

FINAL PROGRESS REPORT
on
ROBOTIC LUNAR ECOPOIESIS TEST BED

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ROBOTIC LUNAR ECOPOIESIS TEST BED

FINAL PROGRESS REPORT

1 INTRODUCTION (ABSTRACT)

The long-term concept of this project is to let a living ecosystem create itself in an engineered dome on the moon under controlled Mars-like conditions. Under robotic control a community of organisms creates its own environment that is no longer hostile to living things. For example, the energy to self-construct the bubble is initially obtained from fuel cells that also produce the water that the enclosed system will use to moisten the regolith. Initially, robotically controlled bottled gases will control the internal pressure at 1.0 – 1.5 kPa, heat from the sun will be controlled by radiators initially actively positioned by photovoltaic electric motors or solar-powered Stirling engines. Then chemoautotrophic microorganisms gain energy from the lunar regolith producing organic matter for fungi, which produce CO_2 for algae, which will produce O_2 for some simple invertebrate animals. This would be a precursor to terraforming studies (fairly controversial) for Mars, but accessible and controllable owing to the relative proximity of the moon. This approach differs from Closed Environment Life Support Systems (CELSS) approach in that the Ecopoiesis Test Bed is an architecture that causes the environment to evolve on its own, starting with water and nitrogen and spores or inactive cells of appropriate prokaryotes, seeds, and eggs of organisms that eventually occupy the test-bed module. Experimental ecopoiesis is a new field, so experiments will be designed in Phase I, begin in the laboratory in Phase II and evolve to ISS in at least three phases before a lunar module is considered. A gradual, stepwise multi-year approach is proposed, in which Phase I is a feasibility study, Phase II consists of laboratory experiments and spaceflight planning, and Phase III is a multi-institution undertaking of indefinite duration culminating with a robotic lunar ecopoiesis laboratory. This concept is sketched in Figure 1. Progress during the six months of Phase I research is described in this report.

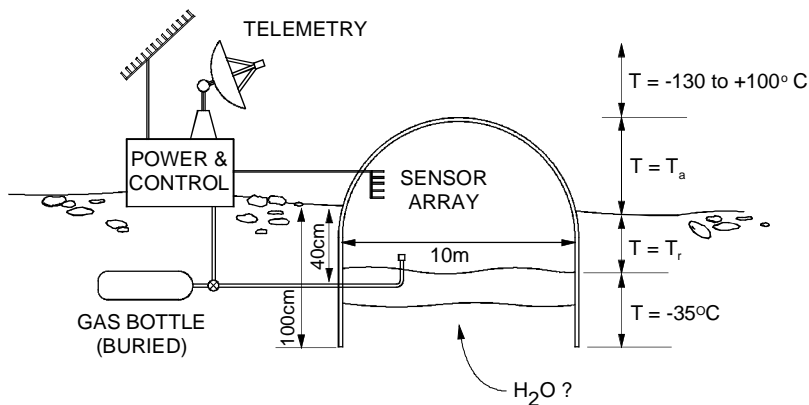


Figure 1. Artistic concept of a robotic lunar ecopoiesis test bed. The long-range goal of the proposed program, showing positioning of the in situ polymerized inflated dome to take advantage of lunar thermal characteristics.

2 OVERVIEW OF PROGRESS ON WORKSCOPE (EXECUTIVE SUMMARY)

The four tasks designated in the workscope have been completed. Organizational events included the completion of the contract between USRA and SHOT and the composition of The Lunar Ecopoiesis Test Bed team, namely:

Principal Investigator: Paul Todd, Chief Scientist, SHOT, Inc.

Co-Investigator: Penelope J. Boston, Director, Cave and Karst Research Program, New Mexico Institute of Mining and Technology and Director of Research, Complex Systems Research, Inc.

Project Lead Engineer: Heidi Platt, Chemical Engineer, SHOT, Inc.

Project Engineer: William J. Metz, Mechanical Engineering Technologist, SHOT, Inc.

Project Chemical Engineer: Lara Deuser, Laboratory Scientist, SHOT, Inc.

Final progress is reported on the project objectives and deliverables. The objectives were (1) the completion of a workshop conference on extremophile selection, (2) detailed planning including identification of the components of laboratory test beds, (3) an evaluation of low-gravity and terrestrial venues for Mars ecopoiesis research, and (4) scaling rules for test beds. An executive summary of each follows in this section.

2.1 Workshop Conference on Extremophile Selection

The NIAC fellow and the Co-Investigator, assisted by SHOT team members, successfully organized and held the workshop on “Extremophile Selection for Ecopoiesis Friday and Saturday, 30-31 January, 2004, Albuquerque, New Mexico. As planned, a total of 13 experts participated vigorously, and all participants were prepared to contribute in the spirit of the workshop objectives. Three subgroups were created, and these reported their conclusions concerning the selection of pioneer organisms, analytical methods suitable for test-bed research, and evaluations of potential test-bed venues. The recommendations in broad terms were, respectively, begin with cyanobacteria as primary producers and greenhouse-gas producers as secondary consumers with due consideration for the possibility of vascular plants; use the most revealing and automated analytical methods with emphasis on those relevant to the pioneer organisms; consider the moon as a test-bed venue in the context of other venues using several selection criteria and a figure-of-merit approach. An important notion that emerged from the workshop was a miniaturized test-bed that could be reproduced in multiple copies in a portable format for use in essentially any venue, but especially laboratories in educational institutions and aboard orbital spacecraft. The participants agreed that the proceedings of the workshop should be published as a single article co-authored by the interested participants.

2.2 Preliminary Test-Bed Chamber Design

A combination of commercial “off-the-shelf” components was identified and assembled as three-dimensional renderings of an integrated test bed that provides a high-fidelity replica of the surface of Mars at various locations on the planet. Major components include a fused silica low-pressure vessel with connections for environmental gas composition control and regolith analysis; an environmental control chamber that contains the vessel and regulates temperature accurately over the entire range of Mars surface and regolith temperatures; a solar-spectrum illuminator capable of simulating the spectrum and intensity of sunlight on the Martian surface;

associated gas bottles, valves, gauges and piping; and a computer and software package for imposing daily cycles on temperature and illumination using operator selected parameters. According to the completed parts list the cost of parts is expected to exceed \$55,000. As an added bonus, a design was developed for a portable modular test-bed suitable for use in standard laboratories, classrooms and other venues. Modules are to be periodically recharged and analyzed using a docking station.

2.3 Identification of Low-Gravity Venues

During the course of Phase I research and within the workshop, a list of Mars ecopoiesis research venues was created, and each venue was assigned a figure of merit for each feature, such as gravity, day length, atmosphere, soil chemistry, achievable temperature profiles, accessibility, feasibility and cost. The lunar venue, proposed in this project, was found to be less than ideal. One significant outcome was the notion of the modular test bed mentioned in the previous paragraph. In principle this concept could function anywhere, and several of these, each with its own atmosphere and regolith, might function on the International Space Station and the Moon, for example, with minimal difficulty.

2.4 Scaling Rules

Progress on scaling rules included the calculations of heat dissipation in the Laboratory Test Bed and the Modular Test Bed, water content of the Laboratory Test Bed, and gas loss through the lunar regolith. This last calculation clarified the need to seal the bottom of the lunar test bed and to drastically reduce the diameter of the proposed lunar test-bed (Figure 1) from 30 m to 1 m. Scaling calculations will continue to be pursued in Phase II.

2.5 NIAC Deliverables and Activities

Two critical NIAC events were attended. A poster was presented at the NIAC Annual Meeting, which was attended by the NIAC Fellow and the Co-Investigator, and a presentation of progress was made at the NIAC Phase I Fellows Workshop in March, 2004. A paper was presented at the annual "Space Technology and Applications International Forum" (STAIF-2004) in January 2004 in Albuquerque, NM and the corresponding article was submitted for publication in American Institute of Physics Conference Proceedings, Mohamed S. El-Genk, Editor. This completed manuscript is included in this report as Appendix A. As an outcome of the workshop, an additional manuscript has been prepared, "Quo Vadis Ecopoiesis" by the workshop participants. This manuscript is included in this report at Appendix B.

3 PROGRESS ON OBJECTIVES

3.1 Objective 1. Identify pioneer organisms

As specified in the Work Plan, a workshop symposium was to be organized around the following questions:

- What known organisms thrive and grow most rapidly in terrestrial polar environments?
- What known organisms will metabolize and proliferate in minimal water and pressure?
- What organisms are most appropriate to start a community using mineral energy?
- What conditions must humans create in the atmosphere to encourage cell proliferation?
- What conditions must humans create in the regolith to encourage proliferation?
- What should be the expected succession of organisms in an ecopoietic environment?
- What time scales are appropriate for experiments in model architectures?

- What are the appropriate analytical methods for detecting growth, metabolism and environmental modification and succession?

3.1.1 Workshop Conference on Extremophile Selection for Ecopoiesis

The workshop symposium titled “Extremophile Selection for Ecopoiesis” was held January 30-31, 2004, at the Wyndham Hotel in Albuquerque, New Mexico. Invitations were distributed to distinguished researchers in the fields of planetology, environmental microbiology, astrobiology and extremophile biology. Responses to invitations were extremely positive, and there were 13 participants present at the workshop including two NIAC representatives.

One of the objectives to be accomplished was the identification of potential “pioneer organisms” suitable for Mars environments to be simulated in the laboratory, on the Space Station and, eventually, on the moon in a test bed facility. Answers to the above questions were sought through a consensus process in which each participant presented a case and cases were discussed approximately two at a time. One of the trade-offs addressed was the selection of sites on the Moon for the location of an ecopoiesis facility and on Mars as potential future ecopoiesis introduction sites based on temperature vs. water availability. We were also seeking maximum extremophile versatility (resistance to cold, drying, solidification, radiation, temperature cycles) among potential pioneer organisms. Pioneer organisms were evaluated on the basis of a specified list of requirements. The initiation of the ecopoiesis process is expected to include the provision of small amounts of initial, but not sustaining, “nutrient” materials (gases, salts) for the very first pioneer organisms.

3.1.1.1 The Workshop Program and Participants

The final program for the workshop was as follows:

**Workshop: Extremophile Selection for Ecopoiesis
Friday and Saturday, 30-31 January, 2004
Albuquerque, New Mexico**

Friday A.M.

- 8:00 Coffee, juice and pastry provided
- 8:30 Introductions and logistics (Pat Russell, Paul Todd, Lara Deuser)
- 8:35 Session I: Mars Simulation Testbeds
 - Habitability and site selection (30 min) Penny Boston
 - Terraforming organism requirements (30 min) Chris McKay
 - Discussion of Mars simulation requirements (30 min)
- 10:05 BREAK
- 10:25 Session II: Planetary environments
 - Water on Mars, regolith chemistry (30 min) Lawrence Kuznetz
 - Water on the moon, regolith chemistry (30 min) Alan Binder
 - Discussion of water, regolith provisions in test bed (30 min)
- 12:00 LUNCH

Friday P.M.

- 1:00 Session III: Pioneer organisms I
 - Cyanobacteria (30 min) David Thomas
 - Halobacteria (30 min) Adrienne Kish
 - Discussion of selection of extremophiles (45 min)
- 3:00 BREAK
- 3:30 Session IV: Pioneer organisms II
 - Optimized prokaryotes (30 min) Imre Friedmann
 - Cold, dry ecology eukaryotes/heterotrophs (30 min) Roseli Ocampo-Friedmann
 - Discussion of pioneer-organism ecology (45 min)
- 5:30 Wrap-up of day's transactions, plans for Saturday sessions
- 6:30 Dinner together (venue TBD)

Saturday A.M.

- 7:30 Coffee, juice and pastry provided
- 8:00 Session V: Laboratory, ISS and lunar test-bed scenarios
 - Mars simulation experiments (30 min) David Gan
 - Designs to date (30 min) Paul Todd
 - Discussion of test beds (30 min)
- 9:30 Division into working subgroups
 - Extremophile selection
 - Test-bed configuration
 - Analytical methods
- 9:40 BREAK
- 9:50 Session VI: Recommendations
 - Separate meeting of three working subgroups (70 min)
 - Subgroup reports, written recommendations (60 min)
 - Wrap-up discussion (Additional writing assignments?)
- 12:30 Adjourn

The participant list is given in the caption of Figure 2.



Figure 2. Participants in the “Extremophile Selection for Ecopoiesis” workshop. Back row: David Thomas (Lyon College), Larry Kuznetz (Johnson Space Center), Alan Binder (Lunar Research Institute), Chris McKay (Ames Research Center), Patricia Russell (NIAC/USRA), E. Imre Friedmann (Ames Research Center). Front row: David Gan (University of California), Lara Deuser (SHOT), Adrienne Kish (University of Maryland), Penelope Boston (New Mexico Institute of Mining and Technology, co-chair), Paul Todd (SHOT), Roseli Ocampo-Friedmann (Ames Research Center). Photo by Ron Turner (NIAC, missing from the photo). Photo provided by David Thomas.

The above agenda was followed exactly and successfully. The detailed conclusions of the workshop are summarized in the following sections of this final report and, according to the wishes of the participants, prepared for publication in a suitable archival journal (Appendix B).

3.1.1.2 Workshop Deliberations

A synopsis of the deliberations of the three subgroups follows:

Subgroup 1, “Extremophile Selection”, worked from a matrix that was filled out and is summarized in Table 1. This table is not the final product but the result of notes taken during the group session. No organism was identified to have a “Y” in every column, and considerable discussion focused on the consideration of combinations of organisms that perform complementary functions while surviving extreme conditions. *Chroococcus*, *Chroococcidiopsis* and *Anabaena* emerged as leading candidate autotrophs, although not all appear in the table.

Table 1. Preliminary selection matrix for extremophiles. Organisms not discussed during the subgroup session are shown in non-highlighted rows.

organism	dehydration	Cold function (below 0)	Low pressure	High CO ₂	photosynthesis	lithotrophy	UV resistance	radiation	Black pigment	Nutrient production	Nitrogen fixation	Greenhouse gas
E. Coli												
Halophiles												
Halobacterium – strain (NRC1)	Y	?	Y	Y	N	N	Y	Y	N	N	N	N
Tardigrade												
Rhodospirillum												
Methanogens (contact expert)	?	Y	?	Y	N	?	?	?	N	N	N	Y
Proteus morgani												
Pseudomonas aeruginosa	Y	?	Y	Y	N	N	N	N	N	N	N	N
Streptococcus												
Serratia												
Psychrophiles												
Bacillus subtilus	Y	N	Y	?	N	N	As spores		N	N	N	N
Chroococcidopsis	Y	Y	?	?	Y	N	Y	Y	N	Y	N	N
Antarctic strain (black yeast)	Y	Y	?	?	N	N	Y	?	Y	N	N	N
Antarctic heterotrophic bacteria	Y	Y	?	?	N	?	?	?	N	N	N	N
Deinococcus	Y	Y	?	?	N	N	Y	Y	N	N	N	N
Cyanobacteria												
Nitrogen-fixing bacteria	?	?	?	Y	N	N	?	?	N	Y	Y	N
Streptococcus mitis	Y	?	Y	?	N	N	?	?	N	N	N	N

Subgroup 2, Test-bed Configuration, worked from a matrix that was filled out and is summarized in Table 5 in section 3.3.3, the selection of low-gravity venues. Figures of merit were assigned, on a scale of 0 to 4, for the fidelity and convenience with which each desired characteristic of the Martian environment could be provided.

Subgroup 3, “Analytical Methods”, was tasked to identify feasible and meaningful analytical methods (biochemical, atmospheric, microbial, etc.) that would reveal progress in a “growing” ecopoiesis test bed.

1. Analytical challenges

- a. Direct measurement of biomass and cell number very challenging in solid or soil media
 - b. Need benign, live/dead method, maybe fluorescence
 - c. Optical fiber linear arrays (like a comb) to image throughout the solid medium or soil column
2. Analysis Techniques in hand
- a. Passive sensing
 - Gas sensing ion-selective electrodes
 - IR detectors for CO₂, etc.
 - b. Active Head Space Analysis
 - GC/MS, identify trace gas unknowns, stable isotope signals, etc.
 - c. Chlorophyll fluorescence – CCD fluorescent system
 - Fluorescence tagging of plants
3. Post experimental analyses
- a. Freezing whole experiment for thin sectioning
 - b. Microbeam imaging and chemical analyses
 - c. DNA extraction perhaps
4. Plant module special considerations
- a. Axenic plant -
 - b. Land in the dark, three days before lunar dawn, 16 days of sunlight maybe modified by shading
 - c. Soil moisture, O₂, pH, CO₂, Ammonium, nitrate, nitrite, other root zone trace gases
 - d. Head space gases, O₂, CO₂, ethylene
 - e. Multiple imaging techniques, surfaces, movement, circadian rhythms
 - f. Spectral determination of plant health
 - g. Fluorescence – natural and artificial for health monitoring
5. Large Scale Facility
- a. Field methods come into play because of size
 - b. Monitoring and Study Phase
 - c. Breeding experiment – application of “mars-like” conditions
 - d. Transition from experimental facility to production facility for seedstock and organism stocks for real Mars ecopoiesis
 - e. Engineering aspects
 - f. Monitoring during the transition phases

Subgroup 1 also addressed the seven organizing questions and suggested a few responses. These are inserted in the original list of questions as follows:

What known organisms thrive and grow most rapidly in terrestrial polar desert environments?

- Black yeast under lab conditions; nothing grows fast in the cold, but this one grows the fastest, relatively

What known organisms will metabolize and proliferate with minimal access to water and in low-pressure atmospheres?

- Chroococcidiopsis
- Black yeast possibly

- Halophiles possibly

What conditions must humans create in the atmosphere to encourage cell proliferation?

- More greenhouse gases, increased temperature

What conditions must humans create in the regolith to encourage proliferation?

- Nutrient production?

What time scales are appropriate for experiments in model architectures?

- 15C- weeks
- 0C- months
- -20C or below- years

What is the possible degree of autonomy of an entirely subsurface biosphere?

- Depends upon the subsurface conditions

3.1.2 Summary of Conclusions and Recommendations

The conclusions and recommendations that follow are a combination of direct statements by participants in the workshop and the lessons considered relevant by the Phase I project teams.

Organism selection: Growth and metabolism is required, not just survival. Very robust species of nitrogen-fixing cyanobacteria are prime candidates, possibly along with chemo-lithoautotrophs, as absolute pioneer organisms in a minimally modified Mars shallow regolith environment. The adaptability of certain species of cyanobacteria under varying CO₂ levels is known. In a substantially modified environment, especially where water is in limited supply, certain vascular or more primitive green plants would be an efficient source of photosynthesis products for use by secondary consumer organisms. Early secondary consumer organisms could include halophiles, owing to their capabilities to withstand osmotic extremes and to repair DNA. Methanogens, as archaea, should thrive in primitive environments with suitable carbon availability and generate methane, a greenhouse gas that will contribute to the absorption and holding of heat radiated from the regolith.

Site selection: The most available venue for experimental ecopoiesis is the high-fidelity laboratory test bed. A practical means of placing a high-fidelity test bed at 0.38 g on an orbiting spacecraft (International Space Station, ISS) would add the low-gravity dimension but would be constrained by weight and power. A pallet-mounted enclosure outside the ISS could not actually take advantage of the full solar spectrum owing to the incorrect day length (90 min total), if the failure to reach thermal equilibrium in earth orbit. A lunar site would be at thermal equilibrium and at reduced gravity (0.17 x g) but would require the addition of a Mars-type regolith and artificial day-length control. Very large government simulators (such as at Johnson Space Center and Jet Propulsion Laboratory) might be available on a limited basis, although control over environmental parameters may be limited. University-based small-scale simulators also exist, such as at the Universities of Washington and Arkansas. Very small scale “Mars jars” had been recommended some time ago and were heavily supported by Chris McKay. Such miniature test beds could be established almost anywhere, including orbiting spacecraft and high-school class rooms. Considerable enthusiasm was generated for this concept, and a design study was added to the Phase I project (see Section 3.2.3, Mars Atmosphere and Regolith Simulation Modular Test Bed (MARS-MTB), below).

Building an architecture: To build an architecture around the ecopoiesis test bed concept the following are required: (1) laboratory research on extremophiles deliberately undergoing adaptation to a simulated Mars environment, (2) a system of test beds on Earth accessible to as many interested investigators as possible, (3) an advised program of selection of extraterrestrial venues for ecopoiesis research, and (4) in view of new NASA initiatives an inclusion of issues studies, such as planetary quarantine, human settlement and terraforming.

3.2 Objective 2. Develop Preliminary Laboratory Chamber Design

3.2.1 Overview of Objective

According to a previous report “a parts and price list and top-level drawings for the Robotic Laboratory Ecopoiesis Test Bed and initial scaling calculations” are targeted for completion during Phase I. Using the design sketch shown in Figure 3 (from the Phase I proposal), parts lists, costs, and a top-level drawing tree were begun. As a result of deliberations with colleagues, especially in the Workshop conducted to fulfill Objective 1, a modular laboratory test bed was also considered, and a preliminary design is provided. Thus the full-scale laboratory unit has been named Mars Atmosphere and Regolith Simulation Laboratory Test Bed (MARS-LTB), while the modular test bed design is designated MARS-MTB. The latter constitutes a significant conscious addition to the scope of the Phase I project.

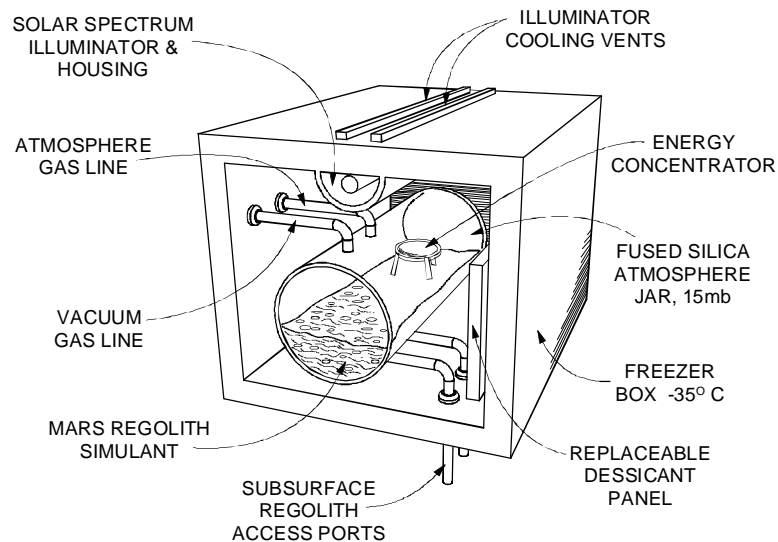


Figure 3. Laboratory Mars ecopoiesis test bed design sketch, which served as the starting point for Objective 2, Simulation Chamber Design.

In overview, the expected purchased or fabricated items are the following:

Simulator-unique requirements

- Mars regolith simulant
- Moon regolith simulant
- Solar spectrum simulator with suitable intensity
- Gas bottle with special mixture

Major off-the-shelf and constructed components

- Freezer-heater combination environmental chamber -135 to +26 °C
- Vacuum pump

- 2-stage regulator & pressure control system (10 mbar at chamber, hundred psi at bottle)
- Fused silica experiment chamber

Each of these subsystems has a complexity of its own, and these were the subject of Phase I research. Design progress was substantial, and the MARS-LTB has been designed in sufficient detail that construction can begin immediately upon authorization to proceed with a Phase II project.

The environmental parameters that the MARS-LTB will control include:

- Temperature level
- Temperature cycling
- Humidity
- Atmosphere composition
- Atmosphere pressure
- Light level
- Light cycling

3.2.2 Laboratory Test Bed Description and Subsystems

The laboratory test bed (MARS-LTB) consists of components that can be purchased and assembled. The subsystems consist of

- Environmental Control Unit – a low-temperature, variable-temperature cabinet
- Low-pressure vessel to contain atmosphere and regolith simulants
- Illuminator for solar spectrum simulation
- Gas control subsystem
- Operating computer and software

All assembled, the Test Bed will have the appearance shown in Figure 4. Each of its subsystems is described in the following subsections.

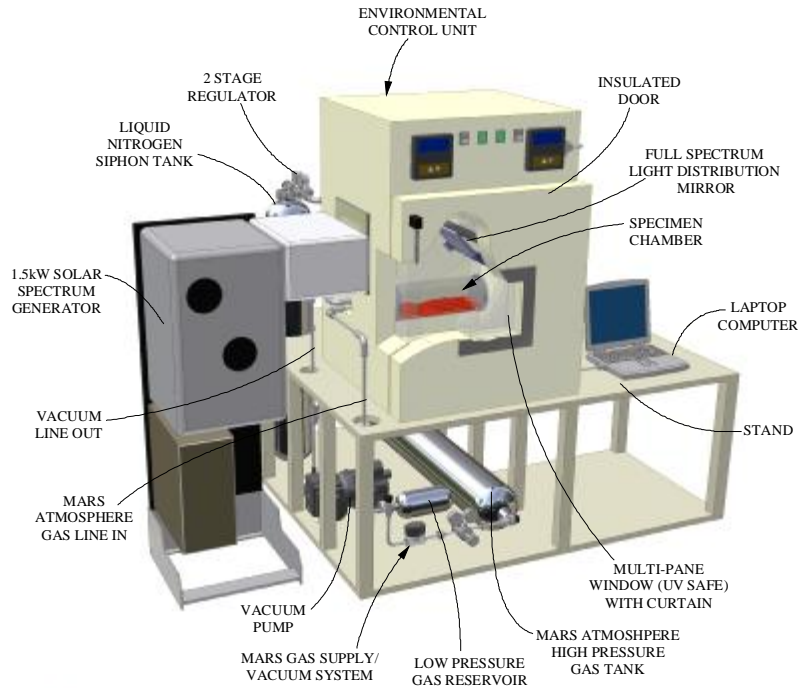


Figure 4. Overview of MARS-LTB

3.2.2.1 Environmental Control Unit

The Environmental Control Unit (ECU), a product of Associated Environmental Systems, Inc., houses the MARS specimen chamber and controls the temperature and humidity of the air surrounding the test chamber. The Environmental Control Unit will control the temperature of the test chamber from -135 °C to 26 °C and will follow a typical Martian daily profile, such as those shown in Figure 5 for the equator and mid-southern latitudes. Temperature stability is $\pm 1/2$ °C at the sensor.

The Environmental Control Unit has a working volume of 8 cubic feet. The internal dimensions are 24" high x 24" wide x 24" deep and will easily accommodate the MARS-LTB test chamber. The Environmental Control Unit has an insulated door located at the front of the unit (see Figure 6). The door will allow access to the test chamber prior to and after experiment duration. The door will also allow access during the day time portion of the simulated Mars cycle. An 8" square double paned glass window will be located in the door. This window will allow viewing during the simulated Mars day cycle. During normal experimental operation the window will be covered with a light-blocking material to prevent light from the lab from entering into the specimen chamber during the simulated Mars night.

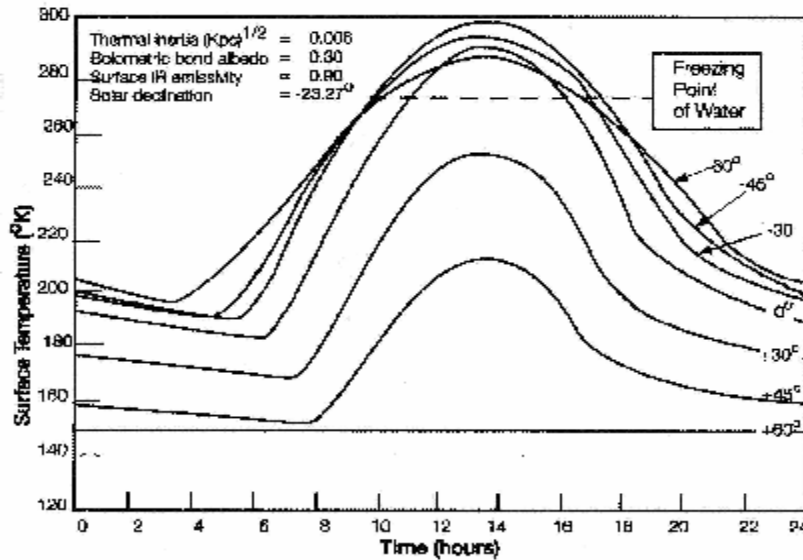


Figure 5. Daily temperature profile at the surface of the Mars regolith at a depth of 1 m, the temperature is a steady -20°C.[Carr, 1996]

A double pane quartz window will be located on the left side of the environmental chamber. Quartz will be used for this window in order to pass light from the solar spectrum generator into the specimen chamber. Inside the Environmental Control Unit (Figure 6) located above the specimen chamber is a full spectrum light distribution mirror. The convex shape of the front side reflective surface will direct and spread the horizontal light from the solar spectrum generator downward into the specimen chamber.

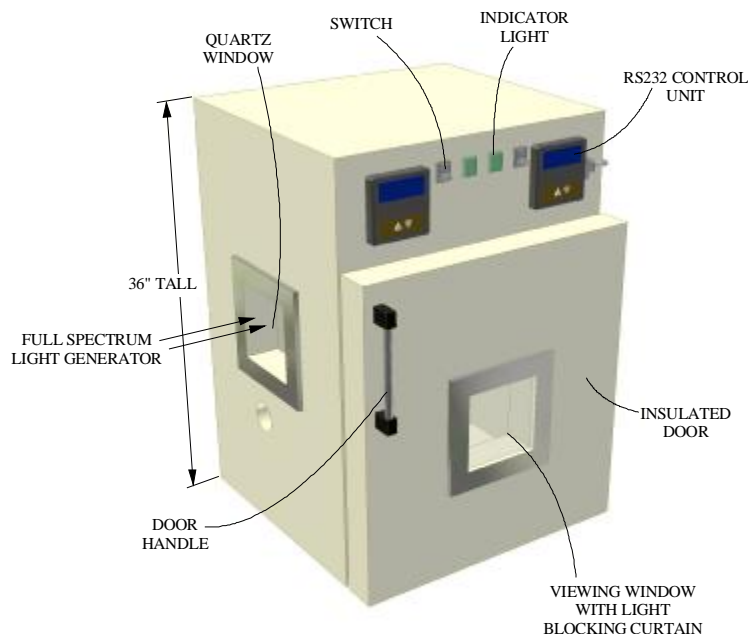


Figure 6. Environmental Control Unit

The Environmental Control Unit temperature and humidity is controlled by a preprogrammed timeline. The timeline file is generated and then is placed in the controlling computer's control

software. The software regulates the temperature by adding liquid nitrogen when cooling and by activating electric heater coils when heating. The humidity needs to be kept low to prevent water vapor from creating ice when cooling is activated. The positive pressure that is maintained inside the ECU's controlled region during the cooling cycle helps prevent moisture from entering the controlled region from the lab. The positive pressure is created when the liquid nitrogen vapor is introduced into the chamber. The humidity levels are monitored by sensors located inside the Environmental Control Unit. When the humidity level has risen to the predetermined set point, a dry carbon dioxide purge cycle is initiated to dry the air.

3.2.2.2 Specimen chamber

The enclosure for the atmosphere and regolith is the "specimen chamber" (see Figure 7). The specimen chamber's main structure is a 0.25" thick quartz cylinder with a 6" outer diameter, and a length of 15". Thus the internal volume is just under 4.0 liters. The two ends of the quartz cylinder are sealed with aluminum end caps. The circular end caps are comprised of a large 6" diameter that will mate against the quartz cylinder and another section with a smaller diameter that will be inserted into the quartz cylinder. Each end cap has an o-ring groove located about the circumference of the smaller diameter. A silicone o-ring will be used to seal each end-cap to the inner diameter of the quartz cylinder. Appropriate spacing exists between the external mating surface of the aluminum end-cap and the internal mating surface of the quartz cylinder to allow for different rates of material expansion and contraction during temperature changes. The cylinder is made from G.E.[®] quartz to allow ultraviolet light to pass through it and reach the Mars simulated regolith and the test organisms. The aluminum end caps have access ports for high pressure tubing attachment to allow for evacuation of the specimen chamber as well as introducing Mar's atmosphere gases. The end caps will be anodized to prevent corrosion from forming on the aluminum.

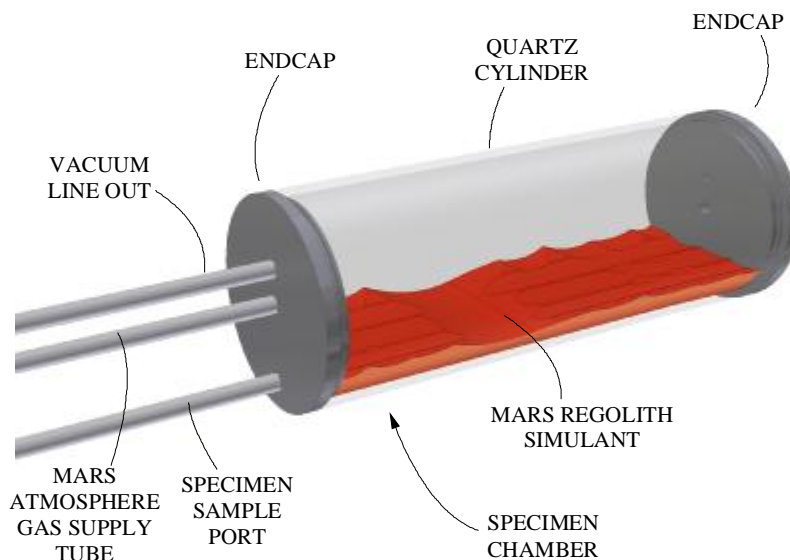


Figure 7. Specimen Chamber

Mechanical Strength: Using manufacturers specification and NASTRAN software, the mechanical strength of the quartz cylinder (Youngs Modulus 720×10^8 Pa (at 0° C) and Poisson's Ratio 0.163 (at 0° C)) and a pressure differential of essentially 14.7 psi applied to the

cylinder wall and its ends, was analyzed. The resulting strain mesh is shown in Figure 8, and the specified stress was found to be readily supported by the quartz cylinder with a safety factor of about 70. The minimum critical pressure was conservatively estimated to be 1,000 psi.

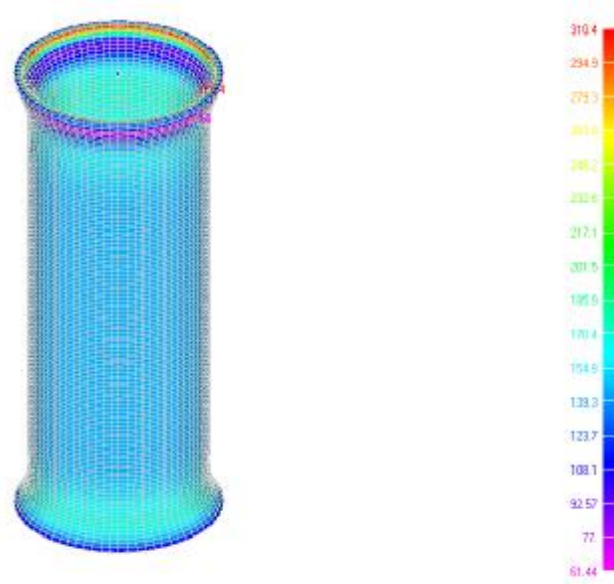


Figure 8. Mesh showing strain generated by 14.7 psi stress on the specimen chamber quartz cylinder.

Regolith Sampling. Removal of the regolith samples from the specimen chamber during a test is achieved by using an array of multiple sample ports at varying positions in the regolith (Figure 9). The regolith sample ports allow an investigator to extract the regolith samples from the conditioned specimen chamber without disrupting the atmospheric pressure or temperature of the specimen chamber volume.

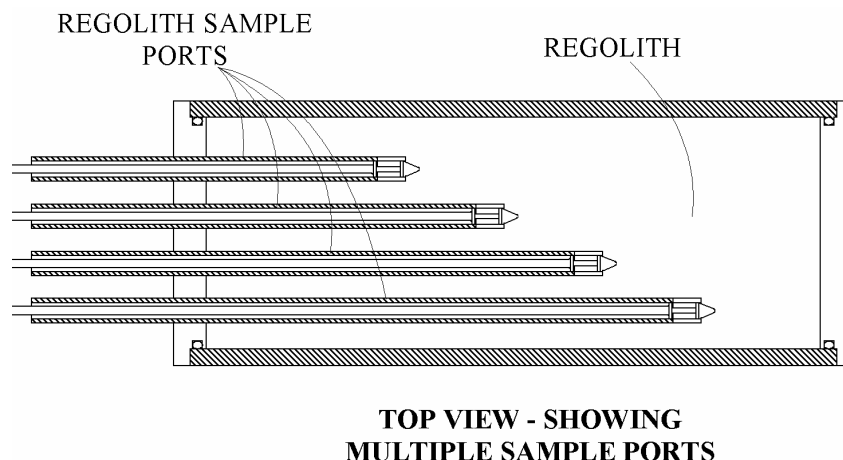


Figure 9. Regolith Sample Ports (Top View)

The regolith sample port consists of a double seal plunger is positioned inside a hollow tube. The regolith sample is pulled from the specimen chamber by inserting the tapered tip of the

plunger into the regolith until only one seal is inside the hollow tube (Figure 10). After the plunger has been inserted into the regolith it is retracted and both seals are contained within the hollow tube. The regolith sample is then translated along the inside of the hollow tube still trapped between the two seals of the plunger. The first seal exits the hollow tube while the second seal remains trapped inside to maintain the seal. The regolith sample is deposited into the sample collection area, ready for further study. These steps are illustrated in Figure 11.

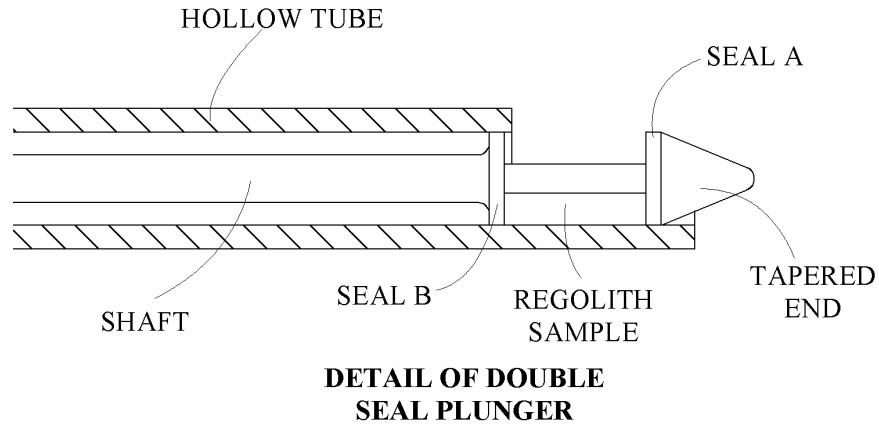


Figure 10. Regolith Sample Port (Detail View)

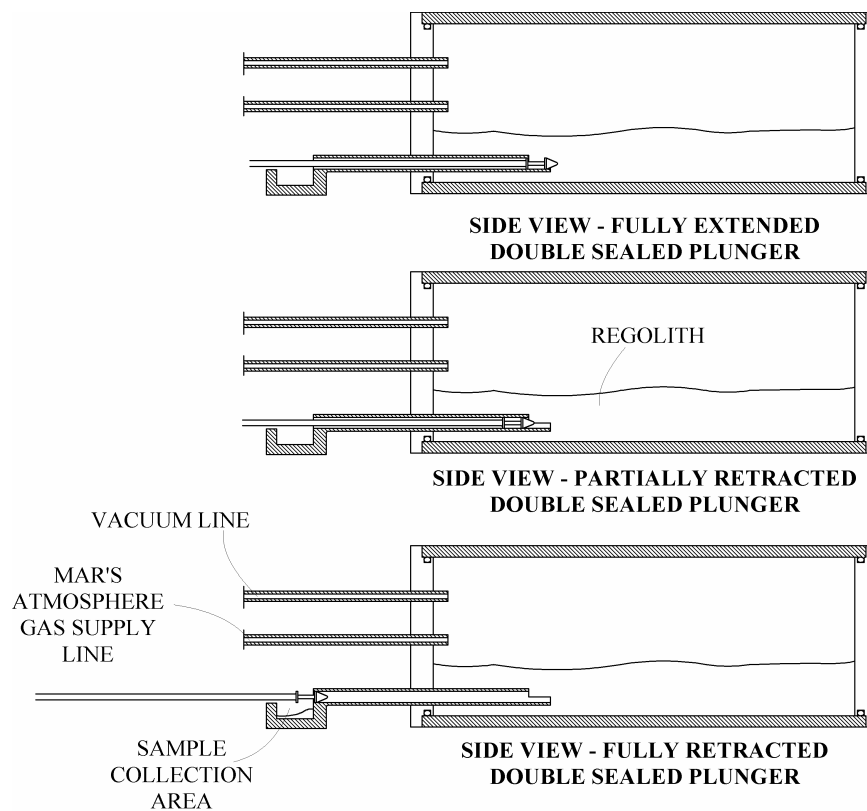


Figure 11. Regolith Sample Port (Process Diagram)

3.2.2.3 Solar Spectrum Generator

Requirements: The radiation spectrum of a xenon lamp is continuous over the ultraviolet, visible, and infrared light ranges. A fused silica bulb radiates a strong spectrum in the ultraviolet light range down to 185 nm. The output radiant intensity is proportional to the lamp current, so output can be regulated to meet intensity requirements, but power-supply stability must be taken into consideration. Radiant intensity varies with ambient temperature, therefore, it is necessary to control current on the basis of measured light intensity. Besides supplying the lamp with stable dc power, the power supply keeps the cathode at the optimal operating temperature with a specified current. The cathode temperature is essential for lamps: when too high, evaporation of the cathode materials is accelerated; when too low, cathode drop is increased, causing cathode sputtering and greatly reducing the lamps life. Since the xenon arc lamp operates at very high pressures and temperatures, and emits ultraviolet radiation, it must be operated in a fully enclosed housing. A safety interlock will be used to prevent access to the lamp when it is on thus preventing operator exposure to the radiation and protects against inadvertent contact with the hot lamp. There will be a thermal interlock that turns the lamp off in the event the temperature within the housing exceeds safe operating levels. In addition, there will be a safety interlock that turns the system power off in the event the cooling fan fails.

The average solar intensity on the surface of Mars is 590 W/m^2 , compared to about 1000 W/m^2 at the Earth's surface. The difference between Mars and Earth is due primarily to the greater distance of Mars from the sun. On Mars, near the equator, the duration of daylight is about 12 hours, followed by approximately 12 hours of darkness. The atmosphere of Mars carries a load of suspended dust, which reduces the intensity of sunlight on the surface compared to the intensity above the atmosphere. The amount of dust in the Martian atmosphere varies with the presence of dust storms. Dust storms can be local, lasting only hours to days, can be regional, or can be global in extent, extending for up to a hundred days in duration. The global dust storms are seasonal, and occur only during the southern hemisphere summer. The solar spectrum at the surface of Mars is modified by the atmospheric dust, making it blue-deficient, and enriched in red and IR compared to the orbital ("Air Mass Zero," or AM0) spectrum. Figure 12 shows a calculation of the spectral transmission of the atmosphere, calculated using a simplified model of dust properties, shown for a zenith angle of 0 (sun directly overhead).

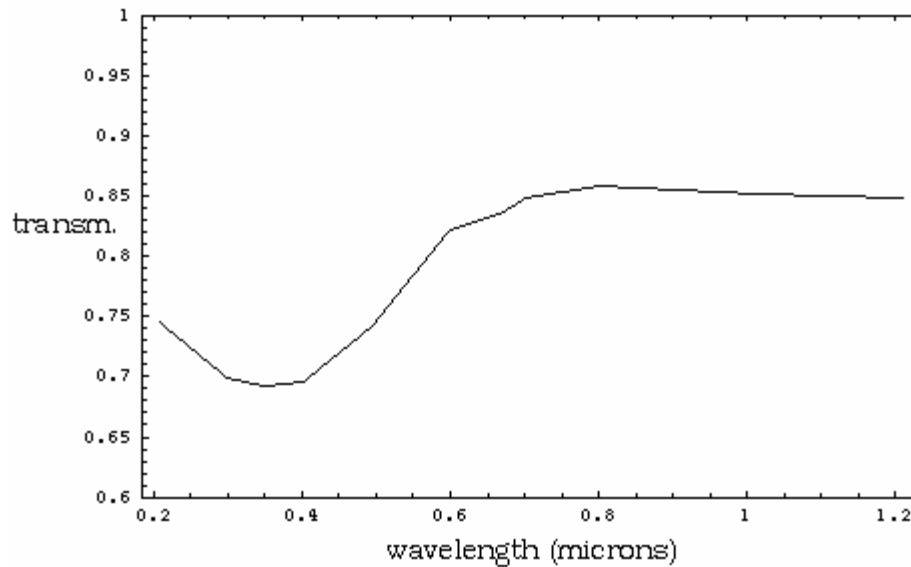


Figure 12. Spectral transmission of the Mars atmosphere from 0.2 to 1.2 microns. Transmission calculated at zenith angle of 0 (sun directly overhead) for $t = 1$.

(<http://powerweb.grc.nasa.gov/pvsee/publications/wcpec2/cells4mars.html>)

The total power at output for the selected solar simulator shown in Figure 4 is 135 W with a 1.5kW arc lamp. With a total surface area of 256 in², the spectral output of the simulator is 817 W/m². This is more than adequate for simulation of the solar intensity on Mars (590 W/m²), but not enough for simulation on the moon (1370 W/m²).

Selection: MARS will utilize a solar spectrum generator that is used to simulate light conditions on Mars. The Sciencetech ® model SS1.5kW high power 1.5 kW solar simulator is a system featuring illumination of an area 8" in diameter with power up to 1 sun. The solar spectrum generator operates on 115VAC.

3.2.2.4 Gas Supply and Control Subsystem

Gas Supply: MARS uses a custom filled gas bottle with a few hundred psi pressure to supply the Mars atmosphere to the specimen chamber. The gas supply system starts with the 70lb compressed gas bottle. The gas mixture is 95.57% CO₂, 2.7% N₂, 0.13% O₂, and 1.6% Ar (the known trace amount of CO is deliberately excluded). A two-stage regulator is located downstream from the supply bottle. It regulates high pressure from the bottle down to 14.5psia on the exit side. A control valve is located downstream from the two-stage regulator. When the control valve is activated, gas from the supply bottle moves through the two-stage regulator and control valve and fills the gas reservoir with gas. The gas reservoir is a 14.5-psia storage bottle. The gas reservoir will supply low pressure gas to the test chamber when the second control valve located between the gas reservoir and the specimen chamber is activated. The gas from the gas reservoir will naturally flow into the 10-15 mbar low-pressure test chamber. This pathway is shown in Figure 13 and schematically in Figure 14.

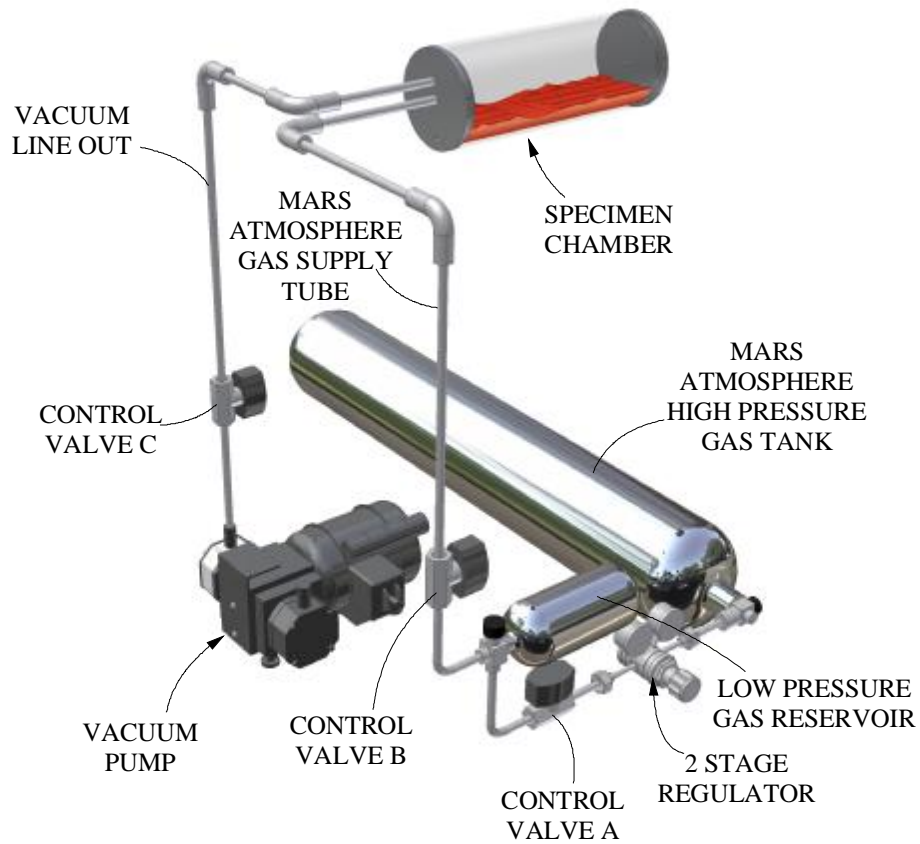


Figure 13. Gas Supply System

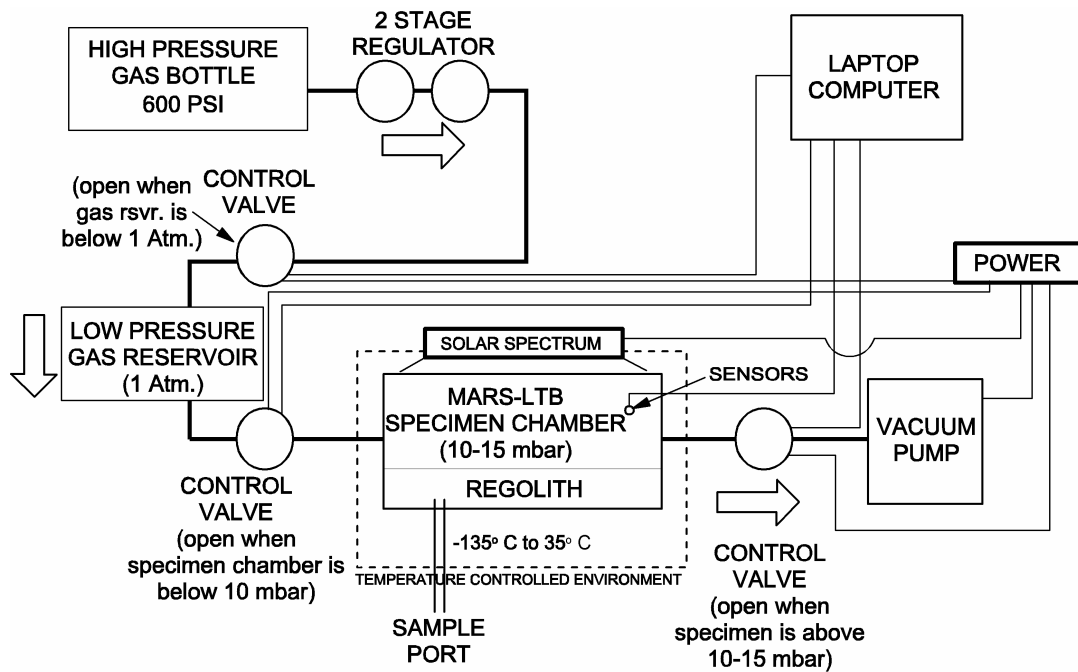


Figure 14. Schematic of gas supply system

Stand: The Environmental Control Unit and laptop computer are located on the top surface of the custom stand (Figure 4). The stand is constructed of high strength steel tubing and plate. The square tube legs of the stand are welded to a top and bottom plate. Reinforcement gussets are welded to the corners of the stand where the legs and the plate meet. The stand is sandblasted for uniformity in texture and for relieving stress after assembly. Corrosion-proof paint covers every exposed surface of the stand. Brackets are used to mount control valves, compressed gas tanks, and other hardware.

3.2.2.5 MARS-LTB Software Architecture

The top-level features of the electronic architecture are summarized in the block diagram shown in Figure 15.

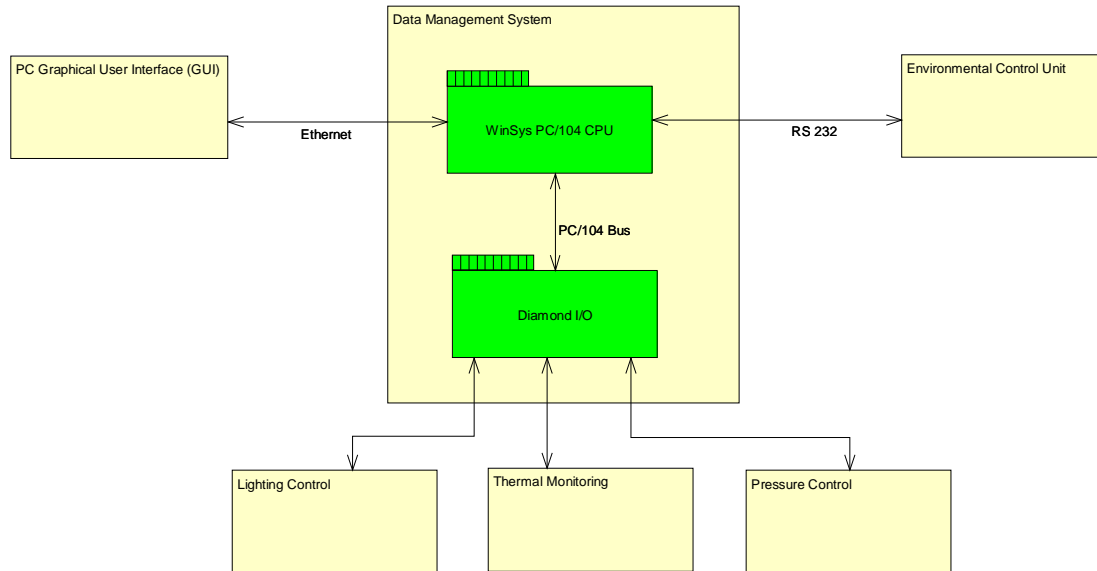


Figure 15. Block diagram of electronics and computer architecture for MARS-LTB.

The MARS-LTB software provides the primary user control and monitoring for the experiment. There are two components that encompass the software.

- The DMS (Data Management System) software accepts commands from the GUI and provides the low-level control of the hardware. The DMS controls processes such as light level sequencing, thermal control, sensor measurements and telemetry generation. The DMS sends telemetry updates and command response information to the GUI via a communications connection.
- The GUI (Graphical User Interface) software is the primary user interface. The operator controls the MARS-LTB via the graphical Windows controls of the GUI. The GUI also displays monitored system data.

These two packages have the following components:

- Data Management System (DMS)
 - PC/104 Central Processing Unit (CPU)
 - PC/104 Analog/Digital I/O Module
 - Interfaces to Environmental Control Unit (ECU) via RS-232 connection with MODBUS protocol

- Interfaces to Graphical User Interface (GUI) on PC via Ethernet
- Thermal Control and Monitoring
- Pressure Control and Monitoring
- Light Control, Monitoring, and Sequencing
- Provides Telemetry to Investigator
- Runs under Linux Operating System
- Object-Oriented Design using C++ Programming Language
- Graphical User Interface (GUI)
 - Allows Investigator to Control MARS-LTB Experiment
 - Displays Experiment Telemetry to Investigator
 - Interfaces to Data Management System (DMS) via Ethernet
 - Runs On PC Under MS-Windows Operating System
 - Written in C++ Programming Language Using Borland C++ Builder

The control of temperature and pressure are programmed using timelines entered by the investigator (to simulate the Martian daily cycle of light and temperature, for example). Pressure will be regulated by a control algorithm. A rise in chamber pressure will be sensed by the chamber pressure sensor, the signal of which is fed to the operating computer, which opens the valve to the vacuum pump. Temperature controls consist of a dynamic PID controller that is programmed to a timeline by the operator typically to follow a diurnal cycle (Figure 5 in Section 3.2.2.1) with a minimum at -135°C and a maximum of $+26^{\circ}\text{C}$.

3.2.2.6 Power and Cost

Power consumption:

Solar Spectrum Generator	1500 watts
Environmental Chamber	2160 watts maximum
Vacuum Pump	150 watts maximum
Laptop Computer	65 watts
DMS	100 watts
Control Valves	30 watts total
Sensors	10 watts

Cost analysis:

A complete cost analysis was performed, and the item-by-item parts list resulted in a total cost of \$55,000 for all of the components of the MARS-LTB.

3.2.2.7 Laboratory Test Bed Operations

The MARS-LTB is to be used by research scientists for conducting extended testing on organisms introduced to the simulated Mars environment. The research equipment can be programmed to operate for short tests (days) or extended test (months).

The setup of the MARS-LTB is divided into three parts:

- Mechanical/electrical preparation of the hardware
- Software parameters and timelines setup on the laptop computer
- Science preparations

Mechanical/Electrical preparation: Before starting a test on the MARS-LTB, several systems must be charged and serviced. The Environmental Control Unit's (ECU) liquid nitrogen tank

must be filled. A compressed gas tank with a siphon tube installed must be connected to the ECU correctly. A minimum of 75lbs of liquid nitrogen is recommended for use in the MARS-LTB. Care must be taken to ensure that the liquid nitrogen tank is positioned correctly and properly secured to the stand. The liquid nitrogen tank's threaded coupling is then connected to a two-stage regulator. The two-stage regulator is already connected with the ECU's high-pressure gas coolant lines. The two-stage regulator lowers the output pressure of the liquid nitrogen tank to the desired pressure of the ECU's coolant system. After the liquid nitrogen tank has been connected the tank valve is opened allowing extremely cold liquid nitrogen to fill the high pressure gas coolant lines. The tubing, regulator, tank, and fittings should be checked for leaks.

Gas supply system setup: The mars atmosphere high pressure gas tank must be filled with the appropriate gas mixture and installed into the gas supply system. The mars atmosphere high pressure gas tank is connected to a two-stage regulator. This regulator feeds the low-pressure reservoir, the valve to which is closed (under computer control) at the time the valve on the cylinder is opened and the second regulator stage is set to a few psi.

Solar spectrum generator: The solar spectrum generator does not require much preparation prior to testing. The 1.5 KW solar spectrum generator must be connected to the 115VAC outlet on a dedicated circuit. The unit's light spectrum may be adjusted by installing the desired light filter. The lamp must be changed at periodic time intervals. Records of bulb use will be maintained.

Software parameters: The software parameters for a desired test protocol must be entered manually into the MARS-LTB GUI of the laptop computer or retrieved from a previous test protocol. All the settings for a desired test must be entered prior to starting operations. These settings included the following:

- Timeline
- Temperature limits
- Temperature cycles
- Light intensities
- Light cycles
- Warning signals for out of parameter values

Science Preparation: Science preparation primarily involves the specimen chamber, regolith, and test organisms. The specimen chamber is the unit that holds the mars atmosphere and simulated regolith. The test organisms are mixed into the regolith in the lab prior to installation into the specimen chamber. After the desired organisms have been mixed into the regolith, the mixture is placed into the open end of the quartz cylinder that is the body of the specimen chamber. After the regolith mixture has been installed into the quartz cylinder, the open end of the cylinder is sealed with the end-cap. The specimen chamber is then placed into the ECU on the support brackets. The specimen chamber is then connected to the vacuum line and the Mars atmosphere gas supply line. A typical science cycle is sketched in the Gantt chart shown in Figure 16.

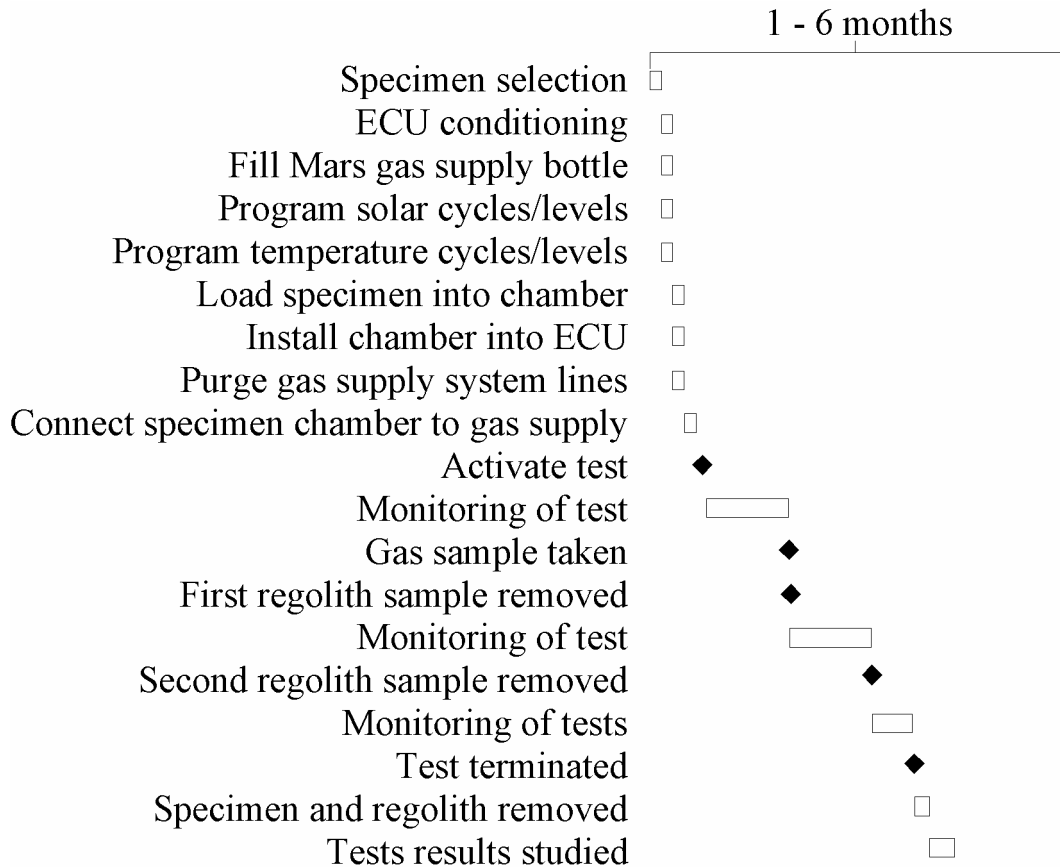


Figure 16. Example of test schedule of events

3.2.3 Modular Test Bed (MARS-MTB) Design

The MARS modular test bed is a compact version of the MARS laboratory test bed. It is designed for use in laboratories and/or classrooms. The MARS modular test bed is where the science takes place. A recharging station is required for refurbishment and collection of gases and control of atmosphere pressure. The regolith will be spread across a 2.7" diameter circular surface area of 5.7 square inches. The gas volume of the specimen chamber is approximately 5.1 cubic inches (about 84 cm³). An overall view of the MAES-LTB is given in Figure 17.

The MARS modular test bed will allow users to conduct single experiments or multiple experiments simultaneously. Experimenters may choose to conduct tests that compare different atmospheres and regoliths and how test organisms adapt to each. Other tests may vary temperatures among several MARS-MTBs or adjust the composition of the atmosphere. Conditions on earth, the moon, or other planets may be simulated as well.

A typical experiment would involve obtaining the MARS-MTB(s) and a recharging station. A personal computer (PC) based tutorial will instruct the user on how to operate the system. The recharge station stores data on each experiment and allows the user to plan the experiment using the onboard software, store data reported during an experiment, and finally to download data to be imported into various PC-based computer software for final study and reporting.



Figure 17. Three-dimensional overview rendering of the MARS-MTB. The diameter of the regolith component (red) is 2.7" (6.9 cm). Volume under the dome is 84 cm³.

3.2.3.1 MARS-MTB Modular Stand-alone Unit

The MARS-MTB is a compact, comprehensive, stand alone assembly. The housing is a one-piece cylindrical shaped, aluminum body. Most of the subsystem components are located inside the housing. Inside the dome-shaped quartz hemisphere that is located on top of the housing is the simulated regolith and experimental organisms. A hinged lid attached to the top of the housing covers the quartz dome. The hinged lid houses the xenon lamp that is the MARS-MTB solar spectrum generator. A solids rendering is shown in Figure 18. Each potential component of the MAES-MTB has been researched as discussed in the following paragraphs.

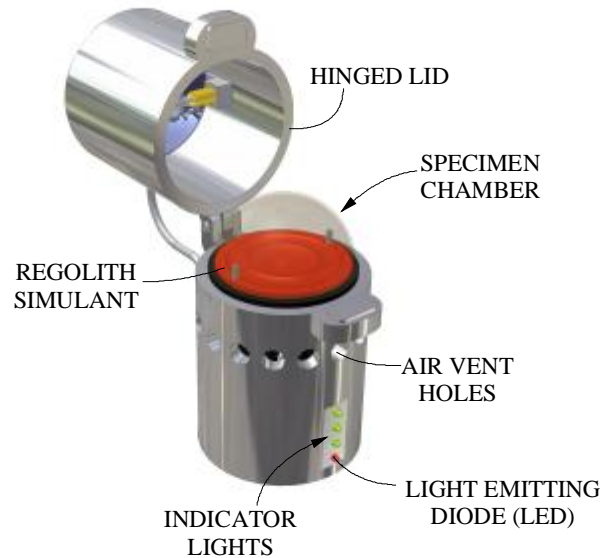


Figure 18. MARS-MTB (Stand Alone Unit)

Quartz / Zeon Plastic Dome – Specimen chamber: The specimen chamber that is formed by a flat aluminum bottom plate and an upper quartz or Zeon plastic hemisphere houses the specimen, atmosphere, and simulated regolith. It is in this chamber that the living organisms are introduced and all the environmental conditions are controlled. The quartz or Zeon plastic dome allows the full spectrum of light from the light array to pass through into the controlled environment. While both Quartz and Zeon plastic have excellent light passing characteristics, Zeon plastic may be chosen over the quartz for its thermal insulation properties.

An alternative to using quartz material for the dome in the specimen chamber is to use Zeonex[®] (polycycloolefin resin) instead. This plastic is manufactured by Zeon Chemicals. Similar to Quartz, Zeonex[®] provides excellent transparency and extremely high light transmittance. The following graph (Figure 19) demonstrates the light transmission capabilities of this material compared to other resins.

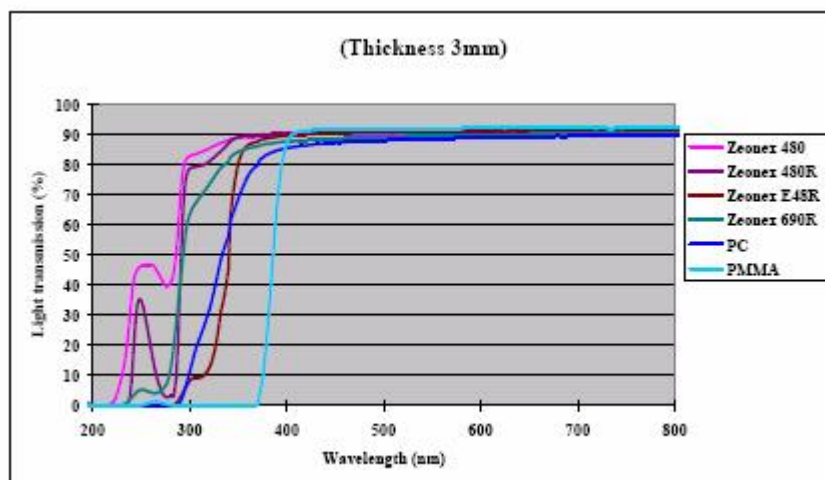


Figure 19. Light transmission of Zeonex[®] grades of polycycloolefin compared with polycarbonate and PMMA (Plexiglas).

Another plastic that could be investigated for use is Topas[®], a cyclic olefin copolymer (COC). There are grades of this material that can also offer outstanding light transmission in the UV-range. Areas of concern for using plastic instead of quartz are the thickness and costs of injection molding this material into a dome.

Hinged Lid – Light array: Directly above the specimen chamber is a hinged aluminum cylindrical lid. The hinged lid has a heavy duty hinge and a magnetic latch that is a safety interlock. The hinged lid remains closed and locked during normal operations. The lid may be opened for specimen viewing during the day cycle of Mars once all environmental condition set-points have been met. An LED on the housing of the MARS-MTB indicates that the day cycle on Mars is in process and tells the user that it is safe to open the lid. The high-intensity Xenon arc light and its special housing is installed at the top of the inside of the hinged lid. Prices range from \$600-\$1000 per lamp. The radiation spectrum of a xenon lamp is continuous over the ultraviolet, visible, and infrared light ranges. The fused silica bulb radiates a strong spectrum in the ultraviolet light range down to 185 nm. The output radiant intensity is approximately proportional to the current flowing to the lamp so a stabilized power supply for the lamp is included. The xenon lamp surface temperature will be maintained at less than 750 °C and the metal base surface temperature (anode side) at less than 200 °C. Forced air cooling with a fan in the lid will maintain temperature. Care will be taken so that the fan does not stop during operation or for several minutes after switching the lamp off. High quality insulation materials will be used to avoid leakage of trigger high voltage when the lamp is switched on. Since the xenon arc lamp operates at very high pressures and temperatures and emits ultraviolet radiation, it must operate with a fully enclosed housing installed in the lid. A safety interlock will be used to prevent access to the lamp when it is on or cooling off thus preventing operator exposure to the radiation and to protect against inadvertent contact with the hot lamp. There will be a thermal interlock that turns the lamp off in the event the temperature within the housing exceeds safe operating levels. In addition, there will be a safety interlock that turns the system power off in the event of cooling-fan failure. If these safety interlocks fail when the hinged lid is opened the lamp automatically shuts off. This safety interlock latch prevents the users from damaging their eyes by exposure to the UV light. During the simulated day cycle of Mars, the

temperatures are close to ambient temperatures in the lab. Allowing the hinged lid to open during the time that the temperature difference between the lab and the controlled experiment volume is small prevents condensation or frost from forming on the quartz dome.

Thermal System: A combination of staged Thermal Electric Devices (TEDs), a heat sink fin, control electronics and high performance insulation provide the specimen chamber with the desired thermal control. TEDs are positioned below the aluminum base plate of the experiment volume for removing heat from the chamber. Thermoelectric devices, utilizing the Peltier effect with dissimilar metallic conductors, have been demonstrated to be an effective means of producing low capacity refrigeration and heating. Thermoelectric devices act essentially as heat pumps. These solid state heat pumps have no moving parts, fluids or gases, which makes them ideal for small compact laboratory equipment. Temperatures within the specimen chamber range from -135°C during simulated Mars night to 26°C during the simulated day cycle of Mars. During the daytime hours while the light array is operating, the TEDs will be operating to remove the heat introduced by the light array. During night cycle when the temperatures reach -135°C , the TEDs will remove heat from the controlled volume to reach the desired extremely cold temperature. The hinged aluminum lid is insulated with high performance insulation to minimize heat loss through the structure. The lid will remain closed during low temperatures to prevent heat loss and for preventing human exposure to extremely cold surfaces. The TEDs are sandwiched between the base of the controlled volume and a heat sink. The heat sink's material is manufactured from highly thermally conductive aluminum. Two pancake style fans move cool lab air from the bottom of the housing across the heat sink and out the vent holes in the side of housing removing heat conducted from the TEDs to the heat sink fin. The air volume that would be surrounding the TEDs is filled with high performance, moisture proof insulation to minimize heat transfer in that area. The moisture proof quality of the insulation prevents water from getting to the TEDs and prevents corrosion from forming. Thermal analysis indicates that the lowest achievable temperature in this configuration will fall short of the desired -135°C and may only reach -80°C or so. This is still considered an acceptable low temperature for laboratory experiments. A fully labeled rendering of the Stand-Alone unit ("Mars jars") is shown in Figure 20.

The passive heat load to be borne by the TEDs is estimated at 3.0 - 5.0 W, including heat transfer from $+25^{\circ}\text{C}$ environment to -135°C inside the MARS-MTB dome. According to one manufacturer a 5-stage TED could reach -72°C from an ambient temperature of 27°C while pumping 2.3Watts. If the ambient temperature is reduced to 5°C (standard refrigerator), then the cold side could reach -80°C . This would require a TED input power around 10Amps and 12volts. Twice this power is proposed in the list below, later in this section. At the equatorial and southern temperate zones of Mars the minimum temperature is -88°C (figure 5). These calculations therefore indicate that the thermoelectric approach to a portable MARS-MTB is worthy of consideration. Alternative approaches include the utilization of insulated solid CO_2 at -78.5°C , but the requirement to manually and frequently supply fresh solid CO_2 could be a deterrent to reliable Test-Bed function.

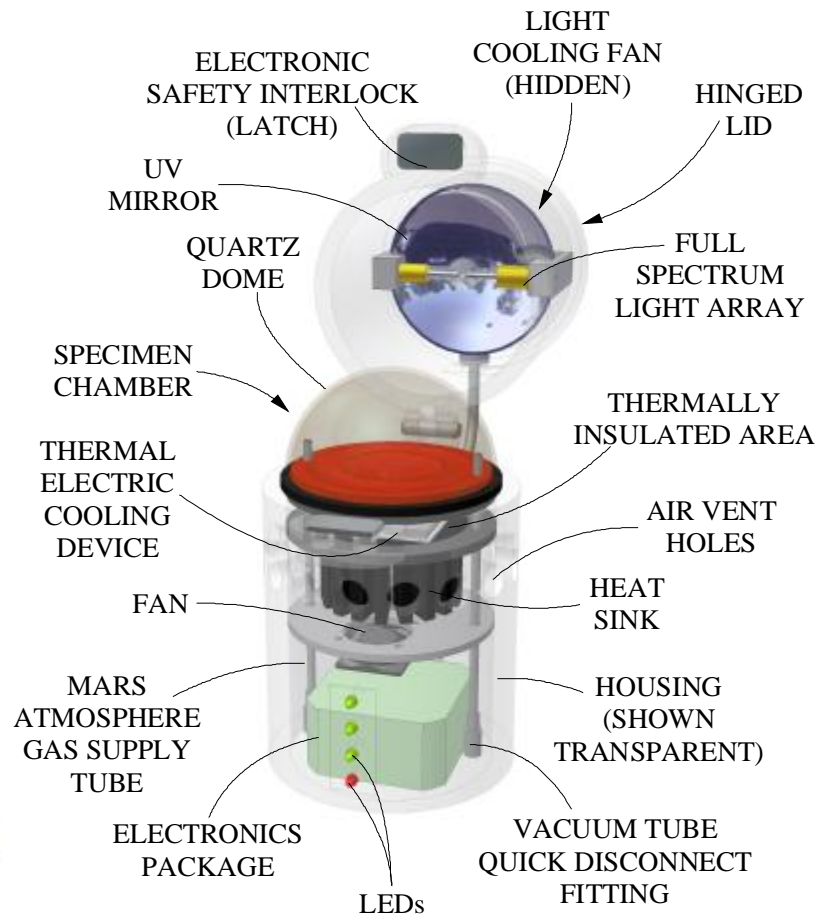


Figure 20 MARS-MTB Subsystems incorporated into “Stand-Alone” portable unit (“Mars jars”)

Electronic Package: The electronics package is located beneath the heat sink fans at the bottom of the MARS modular test bed housing. The electronics unit (a schematic of which is shown in Figure 21) is powered by 115VAC. Maximum power consumption is 373 watts. Power converters, filters and programmable chips are packaged to supply the proper voltage and current to various electronic components of the MARS modular test bed. The following list is an initial rough estimate of the power requirements of the stand-alone unit.

Xenon Light	75 watts
TEDs/Cooling Unit	250 watts
Data Management System (DMS)	8 watts
Light Cooling Fan	5 watts
Heat Sink Fans	15 watts
Power Supply Unit	20 watts
Total:	373 watts

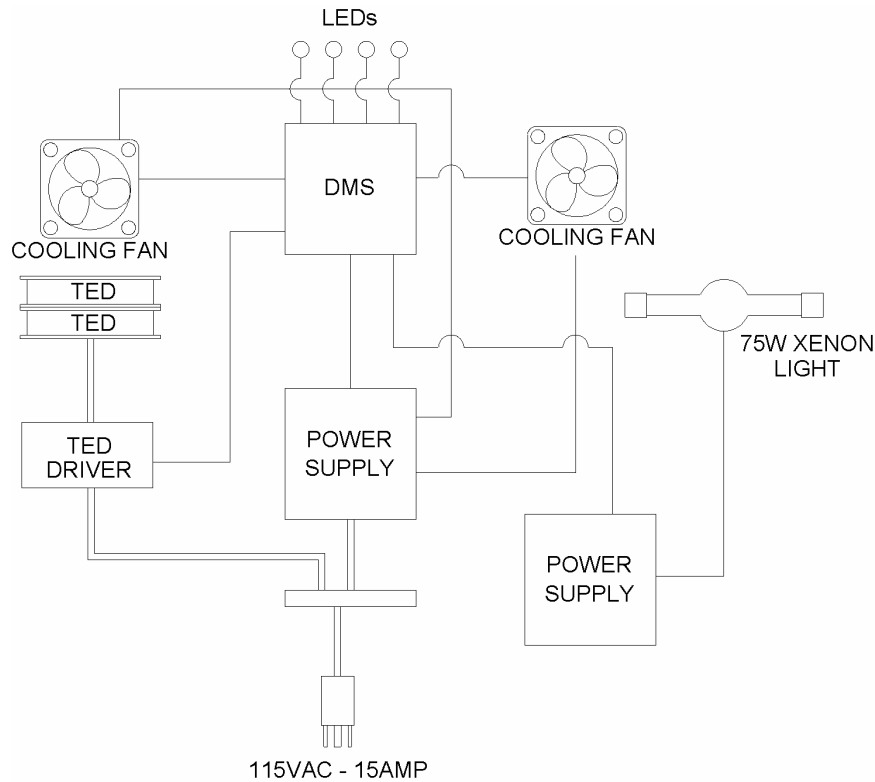


Figure 21. MARS-MTB Electronics diagram

Gas system: Pressure as well as atmospheric gas content is regulated within the controlled volume of the MARS-MTB. Pressure is maintained at levels of 10-15mbar. The quartz dome above the housing is sealed to the base. The base has two portals that allow high pressure stainless steel tubing to penetrate the base and terminate in the control volume. Each tube has a quick-disconnect fitting at one end near the bottom of the MARS-MTB. The tubes connect by seating the unit on the recharge station. Atmosphere is evacuated from the controlled volume after installation on the recharging station. A vacuum pump located in the base of the recharging station is activated until the sensors indicate that the desired vacuum has been obtained in the dome.

The simulated gaseous mixture of Mars is created by activating the control valve connected to the gas supply bottle in the recharge station. The gas mixture is added to the control volume while the vacuum system maintains the desired pressure. The gas mixture is 95.57% CO₂, 2.7% N₂, 0.13% O₂, and 1.6% Ar.

3.2.3.2 MARS-MTB Recharging station

The recharging station for the MARS-MTB is a bench top unit (Figure 22). It has a high fidelity graphical user interface. Silicone rubber buttons are used to toggle between status and control screens. Inside the recharging station's protective base resides a connection to the gas supply bottle that contains the Mars atmosphere in a compressed state. The gas supply bottle is connected to the quick disconnect fitting by high pressure tubing. A two stage reservoir placed in line between the tank and the quick disconnect fitting regulates the input and output pressure.

The base of the recharging station houses a small vacuum pump capable of evacuating the MARS-MTB specimen chamber to 10mbar.

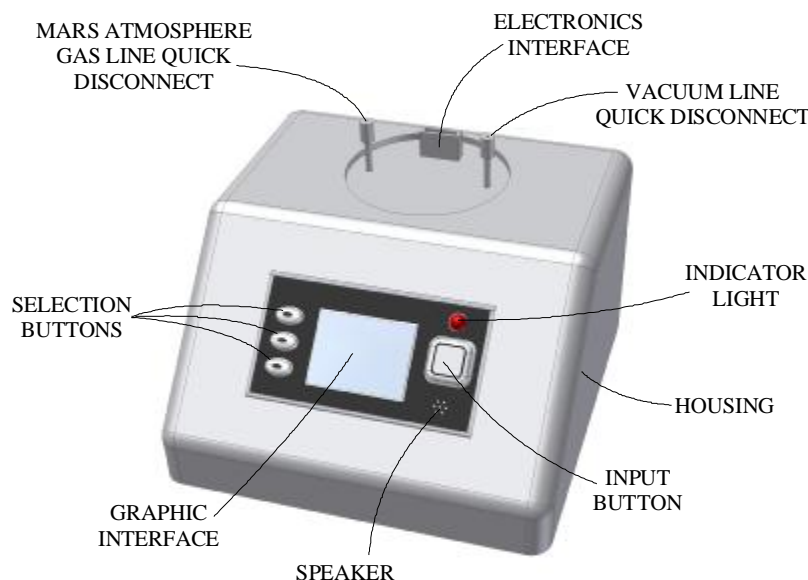


Figure 22. MARS-MTB Recharge station

Data Management and Monitoring Module (DMMM): The control of the Recharge Station is maintained using the DMMM. The DMMM consists of several main parts: information processing circuitry (embedded 16-bit processor), input and selection buttons, graphical interface, speaker and housing. Information processing circuitry is the brains of the recharge station. The electronics circuitry processes inputs from the user as well as monitors and controls system performance. The input and selection buttons are used for moving to different sections of the graphical interface screen. The buttons are also used to toggle between different screens as well as entering data. The input and selection buttons are actually all of one larger single molded silicone button pad. The molded silicone button pad has built in carbon pills behind each “button”. When a button is depressed the carbon pill shorts out exposed traces on the circuit board directly behind the button pad causing an operation to be performed. The GUI used in the recharge station is a high quality organic LED (OLED) display. The OLED is used to display information about the status of the MARS-MTB. The OLED display also displays status information on the recharge station’s systems. The fine resolution and brightness of the OLED display allows the screen to be used for displaying high resolution graphics as well as textual information. A speaker is located on the front face of the recharge station to allow for audible messages and alarms to be presented to the user.

Gas Analyzer: The recharging station also contains a gas analyzer unit. The gas analyzer tees off of the vacuum line. The gas analyzer will evaluate levels of carbon dioxide, methane, ammonia and oxygen in the simulated atmosphere. Gas content is sampled by accessing the gas sampling GUI page. The gas sampling GUI page will allow gas level values to be stored in the recharging station’s onboard memory. A simple screen on the GUI allows the user to study real time information, or averages of values across a set time period. Gas sampling can be initiated in real

time or can be programmed via a timeline to record gas level values on preset intervals or activated manually as each stand-alone unit gets is gas analyzed.

3.2.3.3 Safety

Several areas of the MARS-LTB are potentially hazardous. General safety precautions need to be followed during use of the MARS-LTB. SHOT personnel will use SHOT document 900SP497, Industrial Health and Safety Plan, for general safety guidelines. Hazards specific to the MARS-LTB and MARS-MTB are described in this section.

Environmental Control Unit: The safety precautions are listed associated with the hazard.

Pressurized Liquid Nitrogen Tank and line

- ◆ Extremely cold temperatures
 - ◆ Personal Protective Equipment (PPE) will be worn
- ◆ Depletion of Oxygen in breathable air
 - ◆ Low oxygen alarm will be located in the laboratory
- ◆ Pressurized tank – potential projectile
 - ◆ Tank will be secured to stand
- ◆ Electrical Shock
 - ◆ Equipment will be properly grounded
 - ◆ Shock hazards will be guarded and labeled

Solar Spectrum Generator

- ◆ High Intensity full spectrum light
 - ◆ UV blocking goggles will be worn
- ◆ Hot Surfaces
 - ◆ Hot surfaces will be guarded and labeled
- ◆ Electrical Shock
 - ◆ Shock hazards will be guarded and labeled

Gas Supply System

- ◆ Pressurized Mars simulated gas tank – potential projectile
 - ◆ Tank will be secured to stand
- ◆ Depletion of Oxygen in breathable air
 - ◆ Low oxygen alarm will be located in the laboratory
- ◆ Vacuum Pump - hot surfaces
 - ◆ Hot surfaces will be guarded and labeled

Quartz Specimen Chamber Cylinder

- ◆ Evacuated chamber – risk of implosion, glass cuts
 - ◆ Quartz cylinder structure analysis completed for proper thickness of cylinder wall.
 - ◆ Cylinder is contained within the ECU

Test organisms

- ◆ Contamination of lab, spreading of organisms
 - ◆ Organisms will be loaded using sterile transfer hood
 - ◆ Proper PPE will be worn

3.3 Objective 3. Identify partial-gravity venues and environments

The main features of this objective are pointed out in Section 3.5.1 below as these were presented in a poster at the NIAC Annual Meeting. Three principal accomplishments are described in this section: (1) Since the final goal of the proposed architecture is a lunar test bed, lunar data were gathered in detail with this goal in mind; (2) concepts for modifying NASA's Avian Development Facility (ADF) built by SHOT have been taken under study; and (3) deliberations concerning test-bed venues by participants in the Workshop are summarized.

3.3.1 The Moon as Test-Bed Venue

3.3.1.1 Regolith Composition

The composition of the moon is a basaltic ash, but contains 7 major elements (O, Si, Fe, Mg, Ti, Al, and Ca) and 12 minor elements (including P). Also, traces of CO, CO₂, ammonia, and methane can be found. The mineralogy on the moon is simple; highland rocks are rich in plagioclase, Ca(Na)Al₂Si₂O₈, and pyroxene, (Mg, Fe, Ca)SiO₃, shown in Figure 23. The moon also contains the minerals Olivine, (Mg, Fe)₂SiO₄, Ilmenite, FeTiO₃, Whitlockite, Ca(PO₄)₂, and Apatite, Ca₅(PO₄)₃(OH, F, Cl).

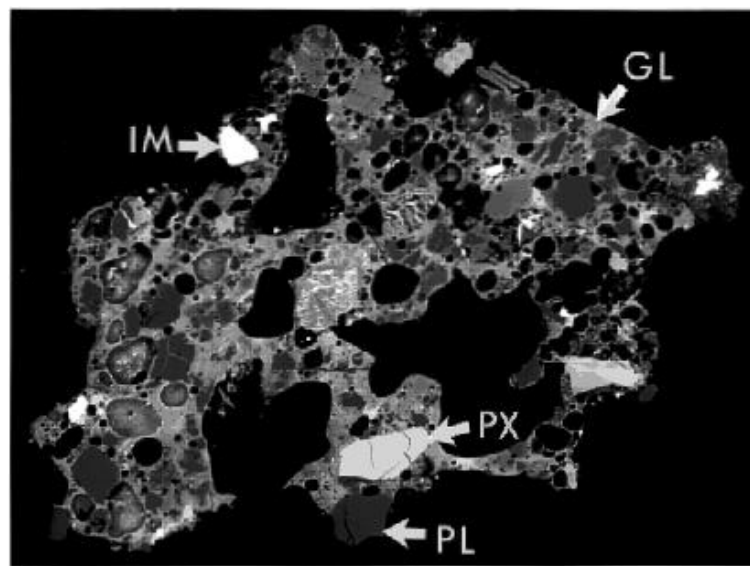
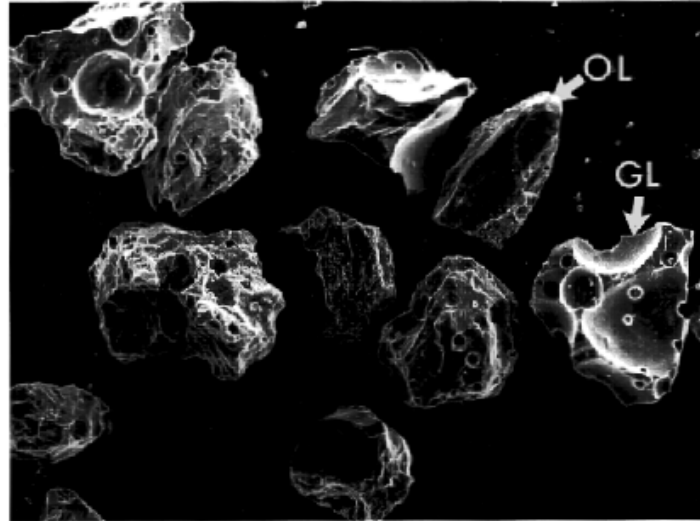


Figure 23. Lunar mare soil grain (78221,8) in polished section. Phases include glass (GL), plagioclase (PL), pyroxene (PX), and ilmenite (IM). SEM back-scattered electron image. Frame width = 660 μ m.

Most of the surface is covered with regolith, a mixture of fine dust and rocky debris produced by meteor impacts (Figure 21). The composition and texture of the lunar regolith varies from place to place depending on the rock types impacted. Generally, the older the surface, the thicker the regolith. The thickness of the regolith varies from about 5 m on mare surfaces to about 10 m on highland surfaces. The bulk of the regolith is a fine gray soil with a bulk density of about 1.5 g/cm³, but the regolith also includes breccia and rock fragments from the local bedrock. About half the weight of the lunar soil is less than 60 to 80 microns in size. Because the regolith is so fine and rocky it is very weak and not very suitable for digging.

3.3.1.2 Lunar Simulants

JSC-1, shown in Figure 24, is derived from volcanic ash of basaltic composition, which has been ground, sized, and placed into storage. The simulant's chemical composition, mineralogy, particle size distribution, specific gravity, angle of internal friction, and cohesion have been characterized and fall within the ranges of lunar mare soil samples.



*Figure 24. JSC-1 glass (GL) and olivine (OL) grains.
SEM secondary electron image. Frame width = 1100 μm .*

3.3.1.3 Chemical Composition of Lunar Samples

The results of x-ray fluorescence (XRF) analysis for element composition is presented in Table 2. The loss on ignition (LOI) value was derived by heating samples in argon for one hour at 900°C. This value reflects the loss of volatiles, including water as well as sulfur and chlorine compounds. The trace element concentrations in JSC-1 are listed in Table 3. Lunar basalts, and the mare soils derived from them, are generally similar to JSC-1 in major element composition. Lunar samples, however, contain no water and have low abundances of volatile oxides such as Na_2O . In addition, lunar rocks were formed in highly reducing environments and contain iron only as Fe^{2+} and Fe^0 (McKay et al, 1994).

Table 2: Major Element Compositions

	JSC-1 (mean of 3)				Lunar Soil 14163*	
Oxide	Conc.		Std. Dev.		Conc.	
		Wt %		Wt %		Wt %
SiO ₂		47.71		0.10		47.3
TiO ₂		1.59		0.01		1.6
Al ₂ O ₃	15.02		0.04		17.8	
Fe ₂ O ₃		3.44		0.03		0.0
FeO		7.35		0.05		10.5
MgO		9.01		0.09		9.6
CaO		10.42		0.03		11.4
Na ₂ O	2.70		0.03		0.7	
K ₂ O		0.82		0.02		0.6
MnO		0.18		0.00		0.1
Cr ₂ O ₃		0.04		0.00		0.2
P ₂ O ₅		0.66		0.01		---
LOI		0.71		0.05		---
Total		99.65				99.8
LOI = Loss on ignition * Papike et al (1982)						

Table 3. Trace Element Concentrations in JSC-1

Element	Conc. (ppm)	Std. Dev. (ppm)	Element	Conc. (ppm)	Std. Dev. (ppm)
Sc	29.2	0.5	Yb	1.99	0.04
Co	47.7	1.6	Zr	125	3
Ni	137	18	Hf	3.55	0.08
Rb	12.3	1.5	Ta	1.96	0.04
Cs	0.339	0.012	U	1.51	0.08
Sr	860	36	Th	5.65	0.07
Ba	822	13	As	18.7	8.9
La	48.2	0.9	Se	< 0.5	0.0
Ce	94.6	1.7	Sb	0.564	0.569
Nd	42	2	W	36.1	2.6
Sm	7.44	0.13	Au (ppb)	40.7	29.4
Eu	2.18	0.04	Br	0.85	0.07
Tb	0.825	0.012	Lu	0.293	0.007

3.3.1.4 Mineralogy of Lunar Samples

The major mineral species in JSC-1 samples were identified by x-ray diffraction (XRD), optical microscopy, and scanning electron microscopy (SEM). The major crystalline phases are plagioclase, pyroxene and olivine. Minor minerals include the oxides ilmenite and chromite, plus traces of clay. The glass and minerals in a typical grain are shown in Figure 25.

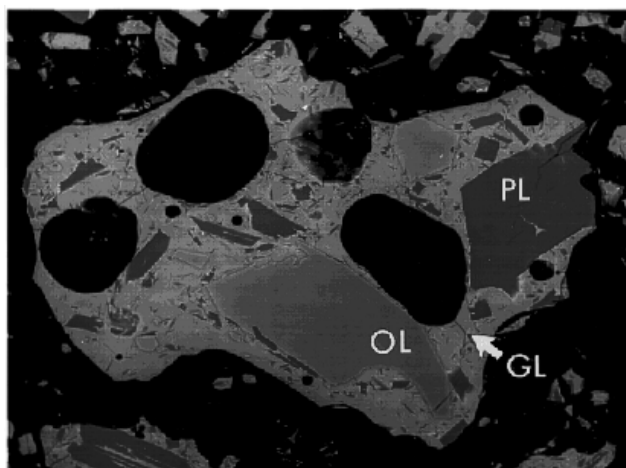


Figure 25. JSC-1 grains in polished section. Phases include glass (GL), plagioclase (PL) and olivine (OL). SEM back-scattered electron image. Frame width = 520 μ m.

The plagioclase crystals are needle-shaped or blocky, as large as several hundred micrometers. Pyroxene and olivine crystals are blocky to subrounded, and up to 100 μm across. Ilmenite and chromite occur as swarms of rounded crystals, each less than 10 μm in diameter. Approximately half of the volume of a typical particle is glass of basaltic composition. Much of this glass contains plagioclase needles and oxide minerals a few micrometers in size.

The minerals found in JSC-1, plagioclase, pyroxene, olivine, ilmenite, and chromite, are also characteristic of many lunar basalts and mare soils. The compositional ranges of these lunar minerals generally overlap the ranges of their terrestrial counterparts. The volcanic glass component of JSC-1 contains more micrometer-scale plagioclase and metal oxide crystals than lunar impact glass, but the JSC-1 glass contains no iron metal.

3.3.1.5 Lunar Regolith Particle Characteristics

Scanning electron micrographs show broken glass and mineral fragments as large as several hundred micrometers (Figure 24). Glassy particles invariably display broken vesicles with sharp edges. Mineral fragments are angular to sub-rounded, and many show the scars of impacts from the milling process.

Lunar soil is a complex mixture of rock and mineral grains shattered by impact, along with impact-derived glass. This agglutinitic glass bonds the rock and mineral fragments into submillimeter particles which are characteristic of most lunar soils (Figure 23). Such particles constitute over half of the volume of many soil samples. The micrometer-scale textures of lunar agglutinates are extremely complex, and are not precisely matched by any terrestrial analog.

JSC-1 is similar in particle size distribution to a typical submature lunar soil, such as Apollo 15 soil 15530 with a median particle size of 102 μm . Mean and median particle size ranges from Apollo soil samples are compared in Table 4 (McKay et al, 1994).

Table 4. Mean and Median Particle Sizes

Sample	Size Range (μm)
JSC-1 (median - UTD)	98
JSC-1 (median - NASA)	117
JSC-1 (mean - UTD)	81
JSC-1 (mean - NASA)	105
Apollo 11 (median)*	48 - 105
Apollo 12 (median)*	42 - 94
Apollo 14 (median)*	75 - 802
Apollo 15 (median)*	51 - 108
Apollo 16 (mean)*	101 - 268
Apollo 17 (mean)*	42 - 166
*(McKay et al, 1991; Table 7.8)	

JSC-1 grains are better sorted, i.e., have a narrower particle size distribution, than most lunar soils. However, several samples, such as Apollo 14 soil 14230 and Apollo 17 core 74002, have comparably high degrees of sorting.

3.3.1.6 Soil Physics

Specific Gravity: The average specific gravity of JSC-1 particles is 2.9 g/cm^3 (Carrier et al, 1991). This value is the ratio of particle mass to the mass of an equal volume of water measured at 4°C . The specific gravity values for lunar soil samples range from $2.9 - 3.5 \text{ g/cm}^3$.

Angle of Internal Friction and Cohesion: The angle of internal friction for JSC-1 is approximately 45° and the cohesion of the material is approximately 1.0 kPa . The angle of internal friction for lunar soil samples ranges from $25^\circ - 50^\circ$ (Carrier et al, 1991). The cohesion values for these samples ranges from $0.26 - 1.8 \text{ kPa}$ (Carrier et al, 1991).

3.3.1.7 Mars Regolith Simulants

Mars soil stimulant (JSC Mars-1) is collected from easily weathered basaltic material on the Hawaiian volcano Mauna Kea, shown in Figure 26 (right). This environment is very similar to the Martian volcanos. It has a reddish-brown color, mineralogy, chemical composition, particle size, density, and magnetic properties similar to the oxidized soil of Mars. Another Mars soil simulant that was used for the CEMSS Mars Millennium Project is Santiam Mars-2 Soil Sim, shown below in Figure 26 (left). In this project “locally grown” volcanic cinders were obtained from the Oregon Department of Transportation cinder cone at the Santiam Junction. Quantities of Santiam Mars-2 Soil Sim were sifted through a system to remove as many smaller fines as possible, shown below in Figure 26 (center) (Mars Society).



Figure26. Mars soil simulants.

3.3.1.8 Temperature

There is no permanent "dark side" of the Moon; all parts of the Moon get sunlight half the time, except for a few deep craters near the poles. The lunar surface temperature varies widely depending upon location. At a depth of 1 meter, the temperature of the regolith is a nearly constant -35°C , but the surface is greatly influenced by the day-night cycle, which is 28 Earth days in length. The mean surface temperature on the moon is about $40-45^\circ\text{C}$ lower than it

is below the surface. During the day the Moon averages 107°C, but can rise as high as 123°C. At night the mean surface temperature is -153°C or -233°C in the permanently shaded south polar basin. A typical non-polar minimum temperature is -181°C. The lunar temperature increases about 280°C from just before dawn to lunar noon. (Heiken et al., 1991.)

3.3.1.9 Water

Evidence from NASA's Lunar Prospector shows that water ice exists at both the north and south poles of the moon. This evidence is indicated by data from the spacecraft's neutron spectrometer instrument. Graphs of the data ratios from the neutron spectrometer reveal 3.4% dips in the relevant curves over the northern polar region and 2.2% dips over the southern polar region. While the evidence of water ice is quite strong, the water 'signal' itself is relatively weak. The water ice is confined to the polar regions and exists at only a 0.3 to 1 percent mixing ratio in combination with the Moon's rocky regolith.

Assuming a water ice depth of about a foot and half (the depth to which the neutron spectrometer's signal can penetrate) it was estimated that the data are equivalent to an overall range of 11 million to 330 million tons of lunar water ice. This quantity is dispersed over 3,600 to 18,000 square miles of water ice-bearing deposits across the northern pole. An additional 1,800 to 7,200 square miles across the southern polar region. Twice as much of the water ice mixture was detected at the Moon's north pole as at the south pole. It was estimated that the most water ice that could conceivably be present on the Moon as a result of meteoritic and cometary impacts and other processes is 11 billion to 110 billion tons. The amount of lunar regolith that could have been "gardened" by all the impacts in the past 2 billion years extends to a depth of about 6.5 feet. On that basis, Lunar Prospector's estimate of water ice would have to be increased by a factor of up to four, to the range of 44 million to 1.3 billion tons.

Currently, it costs approximately \$10,000 to put one pound of material into orbit. NASA is in the process of reducing that figure by a factor of 10, to only \$1,000 per pound. Using an estimate of 33 million tons from the lower range detected by Lunar Prospector, it would cost \$60 trillion to transport this volume of water to space, with unknown additional cost of transport to the Moon's surface. On the human side, a typical person consumes approximately 100 gallons of water per day for drinking, food preparation, bathing and washing. At that rate, the same estimate of 33 million tons of water could support a community of 1,000 two-person households for well over a century on the lunar surface, without recycling.

3.3.1.10 Lessons Learned

Using the deliberations from the Workshop and the lunar data just recited, conclusions are drawn concerning plans to place an ecopoiesis test bed on the moon:

- The regolith will need to be augmented to provide growth minerals for terrestrial organisms.
- The day-night cycle, to have a 24.8 h duration, will need to be imposed artificially, and the experiment will be shut down approximately 2 weeks out of every month.
- The originally proposed large system must be scaled down in size
- Regolith soil mechanics make digging and trenching very difficult
- Pressurized gases, even at 10 mbar, will leak out through the regolith rapidly, and this leakage must be sealed off.

Each of these issues will be targeted in Phase II, and specific approaches to address them will be proposed.

3.3.2 Double-Locker Concept for the International Space Station

A photo of NASA's Avian Development Facility (ADF), which contains centrifuges capable of partial "g" and a controlled internal environment is shown in the poster montage of Figure 27. Using this hardware and the MARS-MTB (Figure 20) as basis, a design concept was created for a "double-locker" facility on ISS. This is depicted in Figure 28. The figure shows four MARS-MTBs mounted on one ADF centrifuge with environment control provided by a Stirling-cycle refrigerator. The power requirement, while not calculated exactly, is estimated to be around 300 W. The system would be operated continuously a few months at a time. MARS-MTBs could be transported to and from ISS while the double locker stays on board, in orbit.

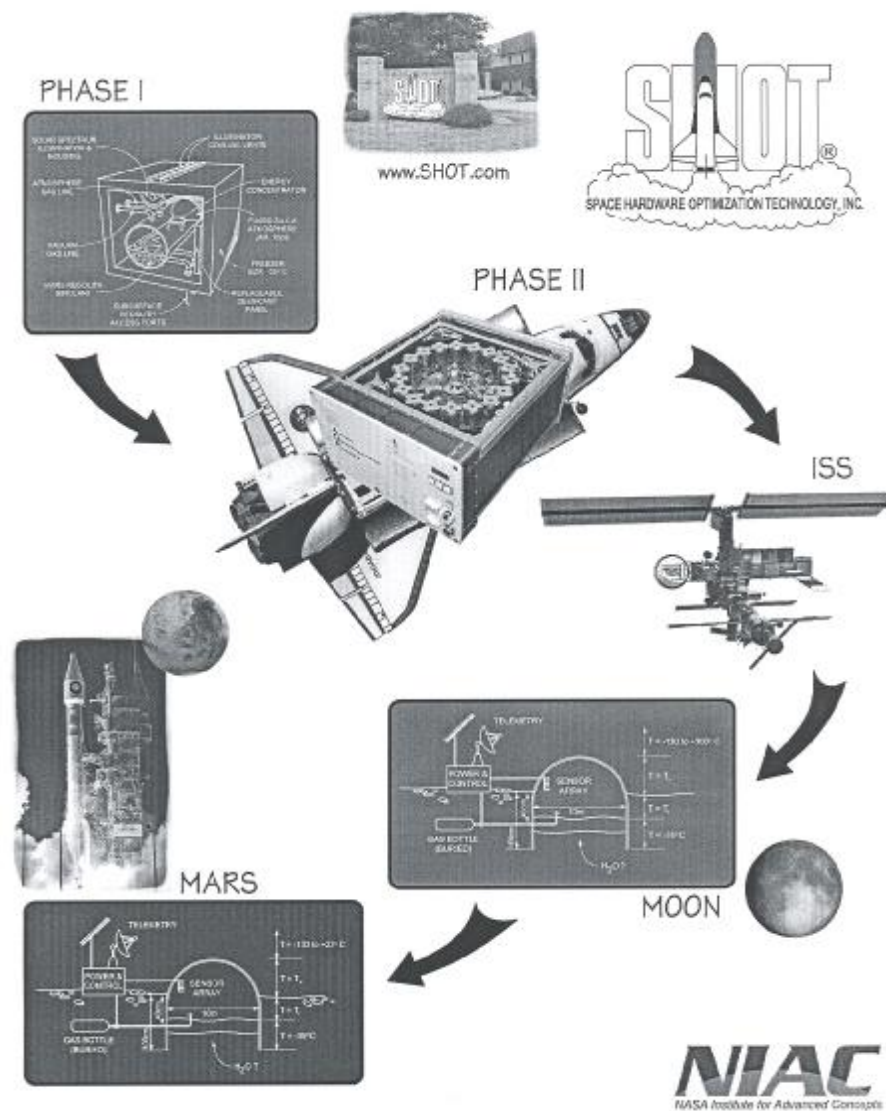


Figure 27. Monochrome view of poster graphics displayed at NIAC Annual Meeting, November 5-6, 2003

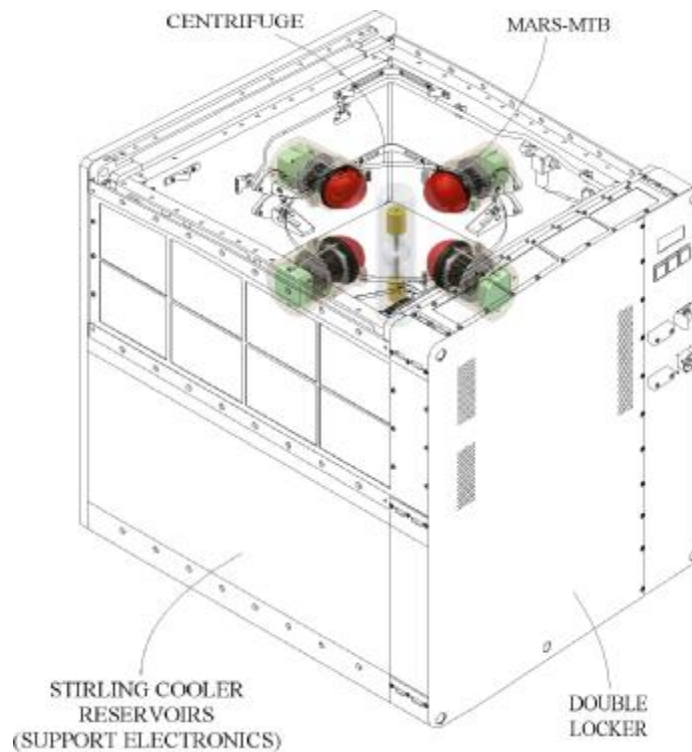


Figure 28. Concept for a partial-gravity ecopoiesis test bed aboard ISS.

3.3.3 Quantitative Comparison of Test-Bed Venues

This subject was treated during the Extremophile Selection for Ecopoiesis workshop. Nearly all possible research venues were canvassed. Figures of merit were assigned to each, on a scale of 0 to 4, for the fidelity and convenience with which each desired characteristic of the Martian environment could be provided (see Table 5). For example, an external pod on a truss on ISS received low figures of merit for day length, integration and cost, since day length on ISS (ca. 90 min) is very different from the Mars diurnal cycle, it requires a space shuttle flight(s) to implement, and the cost is unreasonable because it will be a component of a manned space platform. Two lines are shown as unaddressed partly due to time constraints and partly due to the more distant event horizon for experiments on Mars.

Table 5. Figures of merit with respect to desired features of simulation test beds for Martian ecopoiesis.

Test Bed	Multiple species	Atmosphere comp.	regolith	Light spectrum	accessibility	Ionizing radiation	gravity	complexity	Day length	integration	temperature	cost	pressure	season
Lab chamber	4	4	4	4	4	2	1	3	4	4	4	3	4	4
Miniature lab chamber														
<i>single</i>	2	4	3	4	3	0	1	4	4	4	3	4	4	4
<i>multiple</i>	4	4	4	4	4	3	3	4	4	4	4	4	4	4
Miniature ISS chamber	3	4	4	2	2	0	4	2	4	2	3	2	4	1
External ISS chamber	3	4	4	3	2	2	1	1	0	1	2	2	4	0
Earth test bed	4	4	3	2	4	1	1	2	4	2	3	3	2	1
NASA Simulation facility	4	4	4	4	3	1	1	2	4	2	4	2	4	2
Lunar test bed														
<i>3. Lander + dome</i>	4	4	1	4	4	4	3	1	0	1	3	1	4	2
<i>2. Lander + container</i>	3	4	4	4	2	4	3	2	3	2	4	1	4	2
<i>1. Miniature</i>	2	4	4	4	1	4	3	4	0	3	3	3	4	2
Mars test bed														
<i>3. Lander + dome</i>														
<i>2. Lander + container</i>														
<i>1. Piggy-back</i>	2	4	4	4	1	4	4	4	4	3	4	3	4	4

The original “lunar ecopoiesis test bed” concept was assigned low figures of merit in two major categories: regolith composition and day length. In order to be effective as a Mars simulator the lunar test bed would need its own regolith and a controlled day-night cycle. Therefore three categories of lunar test beds were considered: a robotic dome as in Figure 1, a mid-sized self-contained test bed with its own regolith and controlled light and temperature cycles and a remotely controlled version of the MARS-MTB. Mars regolith simulant would be carried along, and a rotating sun shield would be included to control day length.

An additional significant concept was derived from these deliberations, namely miniature chambers for several venues. These would fit into the ecopoiesis roadmap in a very fruitful way if they could be manufactured inexpensively, and they would support a future ecopoiesis

architecture by attracting hundreds of investigators, affordably, to the field and rapidly increasing the rate of data return. This concept led to considerable engineering planning and is described in detail in Section 3.2.2.

3.4 Objective 4. Develop scaling rules

Following are examples of calculations performed during Phase I

3.4.1 Leakage of test-bed gas through lunar regolith

According to calculations using a modified Verdun equation for flow through porous media (Garcia et al., 1999) and certain assumptions about regolith particle size (80 μm) and gas-phase viscosity, the lunar test bed could lose its full volume of Mars gas at 10 mbar in a matter of hours. This condition is, of course, unacceptable, so a sub-regolith sealed layer is to be recommended in the Phase II proposal, as will a much smaller dome, 1 m rather than 30 m in diameter.

3.4.2 Mars atmospheric moisture in the MARS-LTB

The atmosphere of Mars is approximately 150 ppm water. By scaling to the density of the Mars atmosphere at 10 mbar (approximately $1.9 \times 10^{-5} \text{ g/cm}^3$) and the volume of the MARS-LTB experiment chamber (4000 cm^3) it is estimated that approximately 13 μg of water should be in the chamber at steady state to simulate Mars moisture. Early microbial experiments will begin with considerably more water (up to 100 mg) to simulate the deliberate addition of water to the Mars regolith to initiate terraforming.

3.4.3 Thermal Estimate for MARS-MTB

The passive heat load to be borne by the TEDs at steady state is estimated at 3.0 - 5.0 W, including heat transfer from +25°C environment to -135°C inside the MARS-MTB dome. According to one manufacturer a 5-stage TED could reach -72°C from an ambient temperature of 27°C while pumping 2.3Watts. If the ambient temperature is reduced to 5°C (standard refrigerator), then the cold side could reach -80°C. This would require a TED input power around 10Amps and 12volts. With twice this input power and intense cooling by fan, a scientifically satisfactory temperature should be achievable. At the equatorial and southern temperate zones of Mars the minimum temperature is -88°C (figure 5). These calculations therefore indicate that the thermoelectric approach to a portable MARS-MTB is worthy of consideration.

3.5 Deliverables to NIAC

The deliverables to NIAC are described in Article III.A. of the Subcontract, and these consist of (1) a written status report to the NIAC Director by the 15th day of the 3rd month, (2) a written status report to the NIAC Director by the 5th month, (3) a final report within 30 days following the conclusion of the performance period (report due by 30 April 2004), (4) a poster presentation at the NIAC Annual Meeting and a Status Report at the NIAC Phase I Fellows Workshop. Progress on the due items is presented in the paragraphs that follow.

3.5.1 NIAC Fellows poster presentation at NIAC Annual Meeting

The NIAC Annual Meeting was attended by the NIAC Fellow and the Co-Investigator, Dr. Penelope Boston of the New Mexico Institute of Mining and Technology, also a NIAC Fellow. A poster was presented during the Poster Presentation Period and was discussed with NIAC staff

and other NIAC Fellows, including student associates. The poster presentation was a planning presentation built around the long-term goals of the project. A monochrome view of the graphics component of the displayed poster is shown as Figure 27 in Section 3.3.2, and Figure 29 is a flow chart around which the long-term project is organized.

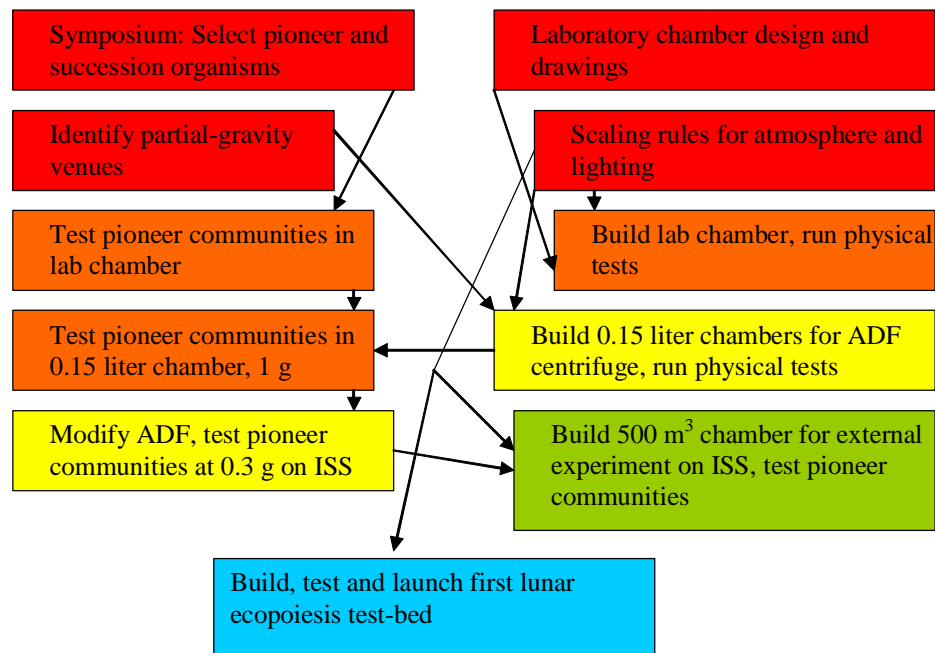


Figure 29. A flow chart indicating pathways from inception and selection of pioneer organisms through lab, spacecraft and lunar experiments. Color code: Red = Phase I, Orange = Phase II, Yellow = Phase III, Green = Future I (ISS), Blue = final (lunar).

Top-level outlines of the approach were provided in each case, as follows:

Phase I Objectives

Seven Identified Principles

1. Problem to be addressed: terraforming of the surface of Mars.
2. Starting conditions: those expected to exist at the best possible Mars location
3. Regolith to be heated to accommodate most robust terrestrial life
4. Pioneer organisms derive energy from mineral content and/or sunlight
5. Pioneer organisms capable of withstanding or protected from radiations
6. Organisms early in succession should produce significant amounts of O₂.
7. Heterotrophic aerobes needed after dangerous levels of O₂ emerge.

Four Levels of Inquiry Concerning Biology and Mars

1. Planetary protection, contamination and quarantine issues (NRC, 1992),
2. The search for life on Mars (Banin, 1989; Banin and Mancinelli, 1995; Ivanov, 1995; Koike et al., 1995; Biemann et al., 1977),
3. Human expeditions to Mars and ecosynthesis (Meyer & McKay, 1984, 1989, 1995)
4. The terraforming of Mars or ecopoiesis (Haynes, 1990; McKay, 1990; Haynes and McKay, 1992; McKay et al., 1991, 1994; Hiscox, 1993, 1995, 1998).

Symposium on Pioneer Organisms and Succession

- What known organisms thrive and grow most rapidly in terrestrial polar environments?
- What known organisms will metabolize and proliferate in minimal water and pressure?
- What organisms are most appropriate to start a community using mineral energy?
- What conditions must humans create in the atmosphere to encourage cell proliferation?
- What conditions must humans create in the regolith to encourage proliferation?
- What should be the expected succession of organisms in an ecopoietic environment?
- What time scales are appropriate for experiments in model architectures?
- What are the appropriate analytical methods for detecting growth, metabolism and environmental modification and succession?

Identify Partial-Gravity Venues

- Modified Avian Development Locker on International Space Station (0.15 liter)
- Single Locker on ISS
- External Pallet on ISS
- Dome on Moon

Laboratory Chamber and Subsystems Design Drawings

- Outer housing controls temperature -130 to +23°C (cryogenic vs. Stirling)
- Sealed illuminator with housing & cooling vents
- Low-pressure “Mars Jar” held at 10 – 15 mbar
- Atmosphere composition analysis and control
- Regolith simulant and regolith sampling

Scaling Rules for Atmosphere and Lighting

- Short optical path in jar atmosphere will not absorb IR radiation when greenhouse gases appear
- Monitor greenhouse gases and scale temperature for Martian field
- Use heat (energy) concentrator to create warm zone in regolith simulant using incoming “insolation”
- Scale pioneer biomass to feasible mass per unit regolith area but sufficient for analysis
- Write algorithms for scaling rules

Phase II

- Build lab chamber & perform physical tests
- Test pioneer communities in lab chamber
- Design 0.15 liter chamber and perform physical tests
- Plan Phase III design and controls for multiple 0.15 liter chambers at 0.3 g

Phase III

- Build 0.15 liter chambers for ADF centrifuge & perform physical tests
- Modify Avian Development Facility design (ADF) to include cryogenics and low-pressure jars
- Install modified ADF on ISS and operate rotors at 0.38 g with analytical capability
- Test pioneer communities in 0.15 liter chamber, 0.38 g

Future I

- Design and build 1 m diameter inflatable spherical enclosure for external testing on ISS

- Install enclosure on ISS and make physical measurements of light and temperature
- Operate for maximum duration in orbit

Future II

- Design and build robotically assembled lunar ecopoiesis test bed
- Perform physical tests at Earth venue
- Perform biological tests with pioneer communities at Earth venue
- Launch to moon and install robotically near a selected location
- Monitor vapor phase and regolith for several years, attend as needed

3.5.2 Written status report by 15th of 3rd and 5th month

In addition to the objective-related progress cited above, an original article, based on all of the objectives, was submitted for publication and was presented at the conference “Space Technology and Applications International Forum” (STAIF-2004) in January 2004 in Albuquerque, NM and published in American Institute of Physics Conference Proceedings, Mohamed S. El-Genk, Editor. This completed manuscript is included in this report as Appendix A.

3.5.3 NIAC Phase I Fellows Workshop

This Workshop was held in Washington, DC, 23-24 March, 2004. The report presented at this event included the conclusions and recommendations derived from the workshop symposium on Extremophile Selection for Ecopoiesis and further progress on the MARS-LTB.

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4.2 Ecopoiesis Bibliography

A bibliography of more than 100 citations was compiled during the course of this research. The list below is by no means comprehensive nor does it contain all of the allusions utilized in this research. This list serves two purposes: a favor to the reader interested in further details and an indication that, despite a sizeable literature in exobiology and astrobiology, rather few articles are found on *experimental* ecopoiesis.

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APPENDIX A

Robotic Lunar Ecopoiesis Test Bed: Bringing the Experimental Method to Terraforming

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Abstract. The notion of ecologically terraforming another planet (aka *ecopoiesis*) has been discussed by a number of scholars. Some theoretical treatments of various aspects of ecopoiesis have appeared in the literature. However, experimental terraforming studies have been rare to non-existent. This is not surprising because of the planetary scale and long durations typically discussed. We describe a concept to perform basic ecopoietic experiments in a test facility constructed on the lunar surface. Such a facility can provide long-term observation of organisms and their ecological, physiological, and evolutionary interactions in a low gravity environment. Salient features of other extraterrestrial environments (e.g. the 0.38g Mars gravity) can be simulated more easily in the lunar milieu than on Earth while providing much greater access for experimenters than ecopoiesis experiments on Mars itself. Besides application of these proposed studies to possible future terraforming efforts, basic evolutionary and ecological processes could be studied under extreme selection pressures including fractional gravity, high radiation, and with a variety of atmospheres, soils, and other parameters. Novel, genetically engineered and selectively bred organisms could be tested in such a facility without concern for accidental release into Earth's environment.

INTRODUCTION TO TERRAFORMING AND ECOPOIESIS

Recipe for a Biosphere:

Start with a lifeless planet.

Add a few Earth organisms and stir.

Wait about 10,000 to 100,000 years.

Voila! A living, terraformed planet will emerge.

Is this simply a science fiction scenario? A number of scientists and engineers think perhaps not and have given serious consideration to the requirements and ramifications of transferring some of Earth's biota to another planet to create a new biosphere, a process called "terraforming" (Fogg, 1995a, 1998; Haynes & McKay, 1992; Boston & Thompson, 1991; McKay et al., 1991; Pollack & Sagan, 1991; McKay, 1982; Bauman et al., 1979; Avern & MacElroy, 1976; Sagan, 1973). A specific refinement of the terraforming idea dubbed "ecopoiesis" by Haynes (1990) refers to the process of naturally evolving a physical and biological environment on a previously lifeless planet by the deliberate introduction of terrestrial-type ecosystems on remote celestial bodies such as planets, moons and asteroids (Haynes, 1990). This contrasts to a more engineering oriented approach advanced by some authors (e.g. Vondrak, 1974; Freitas, 1983; Cathcart, 1991; Smith, 1992; Nussinov et al., 1994; Taylor, 1998; Turner, 1998).

Planetary engineering concepts are not new and the broad outlines can trace their origins to early futurist thinkers like the Russian space scientist Tsiolkovsky writing at the end of the 19th century (Ober, 1981) and fictional treatments like *Last and First Men* (Stapledon, 1930) and *Seetee Ship* where the term “terraforming” was coined (Williamson, 1950). The modern era of scientific terraforming speculation began in earnest with a Rand Corporation study, *Habitable Planets for Man*, later transformed into a popular book (Dole & Asimov, 1964) and with a monograph by Dyson (1965). Within the next few years, several other important first order analyses of the concept appeared (e.g. Sagan, 1973, based on a much earlier and less developed 1961 effort; Burns & Harwitt, 1973) and the seminal treatise on Mars terraforming, *On the Habitability of Mars* (Averner & McElroy, 1976).

No matter which variant of terraforming one prefers, there is a significant dilemma facing those who consider the prospect of introducing a biosphere to a putatively lifeless planet. Principles of planetary protection prohibit the introduction of any living organisms onto Earth’s neighbors in the solar system (for a good review, see Rummel, 2001). However, some have pointed out the desirability of early modification (of Mars, for example) to initiate processes that will make the planet a more hospitable place for humans should they decide to go there permanently at a later date (Fogg, 1995a). Resolution of this ethical and environmentally sensitive conundrum lay in the future. In either case, knowledge of the possible consequences, risks, and probability of success is lacking, and experimental testing related to the basic understanding of the ecopoiesis process is non-existent. Since the earliest conceivable implementation of *any* activities related to ecopoiesis would occur at least several decades in the future, the experimental study of ecopoiesis would seem an ideal research area to engage in now. To this end, we propose an ecopoiesis test bed facility to be placed on the lunar surface to conduct this research.

MARS TERRAFORMING SCENARIO AND REQUIREMENTS

There is enough basic information available to conduct modest ecopoiesis experiments now although many false starts can be expected. Perhaps later in this new century, when serious consideration might be given to terraforming Mars or other bodies, a great deal more information and wisdom will be available. At this writing, only individual components of ecopoietic systems have been investigated – a few species of microorganisms, certain lower plants and several vascular plants. Ultimately a series of test-beds will be needed as attempts are made to introduce whole communities of organisms into novel environments and as more sophisticated models are proposed to study ecological and evolutionary processes in such model systems. Meeting the requirements of this unique type of test bed presents engineering and scientific challenges that require a highly interdisciplinary approach.

For the scenario we paint here, we begin by assuming that ecopoiesis on Mars (with or without subsequent engineered terraforming) is our proposed case study objective. We have identified a series of steps necessary to meet this objective. A number of basic principles can be derived from that primary assumption. These have been explored by Fogg (1995a). We list them here to provide an initial context for our ecopoiesis test bed.

1. Starting conditions should resemble those expected to exist at the best possible location on the surface of Mars, e.g. the polar caps, where water ice may be found (Titus et al., 2003;

Christensen et al., 2003) or in the subsurface where volatiles or geothermal heat flow may be present (Boston et al., 1992).

2. The regolith must be heated at least to a temperature compatible with the lower temperature limits of the most robust forms of cold-adapted terrestrial life, e.g. temperatures suitable for Antarctic microorganisms (Friedmann, 1982, 1986; McKay, 1993).

3. The first “pioneer” organisms must derive energy from the mineral content of the regolith and/or sunlight, and their metabolism must produce a net increase in atmospheric greenhouse gases – i.e. chemoautotrophs and photoautotrophs (e.g. Boston et al., 2001; Hiscox & Thomas, 1995; Friedman et al., 1993).

4. The first organisms must be capable of withstanding (Lindberg and Horneck, 1991), or be totally protected from (Boston et al., 1992, 2001), the ultraviolet and ionizing radiation present at the Martian surface.

5. Organisms early in succession should produce significant amounts of O₂ (Fogg, 1995b; Friedmann & Ocampo-Friedmann, 1994; Averner & MacElroy, 1976).

While these are reasonable starting assumptions, one could easily criticize some of them as being excessively oriented towards supporting the same type of aerobic, surface biology that we are most familiar with and indeed, belong to. The ultimate goal of terraforming to some thinkers may be the support of human life (Pinson, 2002; Zubrin, 1993; MacNiven, 1995; Heath, 1991; Cobleigh and Warner, 1979) but to others it may be the inception of a self-sustaining ecology on Mars that will evolve in its own direction, not necessarily suitable for the support of humans (Hargrove, 1986; McKay, 1990). These value judgements aside, we have no solid foundation for pursuing *either* option without significant research into the mechanisms and ramifications of terraforming efforts.

ECOPOIESIS EXPERIMENTAL RATIONALE

An effective ecopoietic strategy requires knowing the limits of habitability for Earth organisms, especially under conditions of limited water and oxygen (Banin & Mancinelli, 1995; Carr, 1987, 1986; Fogg, 1995b) and extremes of temperature (Masayori & Yamanaka, 2000; Ray et al., 1998; Stetter, 1996; Blochl et al., 1997). The current NASA Astrobiology Institute (<http://astrobiology.arc.nasa.gov/>) and the parallel activities in ESA (<http://www.esa.int/export/esaCP/index.html>) are supporting some of this type of research already. However, no work is specifically directed towards ultimate implementation in biosphere creation. We suggest that a number of particular organisms are pre-adapted for further development as candidate Martian ecopoiesis pioneers.

Shortly after the Viking missions landed on Mars, Averner and MacElroy (1976) and Kuhn, Rogers and MacElroy (1979) launched a program to study the habitability and planetary ecosynthesis of Mars by designing an energy balance model that calculated the effects of various Mars conditions (as then understood) on various organism types (also as then understood). Since the advent of MacElroy's research program in 1975, a number of living systems have been identified that survive in various Earth environments that represent at least some aspects of the Martian environment. These biota may be classified as "extremophiles," and include classes of anhydrobiotes (i.e. organisms withstanding complete dessication, Dose, 1995), cryophiles (extreme cold-adapted organisms), thermophiles (extreme heat-adapted organisms) and halophiles (high salt tolerant organisms), to name a few. Examples include

cryophiles found in the ice-covered lakes in the Bunger Hills Oasis of Antarctica (McKay, 1993; Friedmann, 1986), and in Arctic permafrost in the Kolyma lowland of Siberia, Russia (Ostroumov, 1995). Thermophiles and halophiles include endolithic bacteria (living within rocks) found in extreme arid deserts (Friedmann, 1982), permafrost inhabitants (Shi et al., 1997), hot environment bacteria (Stetter, 1996), and chemically extreme caves (Boston et al., 2001). Robust evaporite biotas have been found in hypersaline habitats and rock salt (Stan-Lotter & Radax, 2001; Rothschild et al., 1995; Denner et al., 1994) and cryptic microbial mats in the Guerrero Negro, Baja California Sur, Mexico (Javor, 1989).

In view of the history and present state of extremophile biology and its application vis a vis ecopoiesis, a number of self-evident research topics for our lunar ecopoiesis test bed present themselves. If we accept the notion that the pioneer organisms useful for ecopoiesis must derive energy autotrophically from either sunlight or the inorganic constituents of the regolith and atmosphere (Averner & MacElroy, 1976), then we have constrained the necessary research to photosynthetic and chemolithotrophic microorganisms. Beyond this, to be globally useful to the terraforming process, their metabolism must produce a net increase in greenhouse gases to help thicken and warm the atmosphere. The matter of whether oxygenic photosynthesis should be considered an essential property of any pioneer organisms depends upon whether one is trying to make the planet as Earth-like as possible and what the assumed timeline may be. Earth's biota created its free oxygen atmosphere only after over a billion years of development had occurred. We are likely not to be so patient. If oxygenic photosynthesis is deemed desirable in the early stages of ecopoietic succession, the presence of free O₂ will be essential to drive the oxygen-dependent dark reactions of photosynthetic organisms. Certain cyanobacteria that are oxygenic photosynthesizers have been previously considered as potential pioneer organisms (Friedman et al., 1994).

The first organisms to be introduced to Mars must be capable of withstanding, or be protected from, the ultraviolet (UV) and ionizing radiation present on the Martian surface. The Martian atmosphere, devoid of an ozone layer (which attenuates UV on Earth), lets the ultraviolet radiation penetrate to the Martian surface in wavelengths ranging from 190 to 300 nm. UV is successfully absorbed by a very thin layer of regolith, so that even shallowly subsurface organisms can survive unaffected. Ionizing radiation fluxes are extreme because of the lack of a significant magnetic field that could deflect such radiation (Nachtwey, 1989). Tolerance of high fluxes of ionizing radiation have been exhibited by a number of microorganisms (Makarova et al., 2001) and avoidance of ionizing radiation in a subsurface habitat has also been suggested as a successful biological strategy for Mars (Boston et al., 1992, 2001).

The potential toxicity or corrosiveness of Martian materials must be tested and can be tackled experimentally using Mars regolith simulant (e.g. McKay et al., 1994; Banin et al., 1992) based on further refinements of our knowledge during present and future Mars missions. Planetary environment simulation chambers have a venerable history (Sagan and Pollack, 1974; Koike et al., 1991; Kuhn et al., 1979; Hawrylewicz et al., 1962) and can be tailored to match the latest information available about the Martian environment.

ADVANCED CONCEPT DESCRIPTION

The "Robotic Lunar Ecopoiesis Test Bed" is envisioned as a largely self-contained, robotically operated unit that will allow us to experimentally test some of the notions inherent in terraforming briefly discussed in the last section (Figure 1). The essence of the concept is to let

living ecosystems “self-engineer” in a semi-closed environment on the lunar surface. The chamber can provide Mars-like conditions, e.g. fractional gravity, appropriate atmospheric compositions, etc. Initially, the environment will be actively controlled. For example, the energy to self-construct the bubble could initially be obtained from fuel cells that also produce the water necessary to moisten the regolith. At first, robotically regulated bottled gases will control the internal pressure at 1.0 – 1.5 kPa, and heat gained from the sun can be controlled by radiators actively positioned by photovoltaic electric motors or solar-powered Stirling engines.

In one scenario under consideration as a model for how the Ecopoiesis Module experiments might operate, we anticipate that chemoautotrophic microorganisms can gain energy from metabolizing materials in the lunar regolith producing a net gain in organic matter. This biomass increase then serves to feed fungi. In turn, the fungi can produce CO₂ (via respiration) thus providing “feedstock” for algal photosynthesis. The algae will produce excess O₂ perhaps for use by some invertebrate animals. The rationale for this approach is really a time-compressed, truncated version of the way we observe biological trophic levels operating on Earth with initial capture of solar energy or conversion of geologically stored energy and subsequent passing of energy-bearing compounds to the next trophic level with the production of byproducts useful to other lifeforms and a net increase in both biomass and mobilized elements and compounds that were previously locked up in the lithosphere and more inert chemical forms in the atmosphere.

The advantage of using the Moon rather than conducting such experiments on Mars is obviously proximity. A lunar facility will be more accessible owing to the relative nearness of the Moon and could be remotely controllable via short communication turnaround times (~2.5 secs round trip). This contrasts with the great distance of Mars and communication time delays (ranging from ~10 to 30 minutes).

The Lunar Ecopoiesis Facility differs from a Closed Environment Life Support Systems (CELSS) approach in that the Ecopoiesis Test Bed provides an architecture that *induces the organisms and their environment to evolve on their own* with minimal engineering interference. The starting materials will be relatively simple, e.g. water, a source of nitrogen, carbon dioxide, and spores or inactive cells of appropriate prokaryotes, seeds, and eggs of organisms that will eventually occupy the module. Experimental ecopoiesis is a new field, indeed barely in existence, so we envision a significant experimental effort here on Earth to pave the way for subsequent lunar application. Beyond initial Earth-based experiments, a space-faring platform like the International Space Station can provide an additional level of development in fractional g (provided by centrifugation in microgravity). The final stage of this development sequence will be construction of the Lunar Ecopoiesis Test Facility itself.

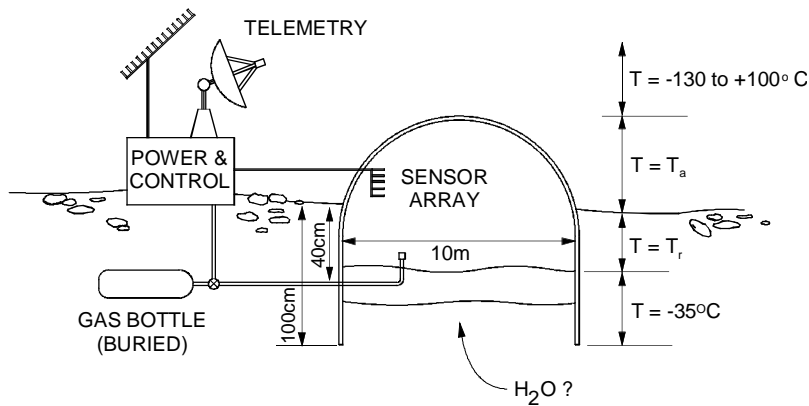


Figure 1. Artistic concept of a robotic lunar ecopoiesis test bed. The long-range goal of the proposed program, showing positioning of the in situ polymerized inflated dome to take advantage of lunar thermal characteristics.

The Moon has less than Mars in the way of raw materials that could be used in an ecopoiesis facility. However, one important factor, growth substrate like soil, could be made *in situ*. Conditioning lunar regolith into soil for agricultural applications has been pursued by a number of investigators and reported by Ming and Henninger (1989) and elsewhere. The development of soils beginning with sterile extraterrestrial regolith was investigated by Drees and Wilding (1989). They concluded that many physical and chemical factors of lunar regolith would make the production of plant-growth capable soils from regolith feasible.

CONCEPT PROTOTYPE

Although the ultimate goals of the Ecopoiesis Test Bed Facility look to the far future, the immediate implementation could be grounded in today's technology. The steps involved in implementing such a program are discussed here as applied to the Mars ecopoiesis case.

1. Identify possible communities of promising organisms for further study.
2. Develop preliminary chamber design. Such a chamber is illustrated in Figure 2.
3. Identify fractional gravity venues and requirements.
4. Develop scaling rules for support of different sized test chambers.

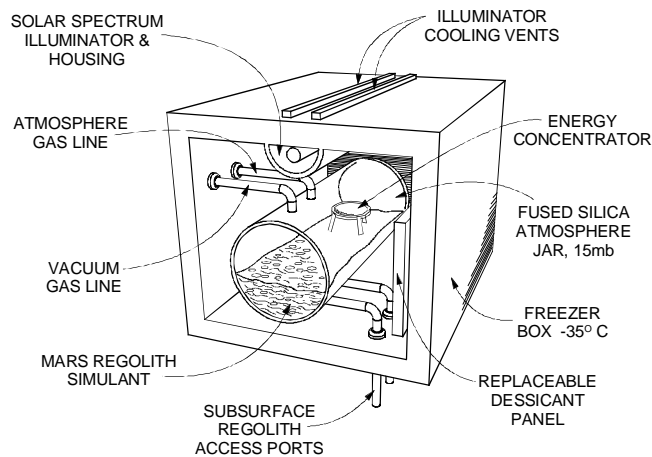


Figure 2: Conceptual version of a "Martian environment simulator" for initial ecopoiesis experiment on the International Space Station. It is comprised of a low-temperature housing, Mars spectrum UV-visible illumination, and maintenance of low-pressure Mars-composition atmosphere. Fractional gravity can be provided by low speed centrifugation in the microgravity environment.

Identification of communities of ecopoietic candidate organisms is a non-engineering component of the proposed Test Facility. To date, there exist only a few published speculations of a handful of authors as intellectual background (e.g. Fogg, 1995; Clark, 1998; Avern & MacElroy, 1976; Boston & Thompson, 1991; Thomas, 1995). Ongoing work on the limits to life conducted by numerous investigators working in astrobiology and extreme environment biology can be gleaned for initial lists of possible organisms for use in the Test Facility. Questions to be answered include:

- What known organisms thrive and grow most rapidly in terrestrial polar desert environments?
- What known organisms will metabolize and proliferate with minimal access to water and in low-pressure atmospheres?
- What organisms are most appropriate to start a community using mineral energy?
- What conditions must humans create in the atmosphere to encourage cell proliferation?
- What conditions must humans create in the regolith to encourage proliferation?
- What should be the expected succession of organisms in an ecopoietic environment?
- What time scales are appropriate for experiments in model architectures?
- What is the possible degree of autonomy of an entirely subsurface biosphere?
- What are the appropriate analytical methods for detecting growth, metabolism and environmental modification and succession?

Development of the preliminary chamber design will be based on the “Avian Development Facility” shown in Figure 3 (Vellinger et al., 2000). This unit was developed by the second author’s organization, SHOT (Space Hardware Optimization Technology, Inc.). SHOT has extensive experience in microgravity life science experimentation. Higher order logistics for accessing low-gravity venues (e.g on ISS) will be derived from these initial chambers. Use will also be made of SHOT’s chemical engineering capabilities to derive scaling rules for gas concentrations, heat capacities, heat transfer, light and radiation intensities, biomass and mechanical properties.



Figure 3. Spaceflight hardware for fundamental biology built by SHOT for NASA – “Avian Development Facility” – with 32 adaptable variable-g centrifuge positions for specimens

This testbed was designed and operated to maintain precise temperature control, contain known toxic fumes, withstand wide pressure swings, inject chemical solutions on command, rotate an artificial gravity centrifuge on orbit, and perform complete avian development experiments automatically without operator intervention. Other examples of test chambers whose features may be incorporated into the prototype facility can be viewed at the SHOT web site www.shot.com.

CONCLUSIONS

This paper describes the outlines of a plan to develop an Ecopoiesis Test Bed Facility to be placed on Earth's Moon. The detailed steps necessary to implement this ambitious goal begin with initial ground-based ecopoiesis test modules and preliminary research on organisms and communities. This progresses through a microgravity test phase aboard the International Space Station. The culmination of development will be emplacement of largely autonomous units on or perhaps under the lunar surface. This concept has been recently funded for a Phase I study by the NASA Institute for Advanced Concepts. As part of this future study, detailed plans and experimental designs will be developed.

Planetary protection is a significant component of the ecopoiesis debate. One of the significant outcomes of the proposed research that we anticipate, may be to force the scientific community to come to grips with these difficult issues. Ideally, the progress of actual experimentation dealing with terraforming and ecopoiesis will gradually force thinkers towards a consensus concerning these subjects. The research proposed here can be considered a direct response to the challenge originally put forth by Christopher McKay and the late Robert Haynes: "... if it is decided to implement such a program of planetary engineering, a slow and conservative approach is essential. Sufficient time must be allowed for a wide range of studies of Mars as it exists at present, and for careful planning, modeling and 'pilot-plant' trials (where possible) of all successive steps in the enterprise." (Haynes & McKay, 1995). We hope to contribute to the development of such "pilot-plant trials".

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APPENDIX B

Outline of Proposed Manuscript by Representatives of the Workshop “Extremophile Selection for Ecopoiesis”

Quo Vadis Ecopoiesis: Playing God in the Laboratory

1. Introduction

In their landmark article “Ecce Ecopoiesis. Playing God on Mars” Haynes and McKay point to several issues associated with planetary terraforming and the precursor events, collectively “ecopoiesis” required for terraforming to occur. They advocated “if it is decided to implement such a program of planetary engineering, a slow and conservative approach is essential. Sufficient time must be allowed for a wide range of studies of Mars as it exists at present, and for careful planning, modeling and ‘pilot-plant’ trials (where possible) of all successive steps in the enterprise.” (Haynes & McKay, 1995). We therefore intend to open test beds required for the implementation of the enabling notions offered by Fogg (1995), McKay et al.(1991), Boston and Thompson (1992) among others.

Three basic methods of planetary warming for terraforming have been proposed [Zubrin], the generation of greenhouse gases by chemical plants, the regional intensification of insolation using orbiting mirrors and darkened regolith (literally “smoke and mirrors”) and biological generation of greenhouse gases. It is not our intent to address the broad issues of planetary terraforming but to address the feasibility of a major research architecture that addresses the critical questions involved in getting life started on a planet with a thin atmosphere.

With this article we initiate a series of dialogues concerning the timing, placement and organization of ecopoiesis research in an architecture that must define the structure of the paced research that Haynes and McKay mentioned but did not propose in concrete detail. Our purpose is to address the where (*Quo Vadis*), the how (technology) and the who (organisms) of ecopoiesis research to be conducted by terrestrial humans.

2. Quo Vadis: Venues for Ecopoiesis Research

Assuming that Mars will one day become the target planet for terraforming (Fogg, 1995), the environmental features of the surface of Mars must be faithfully replicated in test-beds that can undergo small modifications by human researchers to encourage the growth of selected pioneer organisms. These features include day-night light and temperature cycles, regolith composition, solar light intensity and spectrum, atmospheric composition, gravitational acceleration and radiation environment, actual values of which are compared with those of selected research venues below.

2.1 In the lab

2.2 Microbes are not large.

2.3 Low-gravity venues

2.4 Large simulators on earth venues

Large simulators of the Martian environment are available at a limited number of venues. At NASA's Johns Space Center the simulator provides a wide range of temperatures and pressures that includes the range of these variables found on Mars and is large enough to accommodate certain spacecraft. The University of Arkansas possesses a facility deliberately designed to simulate as many Martian variables as possible (). The German space agency DLR constructed a lower-volume high-fidelity simulator with an internal volume of _____ with the composition of the Martian atmosphere, regolith and solar radiation pattern.

Table 1 compares the extent to which each of these three facilities creates an environment similar to that on Mars.

Table 1. Comparison of the extent to which three facilities create an environment similar to that on Mars.

VENUE	PRESSURE	TEMPERATURE	DIURNAL CYCLE	REGOLITH	ATMOSPHERE
Mars	7 – 10 mbar			Oxidized Fe Minerals	N ₂ , CO ₂ , Ar
JSC					
U Ark					

There is a need for further distribution of Mars-surface simulators into the laboratories of investigators interested in ecopoiesis research. These could take on two forms, a single large incubator-type facility or multiple modular "Mars jars".

2.5 Proposed Laboratory Simulators – General Features

2.6 Mars jars

2.7 Lunar large simulator

2.8 Figures of merit for venues

2.9 Technology

3. Pioneer Organisms

3.1 Extremophile selection principles

3.2 Primary producers

3.2.1 Cyanobacteria

3.2.2 Lithotrophs

3.3 Secondary consumers

3.3.1 Methanogens

3.3.2 Halophiles

3.4 Eucaryotes

4. Engaging a Research Community

5. Conclusions

6. Acknowledgments

7. References