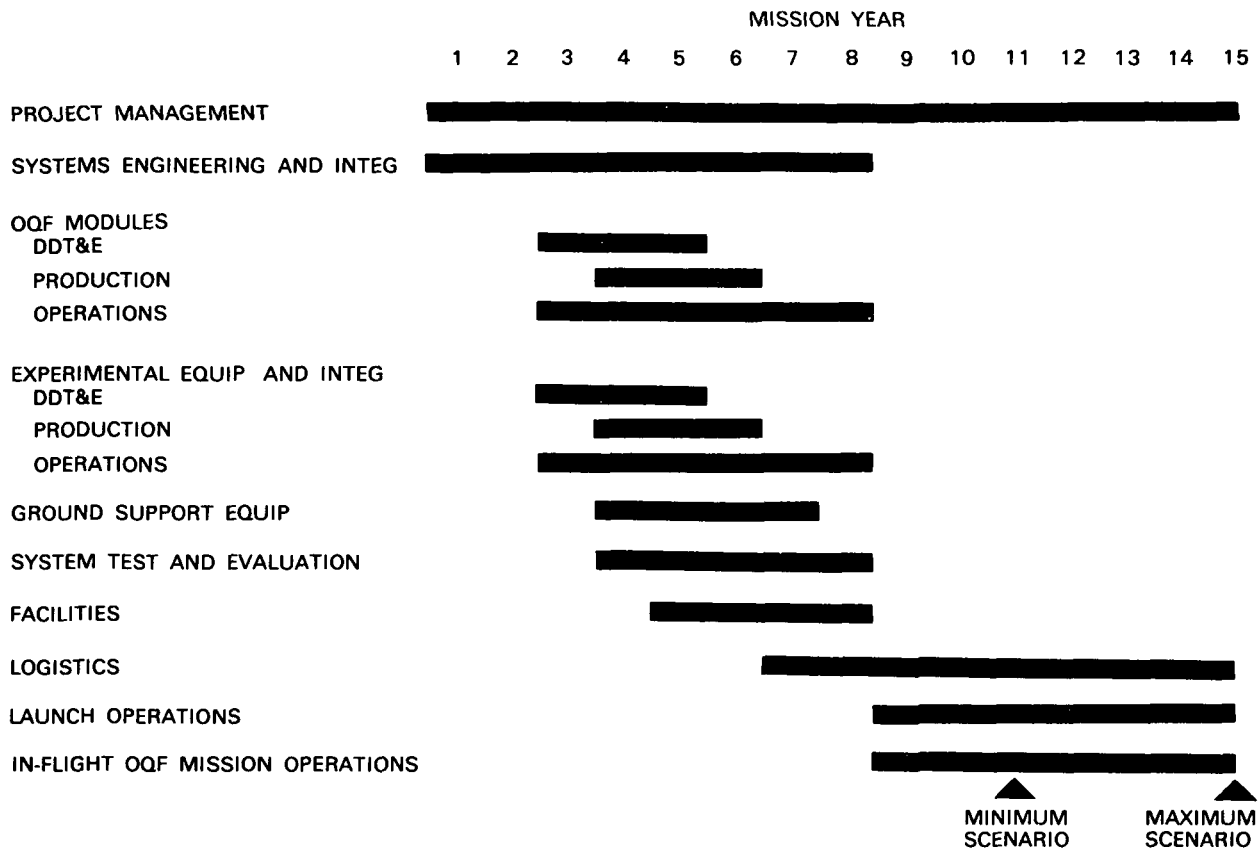


Figure 7-2.—Programmatic time schedule for the OQF mission.

modules for $4\frac{1}{2}$ years less than the long mission scenario, its share of the production costs is proportionately less. Most of these costs are directly proportional to mission length. Some costs, however, are OQF mission specific and are treated differently. For example, in a maximum mission scenario, it is assumed that the total production cost of the Laboratory Module will be allocated to the Mars sample quarantine mission. This assumes the worst case, namely that the Laboratory Module will be contaminated to such an extent that it cannot be used for other missions.

Total operations costs are listed in table 7-3; these figures reflect the costs for missions of various lengths. Most costs are assumed to have a fixed component (one-half the estimated operations cost over 15 years) and a variable component that is directly proportional to mission length. Work breakdown structure elements 40, 50, and 110 are mission specific and have been treated differently. The operations costs associated with integral experiments (work breakdown structure element 40) for a maximum scenario are assumed to be

three times those for a minimum scenario. The operations costs associated with experiment integration (work breakdown structure element 50) for a maximum scenario are assumed to be two-and-a-half times those for a minimum scenario. Flight operations are strictly a function of mission length.

MISSION LENGTH COST EXTENSIONS

The OQF programmatic time schedule, as shown in figure 7-2, permits the mission costs to be spread over time. Once funding is approved, the expenditures by mission phase (and even within phases) are predictable given the programmatic time schedule. The cost extensions over time, for the four conditions described at the beginning of this chapter, are given in table 7-4. These cost estimates are shown graphically in figure 7-4.

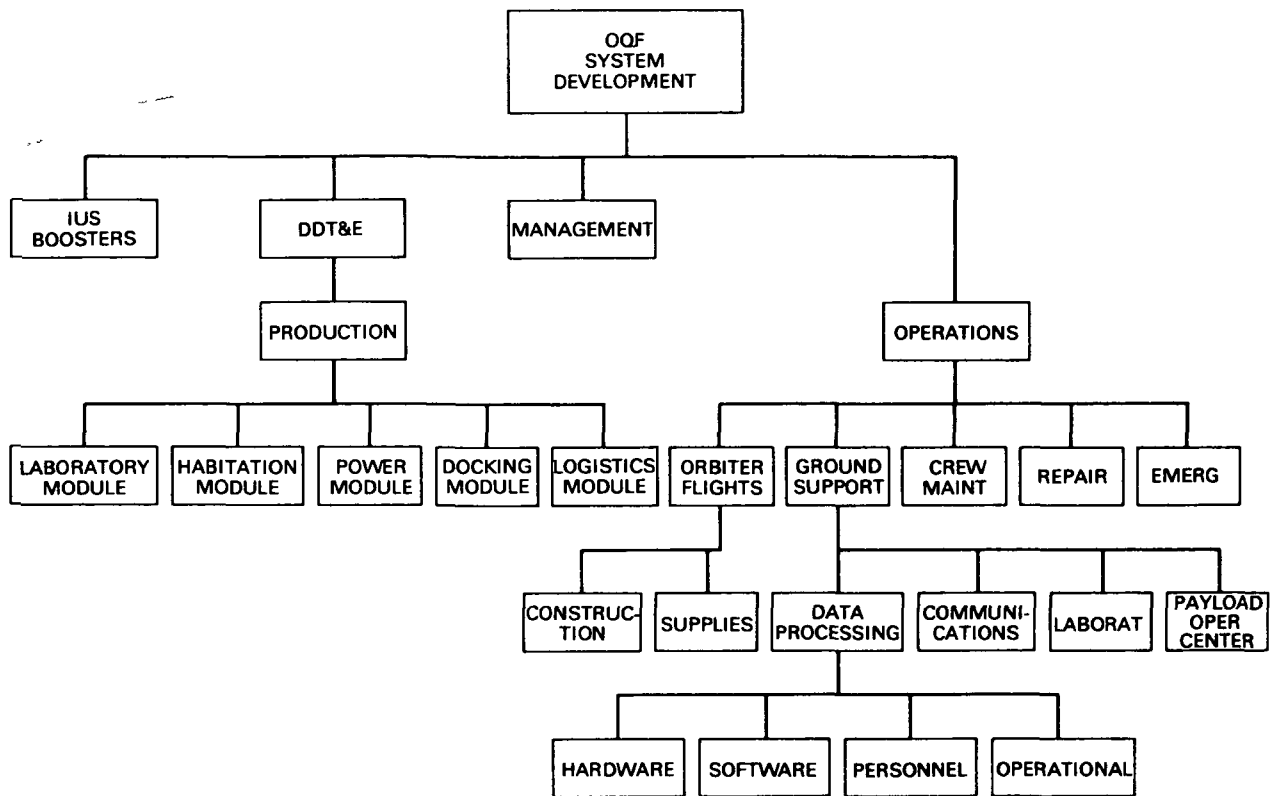


Figure 7-3.—Phases of the quarantine mission included in estimating costs.

TABLE 7-1.—DESIGN, DEVELOPMENT, TESTING, AND ENGINEERING COSTS*

<i>Work Breakdown Structure Category</i>	<i>Cost Element Description</i>	<i>Mission Cost</i>
10	Project Management	64
20	Systems Engineering and Integration	175
30	Orbiting Quarantine Facility	552 ^b
31	Logistics Module	55
32	Habitation Module	134
33	Power Module	194
34	Laboratory Module	118
35	Docking Module	51
40	Integral Experiments	14
50	Experiment Integration	10
60	Ground Support Equipment	116
70	Systems Test and Evaluation	160
80	Logistics	—
90	Facilities	9
100	Ground Operations	—
110	Flight Operations	86
	Total	1186

* Based on FY 1978 dollars, in millions.

^b Sum of following five module costs

TABLE 7-2.—PRODUCTION COSTS^a

<i>Work Breakdown Structure Category</i>	<i>Cost Element Description</i>	<i>15-Year Life</i>	<i>Minimum Scenario</i>	<i>Maximum Scenario</i>
10	Project Management	30	4	13
20	Systems Engineering and Integration	200	27	87
30	Orbiting Quarantine Facility ^b	393	51	241
31	Logistics Module	39	5	17
32	Habitation Module	78	10	34
33	Power Module	136	18	59
34	Laboratory Module	122	16	123
35	Docking Module	18	2	8
40	Integral Experiments	8	8	8
50	Experiment Integration	—	—	—
60	Ground Support Equipment	1	1	1
70	Systems Test and Evaluation	—	—	—
80	Logistics	—	—	—
90	Facilities	—	—	—
100	Ground Operations	—	—	—
110	Flight Operations	108	80	108
	Total	740	171	458

^a Based on FY 1978 dollars, in millions.

^b Each cost figure includes following five costs.

TABLE 7-3.—OPERATIONS COSTS^a

<i>Work Breakdown Structure Category</i>	<i>Cost Element Description</i>	<i>15-Year Life</i>	<i>Minimum Scenario</i>	<i>Maximum Scenario</i>
10	Project Management	20	17	15
20	Systems Engineering and Integration	15	9	11
30	Orbiting Quarantine Facility ^b	219	127	161
31	Logistics Module	24	14	18
32	Habitation Module	54	30	39
33	Power Module	85	48	63
34	Laboratory Module	46	29	34
35	Docking Module	10	5	7
40	Integral Experiments	—	7	22
50	Experiment Integration	—	10	24
60	Ground Support Equipment	24	13	17
70	Systems Test and Evaluation	—	—	—
80	Logistics	50	28	37
90	Facilities	—	—	—
100	Ground Operations	84	48	62
110	Flight Operations	324	43	216
	Total	736	302	565

^a Based on FY 1978 dollars, in millions.

^b Each cost figure includes following five costs.

TABLE 7-4.—MISSION LENGTH COST EXTENSIONS*

Factors	DDT&E	Production	Operations	Total
Minimum scenario/DDT&E included	1186	171	302	1659
Minimum scenario/DDT&E excluded	—	171	302	473
Maximum scenario/DDT&E included	1186	458	565	2209
Maximum scenario/DDT&E excluded	—	458	565	1023

* Based on FY 1978 dollars, in millions.

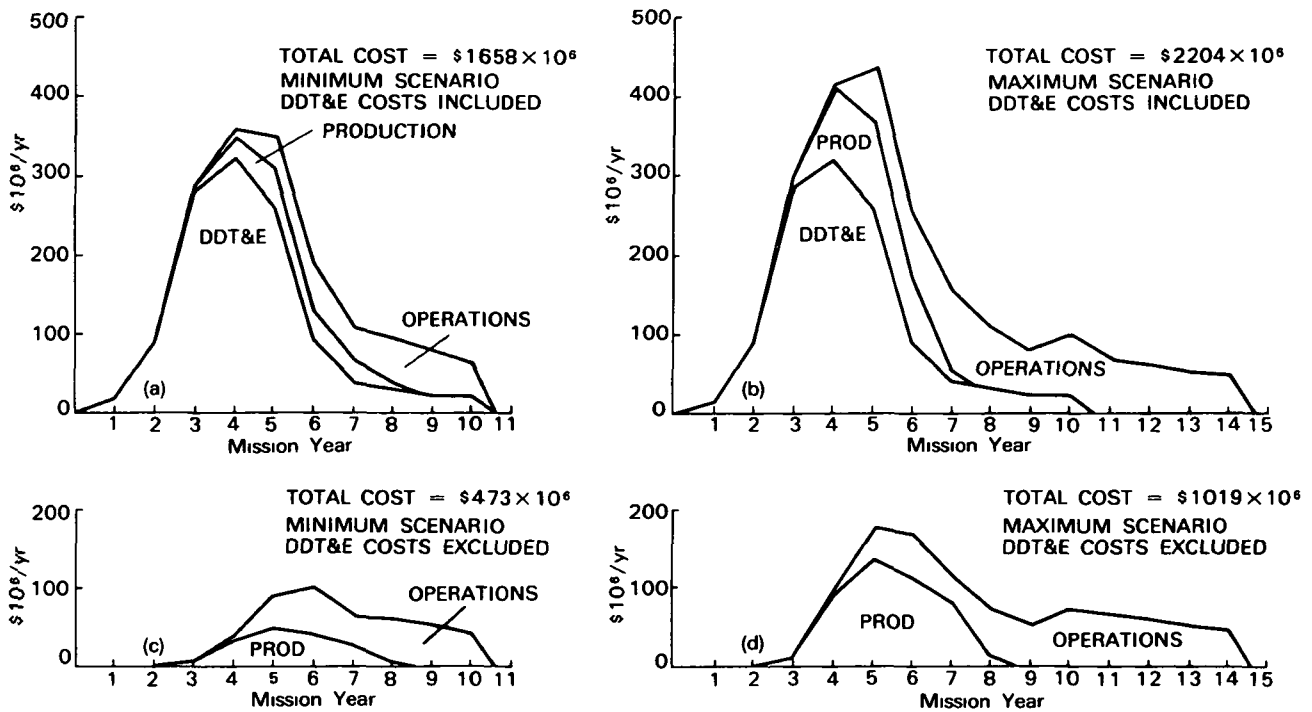


Figure 7-4.—OQF programmatic distribution of mission costs. Top: costs of the minimum (a) and maximum (b) scenario, assuming that DDT&E costs are included. Bottom: costs of the minimum (c) and maximum (d) scenario after excluding the DDT&E costs.

REFERENCES

- Moore, W. F., and Forsythe, C. Buying a shuttle ticket. *Astronautics and Aeronautics*, Vol. 15, No. 1, 1977, pp. 34-40.
- McDonnell Douglas Astronautics Co. *Manned Orbital Systems Concepts Study. Book 4: Programmatics for Extended-Duration Missions*. Huntington Beach, California, September 30, 1975, 147 pp. (NASA-CR-144064, MDC-G5919-Bk-4)
- McDonnell Douglas Astronautics Co. *Manned Orbital Systems Concepts Study. Book 2: Requirements for Extended-Duration Missions*. Huntington Beach, California, September 30, 1975, 168 pp. (NASA-CR-144063; MDC-G5919-Bk-2)

Chapter 8

Additional Uses of the Facility

One of the basic assumptions behind the design of the Orbiting Quarantine Facility has been that the facility should be capable of existing in space for 15 or more years. Given this life span for the laboratory and supporting modules, it is appropriate to consider the adaptability and utility of the OQF for purposes other than the quarantine mission. It should be pointed out, of course, that one option in the quarantine testing protocol calls for performing a long-term, complete study of the Martian sample in space, rather than releasing the sample to an Earth-based laboratory. Although current scientific knowledge about Mars suggests there is a very low probability that the preliminary quarantine findings will warrant such an undertaking, complete dedication of this facility for Martian soil study is a possibility, and if that were the case the laboratory would not be available for other uses during a large part of its life span. On the other hand, it is also possible that the chemical and biological studies prescribed in the established protocol will not detect any life forms, in which case the mission will be completed as early as 60 to 90 days from the initial receipt of the Martian sample. It is because of this latter possibility that options for other uses of the facility have been considered as part of this design study. There are three basic questions that need to be answered in considering additional uses:

1. Is there a need for a scientific laboratory that permits long missions?
2. Is the facility, as designed, adaptable to other space science programs?
3. If so, what are some of the appropriate scientific studies?

LONG-TERM SPACE STUDIES

The findings from the Skylab experiments suggest that many aspects of living systems are affected by zero *g* and other conditions of space and that the

effects of these space conditions differ, in many cases, according to the duration of the exposure (ref. 1). Therefore, flight duration can be considered as one of the most important variables in life sciences space research. Although flights of various lengths of time are proposed for the Spacelab programs (aboard the shuttle) for the 1980s, there is a limiting constraint of a 30-day maximum mission. Hence, the selection of research topics for the Spacelab missions is based on the appropriateness of the study questions as they relate to the duration of the proposed flights (ref. 2). This suggests that there will be many research questions which require long-term experiments that cannot be accommodated by the Spacelab programs as they are proposed for the 1980s. Life sciences questions that require research to be performed in space can be categorized into the following:

1. Effects of weightlessness on biological systems:
 - A. Developmental biology:
 - a. Morphogenesis and reproduction of different animal and plant species;
 - b. Otolith development in animals;
 - c. Development of animal and plant orientation behavior;
 - d. Mutagenesis.
 - B. Biokinetics and bioenergetics.
 - C. Biomedical studies—prevention and (or) control of the effects of zero *g*.
 - D. Behavior and performance studies.
2. Consequences and effects of space flight and space isolation:
 - A. Radiobiology.
 - B. Immunology and pathogenesis.
 - C. Behavior biology, circadian rhythm effects, and social behavior.
3. Effects of weightlessness on life support systems.

-
4. Technological and instrument development for bioengineering, medical sciences, and biological research.

Of these research topics, there are many questions that can be satisfactorily studied only in a space laboratory that can support long-term experiments; i.e., longer than 30 days. Some of the studies recommended by the Space Science Board of the National Research Council/National Academy of Sciences in 1971 and 1975 fall into the long-term category, including studies that deal with the enervation of gravireceptors during their embryonic development and maturation in zero *g*, the influence of weightless duration on the structure and behavior of different species as a function of organism maturity; and bone formation and demineralization under zero *g* (refs. 3, 4). Deutsch and Mallory (ref. 2) reviewed the 25 general research objectives in the NASA Life Sciences Program and designated several topics as appropriate for flight missions of longer duration. In addition, with the initiation of life sciences research in space, a whole new set of research problems will undoubtedly be discovered that can only be answered with longer-duration missions.

These recommendations and other reports (refs. 5 through 11) suggest, then, that there are a variety of research questions that can best be answered by long-term experiments conducted in a space laboratory such as the one described in this report.

ADAPTABILITY OF THE OQF

The adaptability of the Orbiting Quarantine Facility to general life sciences research is determined by the types of equipment on board as well as by the ease with which it can be resupplied and refurbished. Since the assumption has been made that the Space Transportation System will be available to initially orbit laboratory equipment, expendable materials, and life-support materials, it can also be assumed that the STS will be available to transport portable equipment and supplies needed to modify the facility. The Spacelab program's philosophy of having a module that is a dedicated laboratory system, and equipping it with common operational research equipment (CORE) that can be exchanged easily and replaced as experimental objectives change, provides a tremendous flexibility in the various space research programs conducted by NASA (ref. 12). The same approach should be applied

to the design of the proposed quarantine facility, thus enhancing its use in other programs.

Laboratory equipment commonly used in life sciences research is listed in table 8-1, according to the major space research program that might have use for it and whether or not that equipment is required in the OQF (right column). This equipment list is derived partly from the CORE list identified for the Spacelab program (ref. 12) and partly from Kail's report (ref. 13). The table shows that the Laboratory Module, as designed in this study, has much of the laboratory equipment and instrumentation required for other types of life sciences space research. With the eventual availability of portable dedicated laboratory units, the range of life sciences research that can be performed in this facility will be greatly expanded. The most important additional equipment required to carry out many of the biological research programs are animal and plant holding units. Although animal chambers have been developed for Spacelab, it will be necessary to develop technology to accommodate and provide life support systems for animals in space during long-duration flights; in addition, research tools specific for performing animal studies will also be required in a general purpose laboratory. Although plant growth chamber designs have been proposed (ref. 14), they would need to be constructed to permit long-term botanical studies. One way of supporting animal and plant studies in the OQF would be to attach a dedicated module containing animal holding units of various sizes as well as plant growth chambers. Because the Laboratory Module contains many of the instruments and equipment items necessary for life sciences research, it would be used to perform the analytical tasks on organisms maintained in an adjacent animal/plant holding module. In this manner, the OQF could easily be adapted to be a dedicated, long-term life sciences orbiting laboratory.

ADDITIONAL STUDIES FOR A SPACE LABORATORY

Recombinant DNA

Since the 1975 Asilomar Conference and publication of the NIH Guidelines for Research Involving Recombinant DNA Molecules a year later, there has been an ongoing debate on the degree of containment required to adequately protect the public from the accidental release of genetically altered organisms (ref.

TABLE 8-1 — LABORATORY EQUIPMENT AND INSTRUMENTS REQUIRED FOR LIFE SCIENCES RESEARCH IN A SPACE LABORATORY.

[Shading indicates that the equipment could potentially be used in that research program]

<i>Laboratory Equipment</i>	<i>Radobiology and Biological Studies</i>	<i>Space Medicine</i>	<i>Behavioral Biology</i>	<i>Recombinant DNA</i>	<i>Mars Quarantine Sample Studies</i>
Air particle sampler					
Alpha particle analyzer					
Arterial pressure recorder					
Autoclaves					
Automatic cell counter					
Automatic plate counter					
Autoradiograph					
Centrifuges					
Chemistry kits					
Clnostats					
Conductivity meter					
Doppler flowmeter					
Dosimeter					
EEG					
EKG					
Electrophoresis equipment					
EMG equipment					
Freezers					
Gas analyzer					
Gas chromatograph/mass spectrometer					
Glove box					
Hematology and urology kits					
Histology kits					
Holding units—invertebrate					
Holding units—plants					
Holding units—primate					
Holding units—tissues and microorganisms					
Holding units—vertebrate					
Incubators					
Lamb plethysmograph					
Lyophilizer					
Mass measurement devices (macro, micro)					
Metabolic monitor					
Microscope—electron (scanning)					

TABLE 8-1.—LABORATORY EQUIPMENT AND INSTRUMENTS REQUIRED FOR LIFE SCIENCES RESEARCH IN A SPACE LABORATORY—Continued.

<i>Laboratory Equipment</i>	<i>Radiobiology and Biological Studies</i>	<i>Space Medicine</i>	<i>Behavioral Biology</i>	<i>Recombinant DNA</i>	<i>Mars Quarantine Sample Studies</i>
Microscope—light					
Microscope—stereo					
Microbiology kits					
Microdissection kits					
Micromanipulator-micropositioner					
Microprobe analyzer					
Microtome					
Oven-drying					
pH meter					
Physiology kits					
Physical examination kits					
Radiation tracer/detector					
Refrigerators					
Spectrophotometer					
Staining kits					
Surgical and work bench					
Tissue homogenizer					
Vacuum chambers					

15). The question of containment and control of recombinant DNA research rests on: (a) diverse philosophical opinions as to biohazard, bioengineering, and evolutionary manipulation; (b) cost-benefit analysis considerations; (c) governmental versus voluntary regulation of the growth of scientific knowledge; and (d) the potential for misuse of recombinant DNA technology (refs. 16, 17). Although there is growing consensus among scientists and governmental agencies to lower the containment required for this research (ref. 18), there are many facets of DNA research that may continue to require a high level of containment (such as the use of highly pathogenic microbial DNA in recombinant studies).

Thus, if and when a need arises in the future to perform research on hazardous systems, the feasibility of using the quarantine facility to provide maximum containment of, and thus maximum protection from, such activities should be considered. The design of the facility is ideal for any study that requires a high level of protection. Because the facility is equipped with

standard microbiological instruments, it will require only minimal modification to carry out recombinant DNA studies (see table 8-1).

Materials Processing

Patten (ref. 19) suggests that fluid-flow phenomena in high-melting-point materials offers an interesting array of materials processing possibilities; research on topics such as homogeneous and heterogeneous nucleation of materials and material growth patterns in zero g should be done using the environment of space. The planned studies in material sciences and space processing in early Spacelab missions will undoubtedly suggest future possibilities and benefits of space industrialization (ref. 20). Furthermore, early results from the experiments planned for the Long Duration Exposure Facility (refs. 21 through 23) should also provide information suggesting additional physical sciences experiments that need to be performed in a manned space laboratory. Thus, long-term research on

the management and processing of materials in space could be performed in a module attached to an existing orbiting station, such as the OQF.

High-value products of materials processing in space are likely to appear in the fields of health, electronics, electro-optics, and optics (ref. 24). In the weightless environment, crystals can be grown without impurities and without the structural defects and nonuniformities that gravity induces. The containerless processing made possible by zero g permits the formation of ultrapure, nonnucleated glasses and ceramics for optical and electronics applications. Improved mixing and the absence of gravitational flows will provide an opportunity for manufacturing alloys that cannot be formed on Earth, and for processing or casting many other metallic materials of superior strength and purity (for example, superconductors, magnetic materials, and titanium turbine blades). Advances in the reprocessing of organic wastes in space, especially through the use of closed biological systems, will extend the capability of man for long-term occupancy of space environments.

Regardless of the final functions to be performed in a long-term manned space station, the mission can be performed in a module that will be designed specifically for materials manufacturing, physical sciences experiments, or life sciences research, yet will derive its power, communications, logistics, and life support from the core system that previously functioned as the OQF.

CONCLUSIONS

The foregoing discussion suggests that there are many scientifically important and interesting questions that can be answered by experiments and studies in a space laboratory that is available for a duration longer than 30 days. The OQF can remain as an Earth-orbiting space station, serving as the core-system to support additional modules dedicated for materials processing, physical sciences research, and technological development in space sciences. The availability of a crew support module in the system offers a vastly expanded range of possibilities for space sciences development, and its capacity for extended missions enhances its value as a research facility.

REFERENCES

1. Johnston, R. S., and Dietlein, L. F. (eds.). *Biomedical Results from Skylab*. NASA, Washington, D.C., 1977, 491 pp. (NASA SP-377)
2. Deutsch, S., and Mallory, K. M., Jr. Life sciences in the Shuttle era. Paper presented at the Intersociety Conference on Environmental Systems, San Diego, California, July 10-13, 1978, 12 pp. (American Society of Mechanical Engineers Paper 78-ENAS-34)
3. Space Science Board, National Research Council. *Priorities for Space Research. 1971-1980*. National Academy of Sciences, Washington, D.C., 1971, 147 pp.
4. Space Science Board, National Research Council. *Report on Space Science: 1975*. National Academy of Sciences, Washington, D.C., 1976, 228 pp.
5. Alyakrinsky, B. S. Current status of space biorhythmology. *Space Biology and Aerospace Medicine*, Vol. 11, No. 2, 1977, pp. 1-14.
6. Burnazyan, A. I., Vorob'yev, Ye. I., Gazenko, O. G., Gurovskiy, N. N., Nefedov, Yu. G., Adamovich, B. A., Yegorov, B. B., Kovalev, Ye. Ye., and Yegorov, A. D. Main stages and prospects of development of space biology and medicine. *Space Biology and Aerospace Medicine*, Vol. 11, No. 5, 1977, pp. 1-9.
7. Glass, H. B. (ed.). *Life Sciences in Space*. National Academy of Sciences, Washington, D.C., 1970, 51 pp.
8. Kotovskaya, A. R., Galle, R. R., and Shipov, A. A. Biomedical research on the problem of artificial gravity. *Space Biology and Aerospace Medicine*, Vol. 11, No. 2, 1977, pp. 15-24.
9. Parfenov, G. P. Biologic guidelines for future space research. In *Foundations of Space Biology and Medicine. Volume II, Book 2: Ecological and Physiological Bases of Space Biology and Medicine* (ed. by M. Calvin and O. G. Gazenko). NASA, Washington, D.C., 1975, pp. 707-739.
10. Space Science Board, National Research Council. *Space Biology*. National Academy of Sciences, Washington, D.C., 1970, 55 pp.
11. Vinograd, S. P. An appraisal of future space biomedical research. In *Foundations of Space Biology and Medicine. Volume III. Space Medicine and Biotechnology* (ed. by M. Calvin and O. G. Gazenko). NASA, Washington, D.C., 1975, pp. 453-459.

-
12. General Dynamics/Corvair Division. *Definition of Life Sciences Laboratories for Shuttle/Spacelab. Volume 2: Life Sciences Laboratory Concept Definition*. San Diego, California, December 1975, 184 pp. (NASA-CR-144122; CASD-NAS-75-054-Vol-2)
 13. Kail, L. T. *Requirements Study for a Biotechnology Laboratory for Manned Earth Orbiting Missions. Volumes 1 and 2*. McDonnell Douglas Corp., Huntington Beach, California, August 1969, 169 pp. (NASA-CR-1408 and 1409)
 14. Sweet, H. C., and Tremor, J. W. Plant growth chambers on Spacelab. A call for scientific input. *American Journal of Botany*, Vol. 65, 1978, pp. 594-560.
 15. Beers, R. F., Jr., and Bassett, E. G. (eds.). *Recombinant Molecules: Impact on Science and Society*. Raven Press, New York, 1977, 540 pp.
 16. Grobstein, C. The recombinant-DNA debate. *Scientific American*, Vol. 237, No. 1, July 1977, pp. 22-33.
 17. Wright, S. Setting science policy: The case of recombinant DNA. *Environment*, Vol. 20, No. 4, May 1978, pp. 6-15, 39-41.
 18. Dickson, D. NIH may loosen recombinant DNA research guidelines. *Nature*, Vol. 273, 1978, p. 179.
 19. Patten, J. W. Materials processing in space. *Journal of Vacuum Science and Technology*, Vol. 14, 1977, pp. 1289-1291.
 20. Seibert, G. Spacelab and material processing facilities and experiments. *Journal of Vacuum Science and Technology*, Vol. 14, 1977, pp. 1252-1257.
 21. Kinard, W. H. Long Duration Exposure Facility: A multipurpose free-flying experiment carrier. Paper presented at the International Meeting on Utilization of Space Shuttle and Spacelab, Bonn, West Germany, June 2-4, 1976, 26 pp.
 22. Kinard, W. H. Long Duration Exposure Facility: A unique mode of shuttle utilization. *Journal of Vacuum Science and Technology*, Vol. 14, 1977, pp. 1258-1262.
 23. Clark, L. G., and DiBattista, J. D. Space qualifications of optical instruments using the NASA Long-Duration Exposure Facility. In *Optics in Adverse Environments, Proceedings of the Seminar, San Diego, California, August 25-26, 1977* (ed. by E. Bernal and H. V. Winsor). Society of Photo-Optical Instrumentation Engineers, Bellingham, Washington, 1978, pp. 11-18. (SPIE Proceedings Volume 121)
 24. Barter, N. J., and Waltz, D. M. Materials processing in space: A weightless proposition. Paper presented at the AIAA International Annual Meeting and Technical Display, Baltimore, Maryland, May 6-11, 1980, 10 pp. (American Institute of Aeronautics and Astronautics paper AIAA-80-0878)

Units and Conversion Factors

Å	angstrom	A unit of length used for measurement of objects seen under the electron microscope = 10^{-10} m
atm	standard atmosphere	A unit of pressure based on a standardized sea-level terrestrial atmospheric pressure = 14.7 psi = 1.0132 bars = 760 torr
° C	degrees Celsius or centigrade	A temperature scale in which the range of temperature between the freezing point and the boiling point of water is divided into 100 degrees = $5/9$ ($^{\circ}\text{F} - 32$)
cfm	cubic feet per minute	The rate of flow of a liquid or gas
g	gram	Metric unit of weight
g	"gee"	The force exerted by gravity on a body at rest at the mean surface of the Earth; used to indicate the inertial force to which a body is subjected when accelerated = 980.665 cm/s^2 = 32.174 ft/s^2
l	liter	Metric unit of capacity = 1.057 quarts (liquid)
lb	pound	U.S. unit of weight and mass = 0.453 kg
m	meter	Metric unit of measure = 3.281 ft = 39.37 in
mi	mile	U.S. unit of length = 1.609 km
psi	pound per square inch	A unit of pressure or load on a surface; often used to denote the pressure of a gas
rpm	revolutions per minute	Measure of speed of spin
s	seconds	Unit of time
SCC	standard cubic centimeters	Metric unit of gaseous volume = 1 cc at standard temperature and pressure
torr	torr	A unit of pressure = $1/760$ atm
w	watt	A unit of power = 1.301×10^{-3} horsepower
×	times (magnification)	An expression of the resolving power of a magnifying instrument

Metric Prefixes

k	kilo-	1000x
c	centi-	1
m	milli-	1
μ	micro-	10^{-6} x
n	nano-	10^{-9} x

Acronyms

ASEE	American Society for Engineering Education
CDC	Center for Disease Control
CORE	Common operational research equipment
CRT	Cathode ray tube
DDT&E	Design, development, testing, and engineering
ECLS	Environmental control life support
ESA	European Space Agency
EVA	Extravehicular activity
GC/MS	Gas chromatograph/mass spectrometer
GERT	Graphical Evaluation and Review Technique
GMK	Green monkey kidney
HEK	Human embryonic kidney
HEPA	High efficiency particle accumulator
ICBC	Interagency Committee on Back Contamination
IUS	Inertial upper stage
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LRL	Lunar Receiving Laboratory
MOSC	Manned orbital systems concept
MSR	Mars sample return
MSRC	Mars sample return canister
MSRV	Mars sample return vehicle
NASA	National Aeronautics and Space Administration
OMS	Orbital maneuvering subsystem
OQF	Orbiting Quarantine Facility
PP	Planetary protection
RMS	Remote manipulator system
SEM	Scanning electron microscope
STS	Space Transportation System
TELLE	Remote-teleoperated-manipulator
UV	Ultraviolet

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