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ABSTRACT

The crucial challenge to astrobiology research on Mars is for the astronaut crews to conduct the search for life past and present from a Mars surface base. The Mars base will require a highly specialized astrobiology science laboratory to facilitate this research. This paper presents an incremental strategy to develop the laboratory technology and facility necessary to enable the astrobiology investigation on Mars.

The distinguishing characteristic of an astrobiology research apparatus for the Mars surface science laboratory is that the research crew must work across a large pressure differential between the shirtsleeves cabin atmosphere and the Mars ambient atmosphere inside the apparatus. How to simulate that apparatus and its operations through Earth expeditions is an essential aspect of design development.

This development strategy involves four main phases: mobile field lab, research and development testbed for the astrobiology technology, a high altitude pressurized lab, and finally the Mars surface lab. This paper describes each phase in some detail. Each phase will provide an empirical test of the essential technologies and operations.

INTRODUCTION: WHY A MARS SURFACE SCIENCE LABORATORY?

Before delving into the details of this laboratory development strategy, it is valuable to review the findings of two earlier science studies, both now more than a decade old: <u>Science Exploration Opportunities</u> (Nash et. al., 1989) and the <u>Joint Science Utilization Study</u>, JSUS (Siegel, Clancy, Fujimori, & Saghir, 1989). Science Exploration Opportunities addresses human missions to the Moon, Mars, Phobos and an Asteroid, and begins by stating two premises:

> 1. The exploration, which will take place beyond low Earth orbit, will be conducted on manned missions. It will emphasize activities that can uniquely be accomplished or significantly enhanced in precision, versatility, and adaptability by the presence and capabilities of humans. These activities include tasks that would be very difficult or impractical to carry out using solely robotic systems directed from Earth;
>
> 2. The eventual decision to be first to Mars or to the Moon will be strongly conditioned by non-scientific reasons. Science, though a factor, will not be the driver. Thus, the real issue here is, if humans are to go to any planetary body, what science and related activities can be performed to take maximum advantage of the presence of humans on these missions? (Nash et. Al.1989, p. 1).

What is prophetic about these premises manifests itself in the progression of the NASA Design Reference Mission for the Human Exploration of Mars (DRM). The first version of the DRM began with the pre-positioning of a "Hab/Lab" module 26 months before the arrival of the first astronaut crew (Hoffman & Kaplan, 1997). By the third revision/supplement to the DRM, the Hab/Lab dropped out of the pre-positioning launch window (Drake, 1998; Cohen, 1999, p. 1). How very prescient was the statement that science would not be the design driver for a human mission to Mars. However, for science to remain a factor, it is vitally important for the Science Community to develop a clear idea for what they want in a surface science laboratory and to represent it in clear and concise terms. Nash, et al., compiled a list of Mars science laboratory requirements that to this day remain the best of its kind. It appears in the APPENDIX to provide the background for all the functions the Mars surface science laboratory must provide, in addition to astrobiology, although many of these same items also support Astrobiological investigations.

IN SITU ANALYSIS

Rapid Sample Return is not possible from Mars or Europa. It is very doubtful whether it is realisticly possible to preserve planetary biotic samples during a holding period of up to two years on the planetary surface, plus another 8 to 12 months return voyage through interplanetary space. Therefore, it becomes necessary to develop the capability to perform comprehensive, high quality analysis in situ.

On-orbit analysis of life science experiments is a useful analog to in-situ analysis of planetary astrobiology samples. Seigel, Clancy, Fujimori and Saghir evaluated the relative advantages and disadvantages of On-Board (space station) specimen analysis for Life Science research (1989, pp. 77-78). Their evaluation offers an excellent analog to in-situ astrobiology sample analysis These authors found four principle advantages of on-board analysis:

- Allows rapid production of experimental results, enabling iterative research activity.
- Provides a quick-response science capability
- Is critical for characterization of samples which cannot survive return to Earth, or degrade with time.
- Significantly reduces sample storage prior to return to the ground, and reduces specialized return requirements (e.g. thermal conditioning).

They also identified a number of disadvantages, which largely fell into two groupings: greater costs than performing the analysis on Earth and the “High skill levels required of crew members” with the associated expenditure of crew time and effort. However, looking at these disadvantages today, the former group look like a given investment, and the latter like a positive advantage to send world class scientists to Mars as astronauts and explorers. These scientist/astronauts would be the best qualified to find, identify and collect scientifically valuable samples.

ASTROBIOLOGY: THE SEARCH FOR SAMPLES

This discussion of astrobiology as new “science” that integrates many disciplines and many types of investigations must begin with a description of what it encompasses. The search for samples of life in extreme environments and how it originated is central to astrobiology. In preparing plans and proposals for astrobiology, it has been necessary for the team at NASA-Ames Research Center to consider the wide range of potential samples and the environments from which Astrobiologists will want to collect them. These environments correspond in the broadest terms to the three phases of matter: Solid, Liquid and Gas. Scientifically interesting samples will come in all three phases of matter. The precedents for evidence of life in all these kinds of samples exist on the earth, so it is conceivable that they could exist elsewhere in the solar system or the universe. TABLE 1 describes a taxonomy of Solid, Liquid and gaseous samples and the considerations that may be involved in handling them.

Solid Samples

Solid samples are the ones most frequently imagined as representing evidence of extant life or fossils of extinct life. Scientists conceive living organisms as essentially solid. The waste products they leave behind and fossils are solid. Thus, the major orientation of the astrobiology lab development effort focuses on the collection, handling, processing and analysis of solid samples. In terms of planetary exploration, the great preponderance of activity concerns the examination and analysis of solid samples, notably rocks and soil.

Liquid Samples

Liquid or aqueous samples are of interest because of the vast abundance of life forms in the oceans and freshwater bodies. The dominant paradigm in astrobiology states that liquid water is essential for the creation and existence of life as we know it – and probably as we do not know it. Because these liquid habitats are likely “cradles of life,” they provide a primary set of precedents for how life came into existence and how organisms can adapt to extremes of pressure, temperature and chemistry. Levin & Levin speculate that liquid water on may exist today on the surface of Mars, and these pools or reservoirs could serve as cradles of life (Levin & Levin, 1997, 1998). Kuznetz and Gan report an experiment in which they produced liquid water in a bell jar under simulated Mars surface atmospheric conditions. Their data fell within the liquid zone of the triple point phase diagram for water where conventional wisdom says it cannot exist. (Kuznetz & Gan, 2000). Alternatively, the search for water and for life must dig down under the surface to zones of greater temperature and stability and protection from the Sun’s ultraviolet rays.

Despite the remote possibility of finding liquid water on the Martian surface, there is a substantial likelihood that Mars has a deep hydrosphere. It may well be valuable to develop an alternate version of the Phase 1 Mobile Lab that focuses on aqueous extremophiles

Gas Samples

Atmospheric Samples are virtually an inseparable portion of any solid or surface standing water sample. In picking up a fascinating rock from the Mars surface, the astronauts will want to preserve it as perfectly as possible in its native ambient atmosphere. This preservation means maintaining the temperature, pressure, and gas mix, including the various partial pressures of the constituent gases.

Extremophiles

Extremophiles occupy a unique niche in the hearts of astrobiologists. Extremophiles serve as an article of faith that because they live in environments radically different from mammals, they offer a key to understanding the origins and adaptability of life in the universe. Extremophiles that have been the beneficiaries of scientific attention include: freshwater algae under the Antarctic ice; thermophiles around deep ocean thermal vents; microbes that live underground at great depths in complexes of oil shale and limestone; and other such exotica. At present, the universe of extremophiles consists exclusively of single cell organisms.

Nearly all research on extremophiles until now has been field research. Replicating or simulating their natural extreme environments in the laboratory is difficult and expensive. The scientific benefits of laboratory simulations of "captive" extreme environments are not yet well established in any general way. Therefore, for the foreseeable future, extremophile research is likely to remain a field science, with a growing need for highly capable, mobile field laboratories. It may also be advantageous to simulate extremophilic environments as part of an astrobiology technology testbed. Such a simulation will enable researchers to comprehend what types of environments they must be able to create and maintain to preserve planetary samples pristinely in their ambient, natural environment.

TABLE 1. Taxonomy of Astrobiology Sample Characteristics by Phase of Matter

CHARACTERISTIC	**Solid (Rocks and Soil)**	**Liquid (Aqueous)**	**Gas (Atmosphere & Vacuum)**
Search for "Pre-Life"	Organic Molecules	Nutrients	Proto-Amino Acids
Search for Extant Life	Surface rocks, Subsurface deposits, "Bugs under rocks," Deep Drilling cores	Phytoplankton, Zooplankton, Algae, Thermophiles, "Acidophiles"	Airborne Microbes Respiration by products?
Search for Fossils	In Rocks and Sediments	Sedimentary Mats	??
Where to Search	Planetary surface & subsurface	Deep underwater, hot springs, caves, rivers	Atmosphere collection
Preserve Ambient Environment			
• Maintain Temperature	Prevent thermal expansion or contraction	Stabilize organisms	Prevent temperature-induced changes
• Maintain Pressure	Maintain structural integrity	Prevent deep-water specimens from "exploding"	Essence of the sample
• Collect with surroundings	Preserve fossils in bedrock	Collect specimens in liquid medium	??
• Maintain Chemistry	??	Collect resupply medium	??
Protect from "Forward" Contamination	Protect from damaging or polluting sample	Protect from interaction with containment vessel	Protect from interaction with pump lubricants, etc.
Protect from "Backward" Contamination	Protect from microbes and toxics	Protect lab and water system from organisms	Protect from potential toxics or microbes

Table 2 shows the definitions of biosafety levels as established by the U.S. Center for Disease Control in Atlanta, GA. The key point is that Biosafety Level 4 is sufficient and feasible to prevent the escape of exotic organisms. However, protecting an exotic specimen from external or "forward" contamination may be much more difficult, thus the suggestion of a Biosafety Level 5 to protect the specimens.

LABORATORY ELEMENT DEVELOPMENT AND EVOLUTION

The key to a well planned and logically consistent development of the Mars astrobiology lab is to anticipate what types of elements – equipment, operations, accommodations or testing will be necessary to implement each phase in its evolution. As the verisimilitude to a Mars surface base improves with each phase, so would the sophistication and completeness of the analytical equipment. FIGURE 1 and TABLE 3 both portray the four phases of astrobiology laboratory development in this strategy:

1. ***Mobile Lab***
2. ***Astrobiology Technology Development Facility (a.k.a. NASA Astrobiology Research Laboratory)***
3. ***High Altitude Astrobiology Laboratory Simulation***
4. ***Mars Surface Science Astrobiology Laboratory***

FIGURE 1 portrays this incremental development in the metaphor of design development phases and feedback cycles, illustrating the progression from 1) field tests; 2) to a technology development facility; 3) to a pressurized high altitude test; 4) to a deployable Mars surface science laboratory. TABLE 4 Describes the incremental development and improvement of a comprehensive set of laboratory elements and support systems.

The following narrative describes the strategy to develop biosafe astrobiology technology through the four phases of the mobile lab, technology development testbed, high altitude laboratory, and the Mars surface science lab.

Each of these phases leads to the holy grail of human exploration: an astrobiology science laboratory on the Mars surface, where astronaut scientists can collect, examine and analyze specimens in real time. This laboratory will be the key to searching for evidence of life on Mars, and if the explorers find any such evidence, the lab will be essential for characterizing and analyzing it.

TABLE 2. Biosafety Level Definitions

	Center for Disease Control's Biosafety Level Definitions (BSL 1-4)
Biosafety Level 1	Applies to agents that do not ordinarily cause human disease.
Biosafety Level 2	Is appropriate for agents that can cause human disease, but whose potential for transmission is limited.
Biosafety Level 3	Applies to agents that may be transmitted by the respiratory route, which can cause serious infection.
Biosafety Level 4	Is used for the diagnosis of exotic agents that pose a high risk of life-threatening disease, which may be transmitted by the aerosol route and for which there is no vaccine or therapy. ***(Protect the Earth Environment from alien "backward" contamination).***
	Additional Astrobiology Biosafety Definition?
Biosafety Level 5?	***Protect Planetary Samples and Specimens from Terrestrial "Forward" Contamination.***

PHASE 1: MOBILE ASTROBIOLOGY LAB

Anderson, McKay, Wharton & Rummel (1990), Mosher (1992), Tanaka & Watanabe (1994), and Trevino (1997) present the advantages of an Antarctic analog to simulate the future Mars base and exploration living and working environment. In discussing the idea for this paper, Chris McKay recommended that the first phase should be to develop and deploy a mobile apparatus in a refrigerated/ heated truck trailer as a module that astrobiology researchers can deploy to sites such as the Silver Lake desert in California, the Antarctic dry valleys or the Haughton Crater on Devon Island in the Canadian Arctic. The purpose of this first generation mobile lab is to put the comprehensive field analysis capability where the samples are as quickly, simply, and inexpensively as possible.. The "cabin atmosphere" within the "module" will be ambient to the exterior except for temperature and humidity. In this Phase 1 arrangement, there will be no effort to pump down the interior of the research chamber "glovebox."

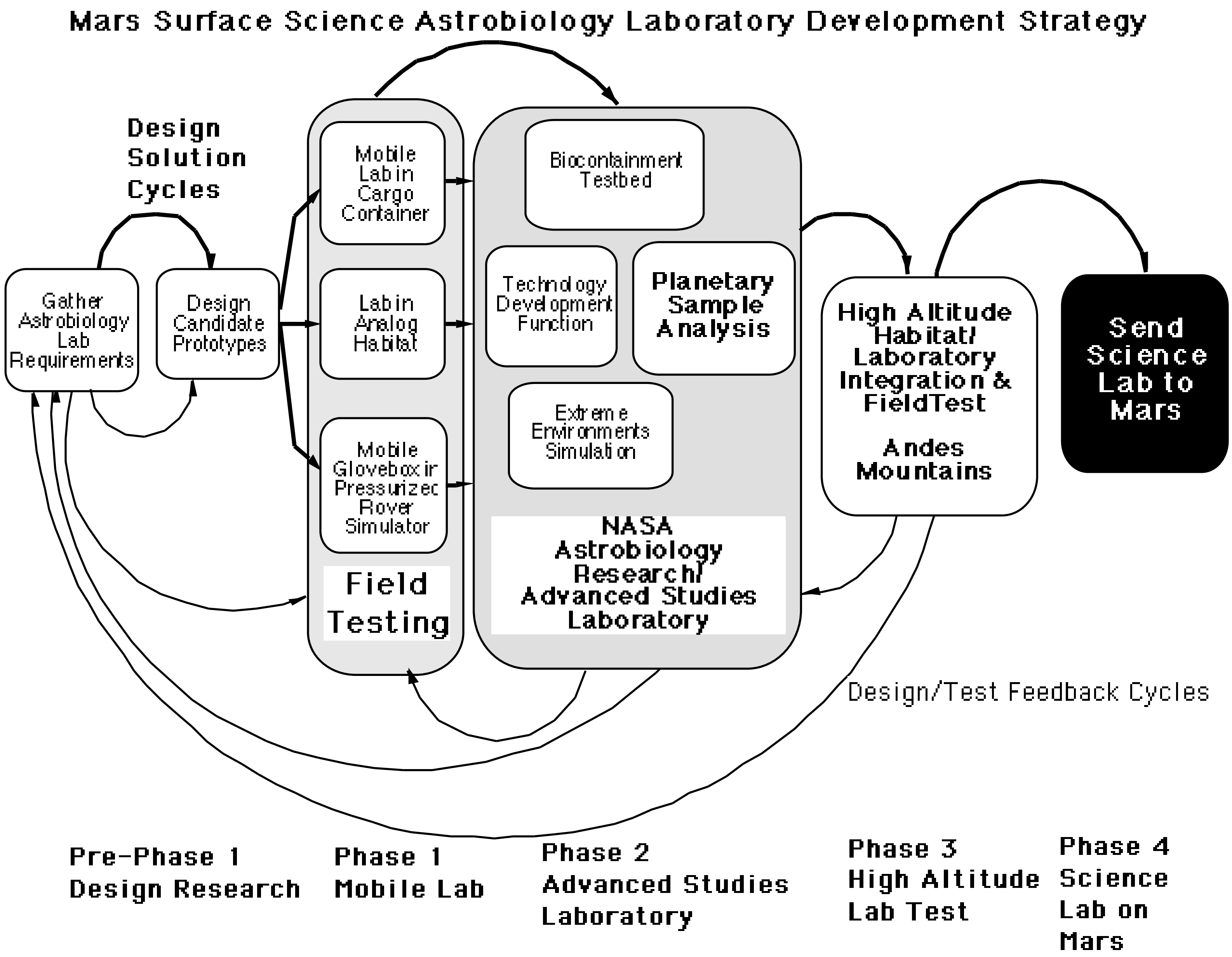

FIGURE 1. Flow Chart for Mars Surface science Astrobiology Laboratory Development Strategy

TABLE 3. Astrobiology Lab Component by Laboratory Phase Development

Components	Phase 1 Mobile Lab: Truck Trailer	Phase 2 Technology Development Facility	Phase 3 High Altitude Lab Andes	Phase 4 Mars Surface Lab
Airlock, Sample Exit	Yes	Yes	Yes	Yes
Airlock, Sample Entry	Yes	Yes	Yes	Yes
Airlock, Sample Transit	No	Yes	Yes	Yes
Analytical Instruments*	Yes	Yes	Yes	Yes
Autoclave Systems	No	Yes	Yes	Yes
Automation	Low	Moderate	Moderate	High
Data Systems	Yes	Yes	Yes	Yes
Data Archiving	Low	Moderate	Moderate	High
Field Test Ops	Yes	No	Yes	Yes
Habitat HVAC & Life Support	No	No	Yes	Yes
Integration in Habitat	No	No	Yes	Yes
Lab Systems Integration	Low	Low	Moderate	High
Lab Test Ops	Yes	Yes	Yes	Yes
Lab, Dry	Yes	Yes	Yes	Yes
Lab, Wet	?	Yes	Yes	Yes
Manipulators, Remote	Low	Moderate	High	High
Manipulators, Direct Linkage	Low	Moderate	High	High
Preparation Chamber	Yes	Yes	Yes	Yes
Pressure Maintenance System	No	Yes	Yes	Yes
Public Outreach & Education	Yes	Yes	Yes	Yes
Real-Time Automated Diagnostics	Low	Low	Moderate	High
Robotics	Low	Moderate	High	High
Sample Canister	Simple	Moderate	Advanced	Advanced
Sample Prep. Equipment	Yes	Yes	Yes	Yes
Sample Storage & Retrieval	Simple	Moderate	Moderate	Advanced
Sample Transport System	No	No	Yes	Yes
Telescience	Yes	Yes	Yes	Yes
Temperature Maintenance System	No	Yes	Yes	Yes
Vacuum System	No	Yes	Yes	Yes

The basic unit will be a deployable truck trailer, with a linear arrangement of the astrobiology lab equipment along one side. The sample airlock would penetrate the side or front of the trailer, with the exit airlock at the distal end, within the trailer. A series of simulated transfer airlocks would link each of the research chambers (“gloveboxes”) in the chain between the entrance and exit airlocks. This concept incorporates three research chambers in series: Sample Preparation, Dry Lab and Wet Lab. The cargo container or trailer itself would be a standard; “off the shelf” insulated trailer of the type used for carrying frozen or refrigerated cargoes. FIGURE 2 illustrates a prototype concept for this mobile astrobiology laboratory.

Putting this *Mobile Lab* in the field and deploying it – or its components – to the Arctic, Antarctic or desert, will help scientists and designers alike to understand the requirements for conducting this type of field research. Thus, the initial *Mobile Lab* intentionally does not include any pressure differential considerations because imposing those requirements early in the design research process would over-constrain the ability to obtain data on how scientists use the facility to conduct their work.

The prototype “glovebox” research chamber in FIGURE 2 offers an ergonomics snd human factors research opportunity to develop more advanced sample handling capabilities. In this context, the circular rings on the “gloveboxes” represent access ports or armholes for gloves, prehensors, or other manipulation devices. However, these rings as gloveports are largely metaphorical, because the pressure differential for a real pressurized research chamber would be too great to use gloves easily or effectively. To avoid misunderstanding that these rings represent only “standard armholes,” the prototype incorporates three of them into the front face, with at least one standing for a mechanical manipulator port. Two additional pairs of access ports appear on each side of the research chamber.

PHASE 2: ASTROBIOLOGY TECHNOLOGY DEVELOPMENT TESTBED

The second phase is to develop, build and test more advanced apparatus in an experimental test bed environment. This laboratory will employ the pumped down research chambers but with substantially more sophisticated analytical tools, procedures and operations. It will provide a setting in which it is possible to conduct definitive astrobiology investigations in complete “Level 4” biosafety. The purpose of the Testbed Phase is to develop and enhance sample-handling capabilities beyond the current state of the art, including the PHASE 1 Mobile Lab.

Working Across the Pressure Differential

The definitive characteristic of this astrobiology sample-processing laboratory is that it must maintain the samples in a pressure regime that is different and separate from the crew cabin atmosphere. The pressure differential, ΔP, is the difference between the Mars-ambient apparatus pressure of about .01 Bar and the breathable crew cabin atmosphere. The .01 Bar apparatus pressure would be necessary within the system of airlocks, gloveboxes and associated chambers to preserve the Mars samples in as pristine a condition as possible, preserving not only pressure, but gas mixture, humidity and temperature as well (Cohen, 1999).

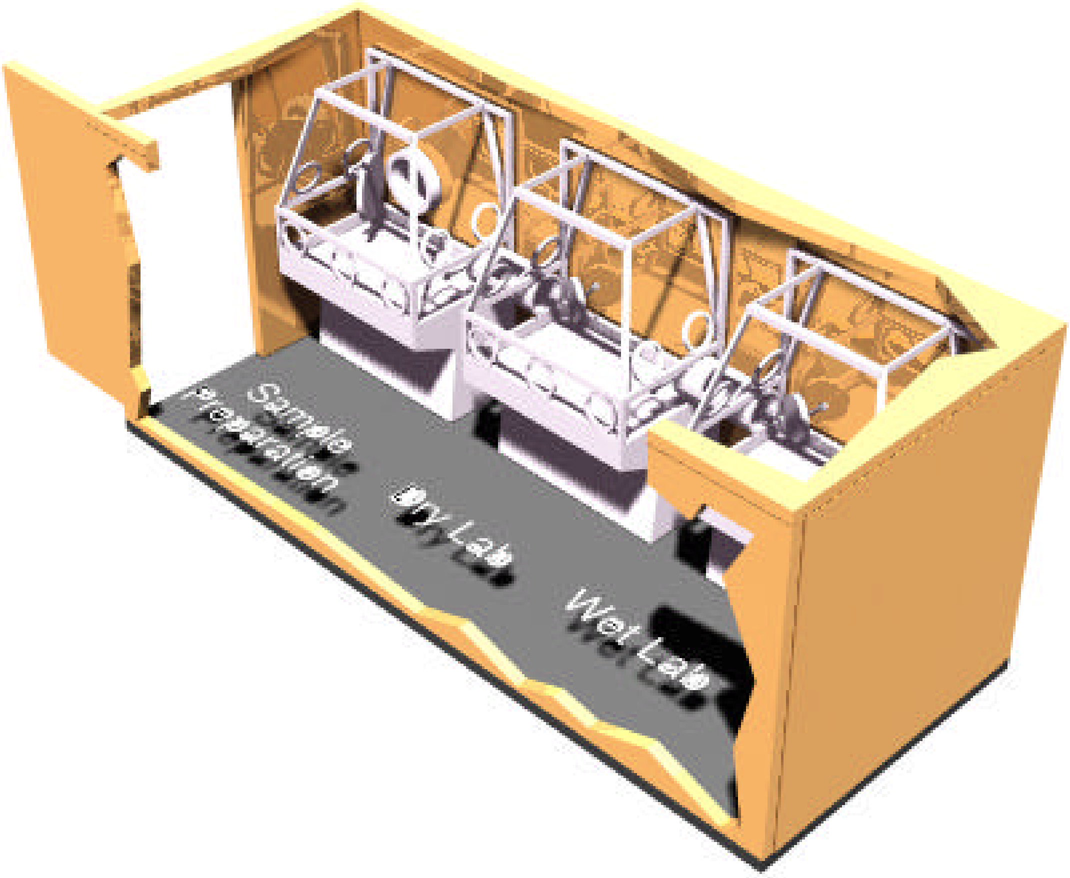

FIGURE 2. Phase 1 Mobile Astrobiology science Lab in an insulated truck trailer or cargo container.

Crew Cabin Atmospheres

The selection of a crew cabin atmosphere is a key design decision that encompasses a wide range of design variables. These variables include crew health and safety, EVA pre-breathe time, hypobaric atmosphere gas mix, pressure vessel structure and mass. Most significantly for the astrobiology laboratory, the choice of cabin pressure will determine the total ΔP between the inside of the astrobiology sample processing chambers, which is given by the Mars-ambient atmosphere of .01Bar and the pressure of the air that the crew will breathe. To maintain crew health and safety it is likely that the crew cabin atmosphere for a Mars base will operate close to one Bar.

This situation is analogous in some ways to the design decision facing the Space Station Concept Development Group (CDG) in 1983-84, when it was necessary to select a baseline atmospheric pressure. The three main criteria were 1) Crew health and safety, 2) Effects on life science experiments, and 3) Reducing pre-breathe time for Extravehicular Activities (EVAs) in space suits. By lowering the cabin atmosphere, it would be possible to reduce the time necessary for astronauts to prebreathe pure oxygen before going EVA, and it would help reduce the need for a high pressure, zero-prebreathe suit. However, lowering the pressure could have drastic and unpredictable effects upon all the life science and biomedical experiments, because all the baseline and control data are at normal atmospheric pressure. One possible compromise was to install airlocks between space station modules to make it possible to operate them at different pressures. Thus, the life science laboratory would operate at a full 1Bar, while the astronaut living quarters might have pressure reduced to .5 Bar to eliminate pre-breathing time.

However, the CDG analysis indicated that placing a pressure barrier between modules could create operational and safety problems that would be unacceptable. Finally, the Space Station design committed to a single cabin pressure at 1 Bar (Cohen, 1985). The Space Station precedent is probably instructive for the Mars surface science laboratory. On Earth, there is very little choice in this matter without incurring great extra expense to build the laboratory testbed itself into a pressure vessel.

Design of “Glovebox” Research Chambers

The glovebox was a focus of design and engineering microgravity life science. For Spacelab, where the glovebox comprised the *General Purpose Work Station* (Dalton, Leon, Hogan, Clarke & Tollinger, 1988 and Savage, Dalton, Hogan & Leon, 1988), the primary concerns were fundamental ergonomics, control of particulates (Funk & Johnson) and chemical containment (Schmidt & Flippen). For the International Space Station, the design and operational criteria expanded and became more rigorous. These design criteria include: much more capable ergonomics for multiple crew members to work together at more challenging tasks (Rasmussen, Bosley, Vogelsong, Schnepp & Phillips, 1988; Sun, Horkachuck & McKeown, 1989; and Sun & Goulart, 1992) and to achieve a higher level of bioisolation (Bonting, Arno, Kishiyama & Johnson, 1988 and Funk & Johnson, 1991.) The results of these pioneering efforts all apply in various ways to the challenge of creating the astrobiology research chamber and its supporting systems, equipment and operational capabilities. FIGURE 3 illustrates the Microgravity Science Glove Box for Space Station, which is a successor in the tradition of the Space Station generation glove boxes (Roark, Baugher, Cockrell, & Gagliano, 1999).

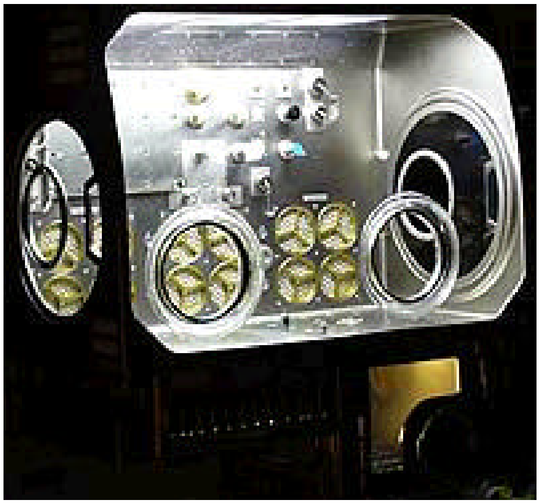

FIGURE 3. Microgravity Science Glovebox for Space Station, (Courtesy NASA-Marshall Space Flight Center).

Biosafe Astrobiology Research Chamber

Most design effort to create a biosafe sample handling capability focuses upon the enclosure in which it must occur. The requirement is to achieve the “Level 5” Biosafety / bioisolation as suggested in TABLE 2. The Center for Disease Control has the technology well in hand to prevent potential pathogens from escaping from the laboratory environment. However, it is much more difficult to protect planetary samples from “forward” contamination than to protect humans and the Earth from “backward” contamination. The reason for this difference, which leads to the suggested “Biosafety Level 5” is that the planetary samples ideally should reside in their ambient atmosphere, at the “native” gas mix, pressure and temperature. Because the Mars atmospheric pressure is about 1/100 that of Earth at sea level, there will be a marked tendency to leak inward, toward the planetary sample.

FIGURE 4. Pressurized ΔP "Glovebox" Research Chamber Prototype.

An key role for the Phase 2 Astrobiology Technology Testbed will be to develop these biosafe research chambers. FIGURE 4 shows a basic concept of the Astrobiology research chamber "glovebox" as a pressure vessel. It has four working positions, on on each of the four sides, each with a window and two "gloveports" or "armholes." These four working positions allow the operators to access the full interior of the chamber, and to work on difficult or complex tasks together at a 90° angle to one another. The window and "gloveports" on the "front" (long side) of the glovebox appear in a single integrated unit that may be replaced or changed out to accommodate the installation of special manipulators or for rapid repair. Each side of the chamber slopes at an ergonomically optimal angle of inclination to allow the best viewing for the scientist while doing work inside the chamber. To determine the necessary and appropriate outfitting of the interior research chamber will require a variety of investigations and full-scale simulations of science human factors. A glovebox having approximate dimensions of 1.5m wide, 1.5m high and 1.0m deep can pass through an access port hatch for ease of assembly and integration in the laboratory module.

FIGURE 5 shows another embodiment of the ΔP research chamber. The principal innovation is that the two long sides (the "front" and the "back") are both curved. The introduction of this left to right curvature opens the possibility of advanced ergonomic design for a "Wrap-around Work Volume" at the primary working position. Sun and Goulart were the first designers to introduce this wrap-around concept for the Space Station Life Science Glovebox (Sun & Goulart, 1992).

For the astrobiology research chamber "glovebox," this curvature offers several advantages. By curving all the surfaces of the chamber, they are naturally stiffer and less inclined to structural deflection under the pressure load. This structural stiffness imparted by the curvature allows the pressure vessel walls to be thinner, lighter in weight, and less encumbered by added stiffeners, bents, or gussets. The curvature in plan also makes it easier to install the research chamber in a circular floor plan such as the one commonly envisioned for the First Mars Outpost in a squat, cylindrical habitat. One key topic for further research is how best to configure the research chamber to optimize all the functional and operational criteria such as reach envelope, anthropometric sizing, crew members working together, and minimizing set-up and clean-up time.

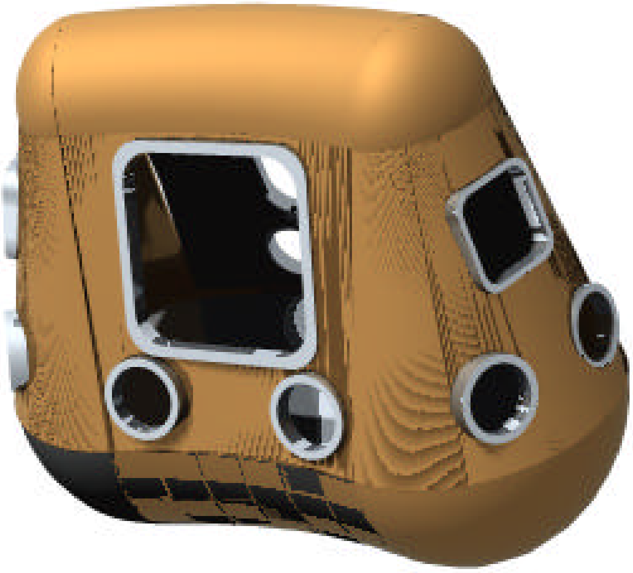

FIGURE 5. Pressurized ΔP Curved Plan "Glovebox" Research Chamber.

Manipulators

The challenge of working across the pressure differential adds considerable complexity and difficulty to the scientist's job. Because of the large difference in pressure, it is not practical to use rubber gloves as the main manipulation device. The pressure stiffens the gloves into a rigid balloon, and it will be very strenuous for the researcher's hands to work against the pressure for any extended period of time. Also, there is the danger of the gloves bursting like a balloon, and there are anecdotal accounts that in fact the rubber gloves at

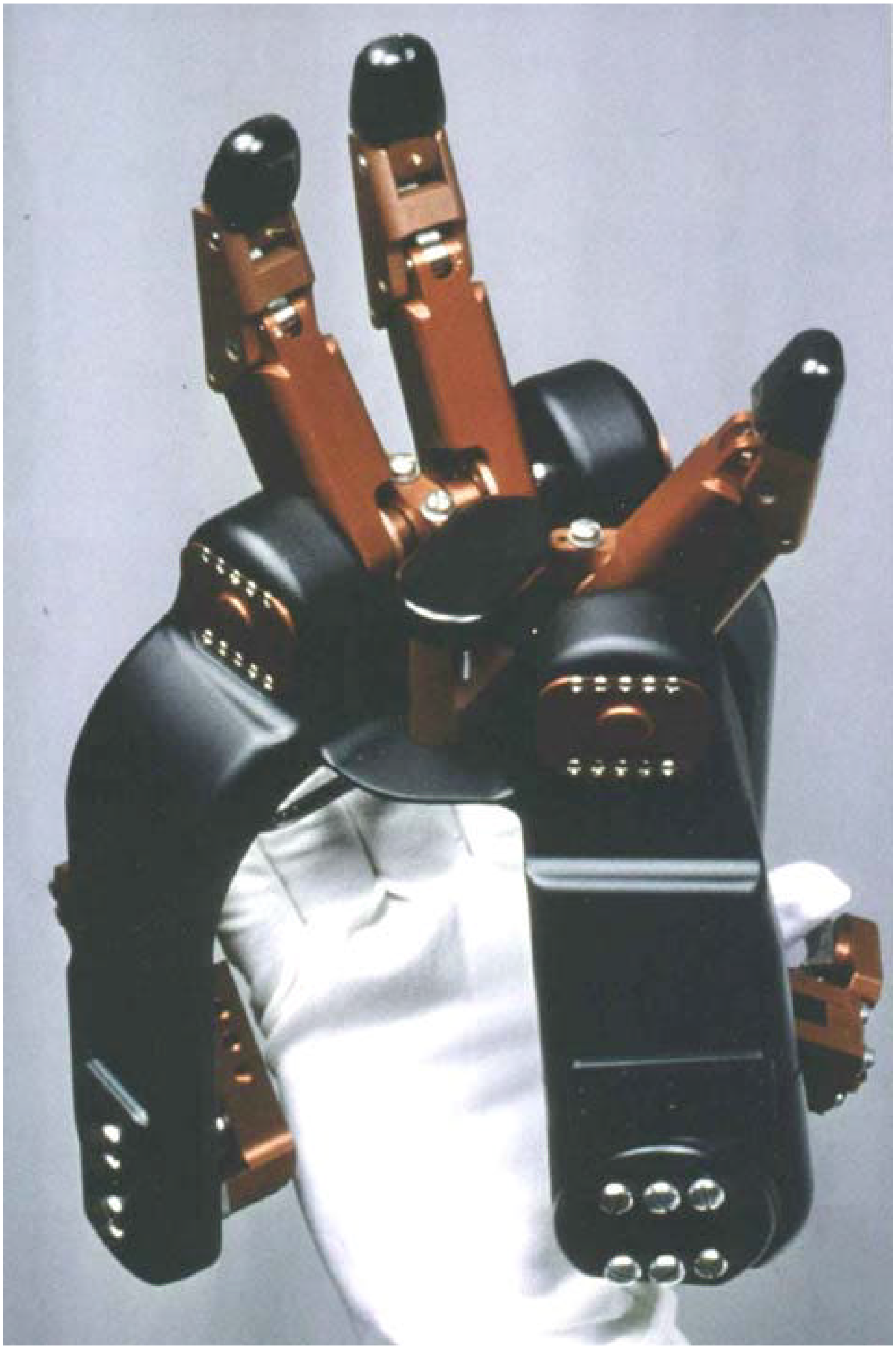

FIGURE 6. Stanford/Ames Direct Linkage Prehensor, invented by John W. Jameson. Further development of such manipulators would be part of the Phase 2 Testbed and Technology Development activity.

the Lunar Rock Receiving Lab burst occasionally during the process of preparing and examining the returned Apollo moon rocks.

Instead of gloves, there are two sets of alternatives: direct linkage manipulators and the suite of automation, robotics, and teleoperators. Each of these alternatives presents advantages and disadvantages.

Direct Manipulators

All the scientists consulted for the research in this paper, said that they would prefer to be able to hold the samples as directly as possible rather than deal with the intermediary of a computer or robot to handle the samples. This consensus would seem to suggest that a direct manual manipulator without electronic or cybernetic components would answer this need or desire. FIGURE 6 shows the Stanford/Ames Direct Linkage Prehensor, developed by John W. Jameson. Jameson explains the purpose and function of the Direct Linkage Prehensor (DLP):

> One of the greatest difficulties astronauts encounter during EVA is simply the use of their hands, resulting primarily from the high stiffness of the gloves due to the suit's pressurization. Although space suit glove technology has improved markedly in the past several years, the higher suit pressures expected for future EVA's will significantly offset these improvements. This and other considerations provide the motivation for the development of hand-powered space suit prehensors . . ..
>
> The primary goal for the design of the DLP was to incorporate as many degrees-of-freedom as possible while maintaining ruggedness and reliability. An anthropomorphic configuration was selected partly because of its proven effectiveness and partly because of the difficulty humans have with simultaneously controlling more than two or three degrees-of-freedom unless the corresponding motions are "natural."
>
> The motion of the operator's hand is conveyed to the mechanical fingers by a system comprised purely of linkages connected by revolute joints. The minimization of moving parts, along with the absence of cables or gears, results in the DLP possessing smooth, accurate and sensitive finger control with good force/position reflection (Jameson, 1987, p. 433).

Automation, Robotics and Teleoperation

The great advantage of automated, robotic or teleoperated systems for the astrobiology research chamber is that it promises to minimize the number of openings and possible leak points, thereby potentially simplifying greatly the potential for cross-contamination. There have been extensive developments in industrial robotics that provide a credible basis for planning to adapt "off the shelf products" to this application. A discussion of the state of the art in robotic manipulators is beyond the scope of this paper.

However, there is one example of a robotic manipulator operating across a pressure differential particularly worth noting. Nering, Sulaiman & Pilamis (1997) describe an experiment in which they substituted a robot for a human "inside observer" during a biomedical test in an altitude chamber pressure vessel. The operator/observers works from outside the low-pressure altitude chamber to control and direct the machine ***across the ΔP of .91 Bar*** (the interior pressure is .09 Bar = 16,900m = 55,000ft). The teleoperated robot positions an ultrasonic monitoring system to perform echocardiography on a human pilot subject undergoing decompression to simulate the experience of flying the F-22 high performance jet aircraft. Nering, Sulaiman and Pilamis describe this Hypobaric Activity Robotic Teleoperator (HART) as consisting of a:

> PUMA 260 commercial robot . . . a light-duty, vertically articulated, 6 degree-of-freedom robotic arm. The arm is controlled by a UNIVAL robot controller that employs a VME backplane and Motorola 68000 microprocessor. The six joints comprising the manipulator arm are independently actuated by DC servomotors with encoder feedback . . .. The aforementioned components yield a robust manipulator capable of accurate and smooth movements with a position accuracy of 0.05mm. A useful feature of this commercial robot is it's ability to be commanded using a number of standard and user-defined coordinate systems from a . . . IEEE RS-422 connected specialized keypad (Nering, Sulaiman & Pilamis 1997, p. 3).

Automation presents a somewhat different promise – that it may be possible to turn over some of the routine tasks to the computer and robotic system to perform, rather than expend precious crew time on jobs such as cutting, grinding and polishing rock samples. Another application for automation and robotics is to transport samples through the pressurized system from one research chamber to another. The potential need for such a sample handling and transport system becomes apparent in the following discussion of the integrated laboratory ensemble.

Recent advances in many aspects of robotics and teleoperations hold great promise for laboratory operations across the ΔP. The progress in microsurgery (e.g., by Intuitive Surgery, Inc in the field of minimally invasive heart surgery) and in microchip fabrication may very likely apply to this laboratory development.

PHASE 3 HIGH ALTITUDE INTEGRATED HAB/LAB

The third phase is to build, deploy and operate a high fidelity simulacrum of the Mars surface science laboratory. It will be a pressurizable module that researchers deploy to a high altitude location to achieve a partial simulation of the pressure differential the lab would see on Mars. Candidate locations include 4000m (13.000 feet) in the Sierra Nevada or Rockies or 6,000m (18,000 feet) in the Andes in Chile. In this phase, the crew cabin will be pressurized to sea level, while the astrobiology research chambers are open to the ambient outside atmosphere. At 6,000m, the atmospheric pressure is approximately .5 bar -- half the pressure at sea level. This half atmosphere pressure differential is "in the ballpark" of the conditions that would occur at a Mars surface base laboratory. This phase will provide a realistic simulation of the structural and mechanical loads on the complete system, as well as the operational challenges.

FIGURE 7 illustrates a preliminary concept for placing a chain of astrobiology research chambers in a semi-circle inside the high altitude laboratory testbed. It derives from the Hab/Lab baseline presented in the NASA Design Reference Mission (Hoffman & Kaplan, 1997). This train of equipment would have the ability to be evacuated by a vacuum pump to simulate the pressure differential that crewmembers would experience in the high altitude and Mars surface astrobiology labs.

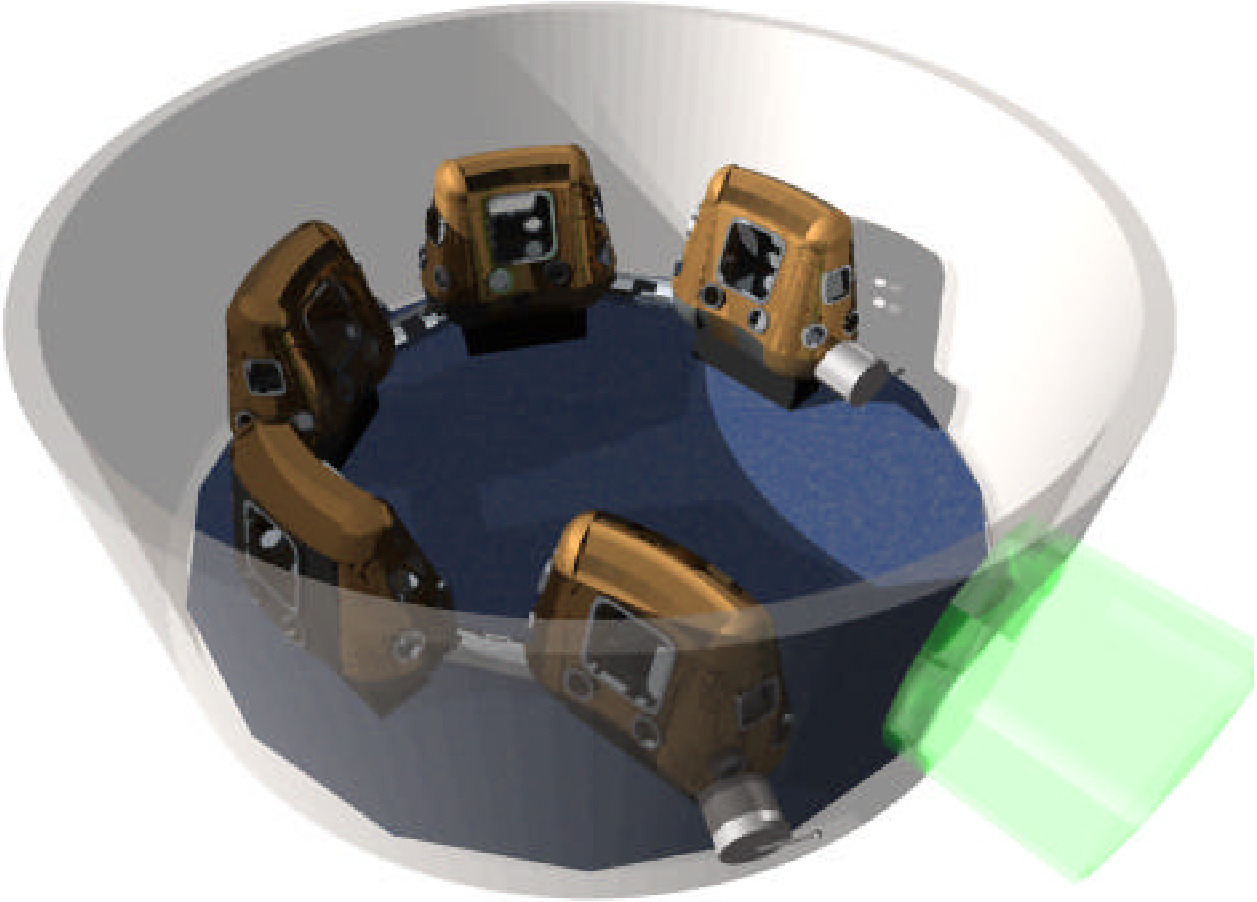

FIGURE 7. Astrobiology Laboratory comprised of ΔP “glovebox” research chambers, installed in a circular arrangement in the Phase 3 High Altitude Mars Lab simulator. This figure presents the lower level of the Hab/Lab integrated prototype, which contains the science laboratory facility.

Astrobiology Chambers at Outside Ambient Atmosphere

The key technology challenge is to open the research chambers to the outside atmosphere in terms of pressure and temperature, while the life support system maintains the crew cabin environment at a comfortable shirtsleeves temperature and 1 bar pressure, with humidity between, say 30 and 70%. It will be necessary to isolate the research chamber interiors from the much warmer crew cabin atmosphere, to prevent heat transfer to the samples.

Pressurized Crew Cabin with Life Support

This high altitude lab testbed will afford the opportunity for extensive testing of the life support system in a quasi-Mars-like situation. Basically, the life support system, and the research chamber environmental systems will be working at cross-purposes to each other maintaining radically different temperatures and pressures. Achieving a stable balance between them, and maintaining it through the whole scenario of research chamber science operations, may pose a real time control challenge for both systems.

In the lower right corner of FIGURE 7, the crew access port hatch and airlock appears. It is a vertical oblong pressure port to afford crew access to the High Altitude Hab/Lab. At the bottom, slightly to the right of center of FIGURE 7 appears the sample entry airlock, a cylindrical unit that passes through the pressure vessel shell of the Hab/Lab module. On the inside, it connects to the first research chamber “glovebox.” This chamber is the first of five in a chain of chambers for sample processing:

1. Sample Receiving, Examination and Preliminary Classification
2. Sample Preparation: Cutting, polishing, chipping, etc.
3. Dry Analysis: Electron microscope, spectroscopy, etc.
4. Wet Analysis: Chemical reagents and other techniques.
5. Sample Completion: final autoclaving, packaging for removal from the biosafe environment.

The smaller cylinders between the research chambers are transfer airlocks for passing the samples from one chamber to the next. At the end of the chain of chambers is the exit airlock, which is essentially similar to the sample entry airlock. Both these first and last airlocks must accommodate the packaging for the samples in addition to the samples themselves, whereas the transfer airlocks are for passing samples packed in little more than a plastic bag.

This ensemble of research chambers and airlocks in the high altitude lab points out a host of design considerations that become apparent through this exercise in “inquiry by design” (Zeisel, 1981).

Need for an Integrated System

The first consideration to emerge from this exercise is the need for an integrated approach that leads to a complete integrated system. It will be neither beneficial nor feasible to design and build this laboratory in a piecemeal manner, as has happened for other comparable human space systems. Each of the research chamber units must be connected and communicate in a carefully coordinated way. The will share critical environmental conditioning systems.

PHASE 4 MARS SURFACE SCIENCE ASTROBIOLOGY LAB

The fourth phase is to build a human space rated laboratory module ready for launch to Mars as part of the pre-positioning launch for a “Hab/Lab” described in the NASA Mars Design Reference Mission. It would be presumptuous to speculate too far as to the design development and detailing of the final Mars surface science laboratory. The design research, empirical knowledge and operations experience from the foregoing three phases will build a solid knowledge base from which to design and construct the Mars surface astrobiology laboratory.

Pressurized Planetary Rover

The pressurized planetary rover is a key part of the Mars surface science ensemble. It will provide the main means by which the crew may search the surface for promising specimens or rock, soil, or liquid. The rover will need a small biosafe research chamber "glovebox" so that the crewmembers may perform real time analysis to determine if a sample is interesting or not interesting (Cohen, 1999, p 8). The pressurized crew rover is also the key to transporting samples from the field to the Mars base, before putting them in a sample storage system, and eventually passing them through the sample-receiving airlock into the lab.

Drilling

Drilling for deep samples is an operation that the science lab and the pressurized rover will support. The sample cores from deep under the Mars surface offer perhaps the best chance for finding liquid water or extant life. However, to preserve those core samples for transport to the surface represents a very great challenge. The Mars surface environment may be harmful to life forms accustomed to the more protected environment underground. Also, any liquid water in a drilling core sample is likely to sublimate direct to the atmosphere unless it is contained, packaged and preserved at depth, before being removed to the surface. The transport canister must be able to maintain that pressure and temperature. Once the sample arrives at the science lab, the entire system from the sample-receiving airlock through the whole chain of research chambers must be readjusted to support a different atmospheric pressure, temperature, humidity and perhaps gas mix.

CONCLUSION

Developing the Mars surface science laboratory for astrobiology and all the allied sciences represents a great technical and scientific challenge for NASA. The challenge consists in developing the ability to collect, transport, receive, prepare, process, and analyze exotic samples while preserving them in their ambient environment and without contaminating them. These samples and specimens will come from a variety of "native" environments, so the overall laboratory system must be able to respond to the changes of a sample collect on Olympus Mons versus Valles Marineris, or from several kilometers deep in a drilling shaft.

The path to achieving this capability will be long and complex. This paper suggests a four-stage approach that will afford NASA and the scientific community a conceptual framework within which to approach this effort.

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APPENDIX

Mars Surface Science Laboratory *strawman payloads list* of requirements from:

Nash, Douglas B.; Plescia, Jeffrey; Cintala, Mark; Levine, Joel; Lowman, Paul; Mancinelli, Rocco; Mendell, Wendell; Stoker, Carol; Suess, Steven; (1989, June 30) Science Exploration Opportunities for Manned Missions to the Moon, Mars, Phobos, and an Asteroid, NASA Office of Exploration Doc. No. Z-1.3-001, JPL Publication 89-29, Washington DC: NASA Office of Exploration.

“The strawman payload list provides a comprehensive suite of instruments and tools that would be necessary to carry out the scientific objectives . . .”

Compiled from pages 31 and 36-37, the requirements of all these separate disciplines add up to an Astrobiology set of requirements.

GEOLOGICAL AND GEOPHYSICAL FIELD SCIENCE EQUIPMENT:

- Sampling Tools for dislodging, acquiring, and stowing rock and soil samples (grabbers or tongs for handling solid rocks, rakes for 1- to 4-cm rock fragments, shovel or scoop for foil and bulk regolith samples).

- Coring tools to obtain cores 5 cm diameter , 10 m deep in regolith; 2 cm diameter, 1 m deep in solid rock.

- Trenching rig for digging trenches and burying equipment.

- Major sieving operation system to prepare separated samples of loose material.

- Vehicle:
  - Range ≥ 500 km.
  - Pressurized.
  - Holds 3 to 4 people.
  - Adaptable arm (backhoe, crane, sample stowage, etc.).

- Portable geophysical instrument packages containing magnetometer, gravimeter, active seismic array, radar/EM sounder, corner cube retroflectors.

- Multispectral imager with close-up and telescopic capability.

* Elemental analysis spectrometers:

  - X-ray
  - Gamma ray
  - Neutron activation.

BASE SCIENCE EQUIPMENT

- Seismometer (pier mounted, short- and long-period sensitivity).
- Local vehicles for excavation and transport.
- Soil mechanics testers.
- Electrical/thermal properties analyzers.
- Dust collectors and mobility analyzers.
- Sample packaging equipment for transporting samples to Earth.
- Radiation counters.
- Cameras.
- Telescope (small, with accessories for image and spectra observations in the visible and infrared).
- Computers for equipment control and data processing.
- Analytical lab (elemental, mineralogical, particle/grain size).
  - Electron microscopes (SEM, TEM, microprobe).
  - Optical microscopes (petrographic, binocular).
  - Thin-sectioning equipment.
  - X-ray diffractometer.
  - X-ray fluorescence spectrometer.
  - UV/Vis/IR spectrometer.
  - Network (e.g., charged particle detectors, heat flow) central node.

ATMOSPHERIC STUDIES PAYLOAD

- Mass spectrometer.
- Ion detector.
- Microwave and radiowave radiometers.
- GCMS, LIDAR, IR radiometer.
- Weather station (plus mini-stations deployable at multiple sites),
- Water-vapor detector.
- Dust collection array.

FIELDS AND PARTICLES STUDIES EQUIPMENT

- Solar Wind spectrometer.
- Magnetometer.
- Electron reflectometer.
- Energetic particle detector and mass spectrometer.
- X-ray monitor.
- Cosmic-ray detector.
- Ionospheric sounder.

EXOBIOLOGICAL STUDIES

- Subsurface sampling equipment.
- Gas Chromatograph/Mass Spectrometer.
- Scanning electron microscope.
- Microbiology laboratory.
- Chemistry laboratory.
- Differential Scanning calorimeter and evolved gas analyzer.
- Contamination, sterilization, and sample preparation laboratory.
- Human safety/toxicity lab equipment.

MATERIAL SCIENCE STUDIES

- Material stability test equipment
- Soil testing and agricultural experiment equipment.