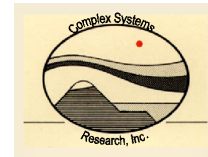


Human Utilization of Subsurface Extraterrestrial Environments: *Final Report*



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I. Project Summary

Natural subsurface cavities (caves) and subsurface constructs present the most mission effective habitat alternative for future human missions in the high-radiation and thermally challenging environments of Mars and Earth's Moon. Additionally, lava tubes, other caves, cavities, and canyon overhangs that will be found on other planets are sites of intense scientific interest. They offer easier subsurface access for direct exploration and drilling, and may provide extractable minerals, gases, and ices. Expanding our NIAC Phase I feasibility assessment of a subsurface Mars mission architecture for the scientific exploration and human habitation of caves and subsurface facilities, we have developed the notion of a complete, functioning subsurface habitat system. This system can integrate a spectrum of missions from both robotic precursors to human expeditionary missions and ultimately colonization.

We have developed a list of critical enabling technologies necessary to implement the idea of subsurface extraterrestrial habitat and science. We designed and implemented simple prototypes of some of these technologies and conducted a "Mouse Mission to Inner Space" (MOMIS) to test some of them with mice as substitute speleonauts. We further designed and built components for a "Human Mission to Inner Space" (HUMIS) that awaits field trials as of this writing. This will involve a proof-of-concept of the ability of speleonauts to do useful science in an Earth cave under mission simulation conditions as a proxy for a future Martian or lunar cave site.

This project developed a revolutionary system to exploit the novel idea of extraterrestrial cave use. It is comprised of a merger of unique technologies that will enable future NASA missions that might otherwise be impossible by solving significant mission-impacting human survival and exploration problems in the hostile Martian and lunar environments.

II. Introduction

The human exploration and possible habitation of Mars is a long-held dream and a return to Earth's moon as a scientific base and technology testbed on the way there may be imminent. However, the present Martian surface environment is extremely cold, dry, chemically active, and high in both ultraviolet and ionizing radiation (e.g. McKay and Stoker, 1989; Carr, 1981; Jakosky et al., 1997). Indeed, even organic materials cannot survive on the surface (Klein, 1978). With all the truly compelling sites on Mars that have been championed as the "best" sites for future Mars missions, why have we chosen to focus on caves? Is it just because we are looking for a new twist on the old theme of planetary exploration, life on other planets, or human colonization of extraterrestrial surfaces? No, we have championed this idea because caves provide both unique scientific targets and critical practical human support functions (Boston, 2000a, b; Boston et al., 1992, 1996, 2001a,b, 2002, 2003, 2004).

Although the search for life or life's past traces on Mars is a high priority within the astrobiology community, we have argued that any present Martian life is more likely to be analogous to Earth's subsurface biosphere than anything currently found on Earth's surface (Boston et al., 1992, 2001a; Boston, 1999, 2000a). Even traces of ancient life will have been preserved more successfully in the subsurface than the surface (Boston, 2000b; Boston et al., 2001). In this capacity, we have been strong advocates of science missions to detect and then investigate extraterrestrial caves, especially those on Mars, and with particular emphasis on life detection missions. However, the high premium placed on Mars life detection missions and the extreme delicacy of the balance between investigation and potential damage or contamination of such life requires extraordinary protocols analogous to those of biohazard containment of the most virulent Earth viruses (Rummel, 2001). This requirement for complete containment must be coupled with the demands of field science, active exploration, robotic functionality, and ultimately astronaut survival. Nothing of this magnitude has ever been attempted in human history. Pristine Earth caves that contain numerous novel species of microorganisms provide genuine biologically sensitive sites for developing and practicing the operations required for application to Mars life detection sites and ultimately extraterrestrial human habitat.

Not only are there sound scientific reasons for focusing on subsurface environments, but humans also can benefit when we take our cues from nature. If it is clear that the intense radiation environment on the surface of Mars makes the subsurface the best place to look for any extant Martian life (Boston et al., 1992), in our view it is also clearly the only currently practicable human habitat choice. Whether natural caves, artificial tunnels, or bermed structures are used, the problems of living in a subsurface environment may be more easily overcome than developing methods to ameliorate the effects of radiation as experienced on the surface. The problem of protecting humans on the surface in suits and

transportation devices even for limited duration forays is intractable enough (e.g. Hodgson, 2001; Newman, 2001).

A. Objectives and Anticipated Impact

The primary objective of this feasibility demonstration was to show that relatively simple, easily-deployable subsurface habitats are constructible in caves, lavatubes, and other subsurface voids. Further, we wished to demonstrate that they are suitable to sustain small animals, plants, and ultimately humans in an otherwise hostile environment.

The secondary objective was to show that humans can do useful work and scientific exploration in a subsurface environment facing some of the constraints that they will meet in the Martian environment including potential biologically sensitive sites.

The third objective was to separate those features of a Mars or lunar subsurface mission that *can* be simulated in an Earth cave (e.g. Mars-derived breathing mixtures) from those that cannot (e.g. lunar or Martian gravity). Experience in select terrestrial caves with high extraterrestrial analog potential will enable mission planners to have some basis for deciding whether to pursue subsurface options for habitat and scientific targets. It will also clearly identify those aspects of subsurface Mars mission architectures that cannot be simulated on Earth and must be studied on the International Space Station, directly on the Moon, or other platforms and missions.

The fourth objective was to demonstrate the feasibility of the individual system subcomponents that we identified as important and worthy of further development. These include: inflatable habitat modules; simple, standardized easily deployable airlock units; Mars-derived breathing mixtures; node-to-node incave microrobot-mounted telecommunication, mapping, and telemetry network; inert gas pressurization of habitat caves; human functionality in the Mars cave environment; and coupling of photosynthetic oxygen production with bioluminescence for provision of light and habitat gas balance.

This project is directly responsive across most of the NASA Strategic Enterprises. It directly addresses four goals within the *Biological and Physical Research Enterprise*: 1) How can human existence expand beyond the home planet to achieve maximum benefits from space? 2) How do fundamental laws of nature shape the evolution of life? 3) How may we understand the human experience in space, and 4) How may we seek to understand Nature's forces in space for the benefit of all.

Within the *Human Exploration and Development of Space Enterprise*, this work will help to 1) Expand the frontiers of space and knowledge by exploring, using, and enabling the development of space for human enterprise, 2) Explore the space frontier, 3) Enable humans to live and work permanently in space, 4)

Enable the commercial development of space, and 5) Share the experience and benefits of discovery.

Scientific work in extraterrestrial caves will contribute to the *Space Science Enterprise* by 1) Helping to solve some of the mysteries of the universe, explore the solar system.... search for life beyond Earth from origins to destiny, chart the evolution of the universe and understand its... planets and life.

Even within the *Earth Science Enterprise*, this project can help answer “How does the Earth system respond to natural and human-induced changes?” and “What are the consequences of change in the Earth system for human civilization?”

B. Why caves?

Caves in general are poorly understood and unappreciated by the vast majority of the population. Scientists and engineers are no exception to this generalization. Because we are surface-inhabiting creatures, we bring a certain amount of *surface chauvinism* to our perception of caves as well as the oceans and the upper atmosphere. However, many modern indigenous and many ancient peoples were well acquainted with the properties of the caves in their environments. They made extensive use of them for shelter, materials acquisition, water and ice repositories, burial chambers, ritual sites, protection from temperature extremes, and refuge from human enemies (Adler, 1996; Arnold, 1971; Arnold and Bohor, 1975; Hatt et al., 1953; Sieveking, 1979; Tankersley, 1997; Watson, 1986; Wright, 1971). A tent-shaped hut was constructed inside a French cave (the Grotte du Lazaret near Nice) about half a million years ago by members of some early human groups (Jelinek, 1975). Evidently, Neanderthal inhabitants built a fireplace and other amenities. Obviously, the benefits of construction within a cave were clear to many who have preceded us!

Conditions in cave interiors are typically radically different from (and more benign than) the surface environment (Boston et al., 2001a). This has enabled microorganisms, larger organisms and even humans to gain protection by using caves as habitat. Many microbial forms are unique to the subsurface and have developed into countless novel strains (Northup and Lavoie, 2001; Boston et al., 2001a).

The tendency of the uninitiated to imagine all caves as nasty, dank, smelly and rather creepy places akin to the dungeons of fairy tales has made them seem unappealing to some. Indeed, some caves *are* like that. However, people as diverse as the mushroom growing epicures of the Loire Valley to the Dogon people of Mali to the gold and diamond miners of South Africa use caves routinely for highly specific economic purposes, shelter from an otherwise unsupportable surface environment, and a source of immense wealth.

In recent times, the use of caves on extraterrestrial bodies for human habitation has been suggested by several groups. Lunar lava tube bases received much of the attention (Horz, 1985; Walden, 1988; Kokh, 1996; Taylor, 1998) because lava tubes were clearly visible in early lunar images (Greeley, 1969). Mars lava tubes have been considered to have great potential as habitat and greenhouse structures (Frederick, 1999; Boston, 1996; Walden et al., 1988). Recent MOC data now shows clear evidence of large tubes visible in a number of volcanic regions on Mars (Figure 1).

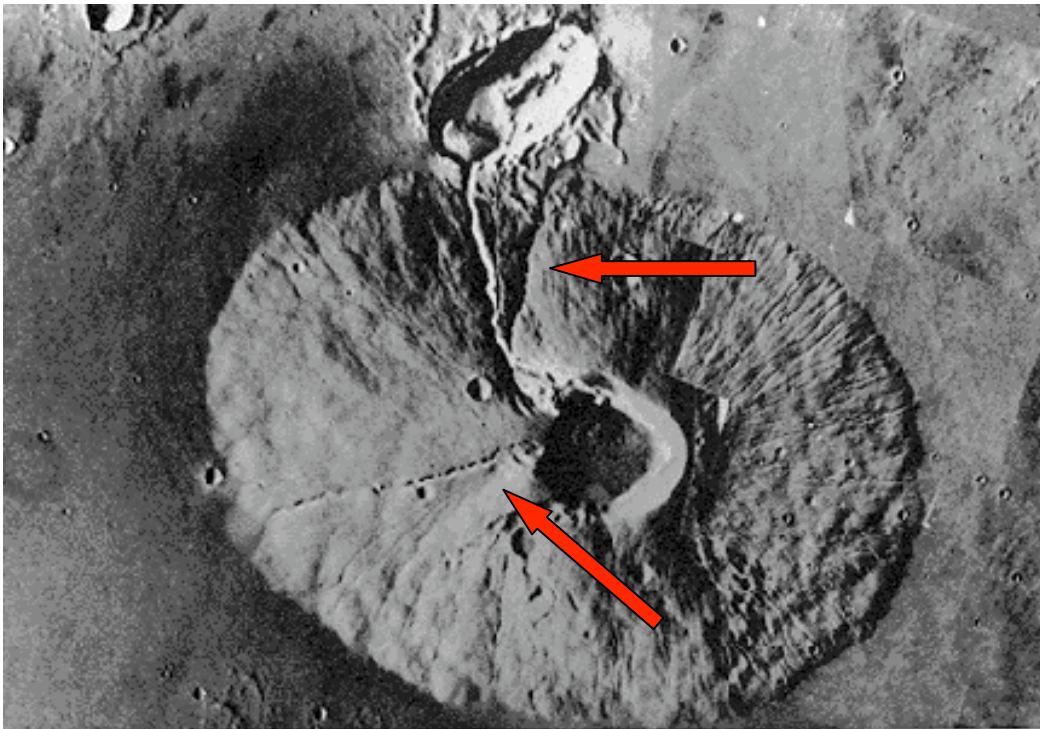


Figure 1: Ceraunius Patera. Large Martian volcano showing distinct lavatubes flowing down its surface. Upper tube drains into an apparent lava lake at bottom. Lower tube shows series of collapse pits along the length of the tube. NASA Malin Space Systems image.

In future exploration of Mars and possibly other rocky bodies in our solar system, caves may provide a natural “pressure vessel” for the construction of subsurface habitats. As prime real estate, they offer several valuable features: 1) protection from ionizing and ultraviolet radiation, 2) insulation from thermal oscillations, 3) protection from impacting objects, 4) sealability to contain a higher than ambient atmospheric pressure, and 5) access to potentially important subsurface resources, e.g. geothermal energy sources, water, reduced gases, and minerals. Thus, for scientific study, human survival, and resource extraction purposes, the subsurface is a target of interest on Mars.

C. Extraterrestrial Caves – Do they exist?

Contrary to popular belief and the advertisements of tourist caverns, on Earth caves are not rare! They are a globally distributed geological phenomenon that occurs in every major rock type and even in polar and high altitude ices. On any planet with a surface that has an internal or external source of energy, there will be cracks in that surface. Those cracks form the basis for cave formation by a variety of terrestrial and non-terrestrial mechanisms from simple tectonic caves to highly complex solutional structures. Additional cave types are produced by melting within a solid as in the case of ices and lavas.

The status of caves on other planets in our Solar System is unclear pending future missions that could detect them, however, the basic physical and chemical processes that produce many of the cave types on Earth have counterparts on other bodies (Boston, 2003). Thus, we expect caves to be widely distributed on many other planets. In particular, the Moon and Mars show clear evidence of lava tube caves (Figure 2).

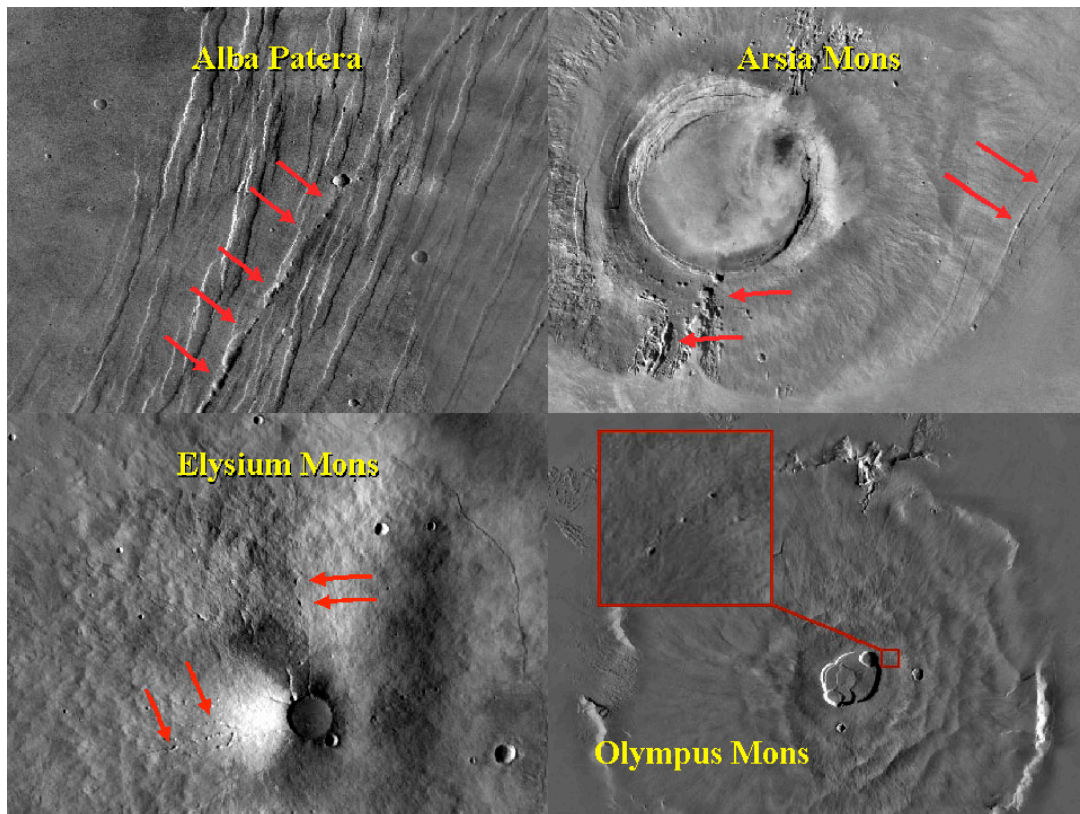


Figure 2: Lava tubes on Mars. Recent MOC data now shows clear evidence of large tubes visible in a number of volcanic regions on Mars (arrows).

The heat flow from the planetary interior drives the type of plate tectonics that we have on Earth, thus resulting in faulting and other motions that create cracks. In lower heat flow cases, like Mars where little or no plate tectonics apparently exists, cracking of the surface results from impact cratering and the types of faulting, slumping, and flow features that are seen on Mars. On icy

planets like Europa and Saturn's moon Titan, the formation of ice caves analogous to those on Earth but more permanent because of the temperature regime is a reasonable expectation. On bodies with volcanic activity, lava tubes and bubbles can be anticipated. Indeed, there is morphological evidence of these features on the moon, Mars, and Venus. On bodies like Io, i.e. in close proximity to gigantic Jovian planets, tidal flexure causes the volcanism itself and could produce lava tube features and perhaps other tectonic cave types.

Although the presence of carbonates has not yet been detected on Mars, there are reasons to predict its presence (Nedell et al., 1987; McKay and Nedell, 1988) and MER rover data implies at least extensive evaporites. Abundant evidence of water-created features exists on Mars (e.g. Malin and Edgett, 2000; Carr and Wanke, 1992; McKay et al., 1992) and recent detection of subsurface hydrogen probably associated with water has been reported (Boynton et al., 2002; Feldman et al., 2002). Ice-created features have also been explored (Squyres et al., 1987 and 1992). Where cracks have been formed in the Martian surface, fluid flow will dissolve at least some of the material depending upon chemistries of the solids and liquids involved. Mechanisms for cave formation on Mars may differ from Earth providing a variety of new features not found here (Grin et al., 1998, 1999; Boston, 2002a, b). The intriguing possibilities for many different kinds of caves are summarized in Table 1.

Table 1 – Cave Types

Site Type	Possible Parent Materials	Possible Formation Mechanisms	Possible Unique Martian Mechanisms
Solutional Caves	Limestone, dolomite, gypsum	Weak carbonic acid (groundwater or rain and dissolved CO ₂)	Liquid carbon dioxide as a solvent?
	Limestone, dolomite, gypsum	Strong sulfuric acid (subsurface H ₂ S dissolving at the water table)	Sulfur-rich crustal materials may make this type of cave more common?
	Quartzite, sandstone, opalinized silicates	Water dissolution	Liquid carbon dioxide as a solvent?
Melt Formation Caves			
Lava tubes or bubbles	Basalt, andesite	Molten rock with differential cooling	Scale of tubes larger than Earth
Glacier caves	Ice masses	Thermal and pressure-induced localized melting in water ice	Melting in carbon dioxide ice and super-cool water ice
	Subice volcanic caves	Lava/ice or lava/permafrost interactions	Lava interactions with CO ₂ ice or ice-clathrate interactions, sublimation of ground ices
	Subsidence caves	None known for Earth	Ground ice sapping and subsequent collapse
Fracture Caves	Solid rock	Faulting	Cratering and fracturing?
		Mass wasting	Cratering and mass wasting?
Erosional Caves			
Sea caves	Solid rock, welded tuff	Water action (waves, floods)	Massive flood events?
Wind-scoured caves	Solid rock, welded tuff	Wind blasting abrasive particles	Global or regional dust storms?
Canyon rock shelters	Solid rock, welded tuff	Data modified from Boston et al.,	2001b; Boston, 2002a, b.

D. Desirable Cave Properties

Caves on Earth differ vastly in their properties. We believe that the evidence suggests that this will also be the case on Mars, the Moon and other planets. Combinations of these various features make some caves suitable for some uses while not appropriate for others. We have developed checklists of properties required or desirable for various uses (Table II).

Table II – Comparison of Various Subsurface Environments

Subsurface Site Type	Scientific Value	Potential Resources	Habitat Protection	Construction Labor Req's	Accessibility
Lava tubes, open	high	minerals	high	sealing	requires discovery
Lava tubes, closed	high	ices, gases, minerals	high	opening, sealing	requires discovery
Solutional caves, open	high	minerals	high	sealing	requires discovery
Solutional cavities, closed	high	ices, gases, minerals	high	opening, sealing	requires discovery
Tunnels	possible	ices, minerals	high	massive drilling, excavation, sealing	requires access to canyons or mountains
Subice structures	possible	ices, gases	depth-dependent	drilling, melting, stabilization	requires polar locale
Natural overhangs	high	minerals	some	major construction, sealing	requires access to canyons or mountains
Created overhangs	possible	minerals	some	major drilling, excavation, sealing	requires access to canyons or mountains
Bermed structures	minimal	unlikely	some	major excavation, Earth movement, stabilization	excellent siting by design

Caves of scientific interest have a high probability of interesting geological and biological features, e.g. extreme age, isolation from the surface, evidence of gases or water. They must be big enough for instrumentation, microrobotic access, or drilling into but not necessarily for humans. Caves of all depths may be scientifically interesting, but very deep caves may be the most interesting for stratigraphy, mineralogy, geomorphology, and life detection. Caves without natural openings are highly desirable because of superior preservation of the contents. Certainly caves in or near geologically or hydrothermally active areas would be of great interest to many scientific disciplines.

In contrast, the caves most suitable for human habitation will be shallow, easily accessible, and relatively horizontal. Obviously, large spacious rooms and passages with smooth walls and floors are highly desirable. Geological stability and formation in relatively impermeable materials will provide safety and a degree of sealing against gas losses from habitat leaks. Natural openings are convenient but not essential as drilling can provide access. Location within a lower area like a canyon or a crater could provide additional protection from

some surface conditions like large dust storms and a slightly higher ambient atmospheric pressure.

Resource-providing caves obviously must contain minerals, volatiles, or other assets. They must provide nearer proximity than surface drilling and mining would afford. They could be used as storage space for geothermal fluids, volatiles, and raw materials. Caves with natural openings would be more convenient, but volatile-containing caves will have to be naturally or artificially sealed. Geothermal activity within caves could be a source of power. Low permeability parent material would allow for filling the cave with inert gases compressed from the Mars atmosphere, thus allowing a “shirt-sleeve” environment with only oxygen breathing gear.

E. Are Earth Caves Good Extraterrestrial Analogs?

Which features of Earth caves can serve as reasonable representations of Mars and other planets and which features cannot be modeled on Earth? What are the relevant variables and the non-relevant variables between Earth caves and those caves found elsewhere? Clearly, the different gravitational constants of other planets are impossible to simulate in terrestrial caves. Indeed, we have not successfully simulated those fractional gravities experimentally anywhere yet. Plans for life-science relevant Mars and Moon gravity experiments via centrifugation aboard the International Space Station have been suggested, but are not scheduled for the near-term ISS period.

The unusual gases (H_2S , CO_2 , CO , NH_3 , and others) contained in the air of some Earth caves present the opportunity to practice protection from and management of poisonous or deleterious atmospheres. The condition of no or little atmosphere is not easily simulated in Earth caves, of course. Conceivably, any caves existing at extremely high altitudes in the Andes or the Himalayas could provide a partial simulation but other logistics probably make it too difficult to be worth the effort involved. However, some caves are depleted in oxygen or heavily laden with toxic gases, thus requiring full breathing gear for investigators (Hose et al., 2000).

The greatest similarity between terrestrial caves and those of other planets exists in the realm of operational considerations within the confines and topography of caves. That is, the very experience of living, working, doing science, and extracting resources in the lightless and potentially hazardous cave environment *is* the primary value of the Earth cave analog. This particularly extends to matters of planetary protection. The minute a human investigator enters a cave on Earth, the potential exists for deleterious impact on the indigenous biota (Boston, 1999a & b; Moser and Boston, 2001). But unlike the way that we deal with extreme biocontainment in the laboratory, in the cave environment investigators must deal with a difficult and dangerous environment and still accomplish their goals while simultaneously protecting the biota.

III. Enabling Technologies Identification

A. Phase I Review

Our Phase I NIAC report identified a number of enabling technologies that we believe are critical to the future success of any use of caves on Mars or beyond (Table III).

Table III: Innovations Unique to Phase I

Innovation	Application	Current TRL*
*Caves as extraterrestrial science targets	Science & Exploration	2
*Earth cave technology test beds	Science, Human Exploration & Colonization	4
*Planetary protection issues in caves	Science, Planetary Protection Protocol Development	4
*Self-deploying, microrobotic incave communication system	Science, Exploration, Human Habitation, & Resource Use	3
*Foamed-in-place airlocks	Human Habitation & Resource Use	4
*Inflatable cave liners with sensing/regulating properties	Human Habitation, Science & Resource Use	5
Inert gas pressurization of caves	Human Habitation, Resource Use & possibly Science	2
*Breathable inert gas mixtures	Human Habitation & Colonization	2
*Bioluminescence/oxygen system	Human Life Support	2
Exploitation of trapped cave volatiles	Human Colonization & Resource Use	4
Homosymbionts	Human Colonization	1
Micromining via bioinjection/nano-injection	Human Colonization & Resource Use	1

- TRL = Technology Readiness Level

Table III: Our Phase I NIAC study (Scientific Exploration and Human Utilization of Subsurface Extraterrestrial Environments: A Feasibility Assessment of Strategies, Technologies and Test Beds, NIAC CP 99-03, Phase I - # 07600-045) explored a complete set of concepts necessary for the scientific exploration and study of Mars caves, requirements for the human use of extraterrestrial caves as habitat, and for the exploitation of these caves as resource providers.

B. Phase II Summary

The enabling technologies deemed worthy of further exploration and potential experimentation in Phase II included:

Habitat Issues:

- Inflatable cave liners
- Foamed in place airlocks
- Inert gas pressurization
- Mars-derived breathing mix
- Bioregenerative systems (unique cave aspects)
- Bioluminescence/O₂ light-piping system

Science Issues:

- Self-deploying microrobots
 - Communication system
 - Automated mapping
 - Biologically sensitive sites
- Cave science “backpack”
- Non-invasive sampling and analysis techniques
- Planetary protection protocol development

IV. Essential Tasks Identification

A. Finding ET Caves

We did not specifically try to develop any totally new ideas for cave detection, but we did assess those techniques that can provide information on possible cave location. The spectrum of possibilities include: orbital reconnaissance, aerial reconnaissance, geophysical methods (e.g. ground-penetrating radar, seismic techniques, microgravity anomaly mapping, etc.), locating of outgassing sources possibly indicative of subsurface access, situational (i.e. geological settings conducive to subsurface cavity formation), specific onsite tools for exploration, use of microrobots (expendable, simple, and numerous) self-deploying communication systems, and robotic mapping networks. Fortunately, direct orbital imaging has already shown us lava tubes on Mars and the Moon (see Figures 1 and 2). Predicting possible caves along fracture zones and other geological features from orbitally-derived maps and images is a research project that we have embarked on separately from this study in collaboration with Dr. James Dohm at the Univ. Arizona, Tucson. Robotic and human explorers may also be able to find caves the way they traditionally have been found on Earth...by coming across them in the course of other missions.

Additional related subprojects that have resulted from this work, while incurring little or no costs in time or money from the Phase II project, included

development of a glider reconnaissance prototype for future Mars aerial cave detection (in collaboration with EISI in Denver), collaboration on robotic cave mapping techniques using a 3D Lidar Scanner system from Cyrex Company, and collaboration with UTD in Arlington, VA on a low resistive force drilling concept for low power robotic or human operation on the Martian surface. The most recent effort is a collaboration with Mr. David Bushman at NASA Dryden Flight Center to develop orbital geophysical techniques for subsurface void detection.

Our remote geophysical tool of choice is one that is being utilized in existing planetary missions. It is called Ground Penetrating Radar (GPR). This is a non-invasive technique for imaging the shallow and midrange subsurface materials and features (Conyers and Goodman, 1997; Doolittle, 1982; Duke, 1990; Huffman, 1992). It employs pulses of ultra high frequency radio waves in the microwave range (300 to 1,000 Mhz) transmitted to the ground through a transducer for depths to about 10 meters with high resolution. For deep GPR, low frequency antennae are used (25 to 200 Mhz) with a poorer resolution. The wavelengths transmitted are reflected differentially depending upon the nature of the materials encountered, specifically of differing electrical conductivities and dielectric constants (Keller, 1987; Olhoeft, 1979; Wright et al., 1996). Returning waves are received by the same antenna. The reflections are compared against the two way travel time, amplified, and plotted. High conductivity materials (e.g. shales, clay, etc.) can only be imaged up to about a meter. Low conductivity materials like granites or dry particulates can be imaged up to 30 meters under favorable conditions. As the surfaces of Mars and the Moon surface are extraordinarily dry, we believe that “seeing” through the upper dry layers should be relatively easy to do. Both 2D and 3D imaging is now commonly done even with small and inexpensive hand units that are typically dragged behind the operator and literally hundreds of square meters can be scanned in a day.

The electrical and magnetic properties of rocks, soils and fluids control the speed of propagation of radar waves and their amplitudes. In most cases, the electrical properties are much more important than the magnetic properties. At radar frequencies, electrical properties are dominantly controlled by rock or soil density, and by the chemistry, state (liquid/gas/solid), distribution (pore space connectivity) and content of water. The electrical properties of the surface of other planets have been a subject of great interest (Kolecki and Landis, 1996; Olhoeft, 1991) and the electrical properties of water in lunar regolith (Olhoeft, 1976). GPR has been suggested for use on Mars (c.f., Olhoeft, 1998). Distinctive signal can distinguish between permafrost (Olhoeft, 1975, 1977; Wong et al, 1977), structures in sand dunes (Schaber et al., 1986; Shenk et al., 1993), organics (Olhoeft, 1986), and oxide minerals (Lindsley, 1991) that we have studied as part of biogenic cave deposits (Boston et al., 2001a).

Currently small off-the-shelf GPR units are already available for rent or sale primarily to industry users (e.g. GeoModel, Inc., GPRS, Inc., GRORADAR™, Enviroprobe Service, Inc., NGPRS Inc., Geophysical Survey Systems, Inc.).

Spacecraft worthy versions are available but may not yet have the resolution that we would need for an orbital deployment for cave detection. However, the idea of an aerial platform like an airplane, glider, or balloon that could put such an instrument within relatively close proximity of the surface is a strong contender as best present technological solution for subsurface void detection.

B. Facilitating ET Cave Science

A laboratory in a briefcase has long been a fond wish of science fiction writers. We all want a *tricorder* (*in sensu Star Trek*) that we can point in the direction of the latest inexplicable phenomenon and get a complete readout of exactly what is going on. While we are still far from this goal, we do have both the need and the potential to develop much more effective, non-invasive, microminiaturized instrumentation for use in harsh environments. For example, DNA analysis on-a-chip technology is becoming a reality (Ehrlich and Matsudaira, 1999). The use of minimal impact, non-invasive analysis is critical for successful robotic missions into caves and desirable for human missions. We envision the development of a biological minilab that is easily transported and useful for a variety of chemical and geological tasks.

For the upcoming HUMIS mission trial (see below), this component will be kept very simple for the Speleonaut activities. We could not truly construct a Lab-in-a-box within the scope of this project, however, a compact and easily used Science Kit has been assembled with temperature, humidity, ion selective electrodes for gas sensing, and simple culturing and sampling equipment for later DNA analyses. Limited incave scientific analysis is scheduled for the Speleonaut mission, e.g. optical microscopy, simple staining and chemical tests, etc.

C. Dealing with the Dark: “Externalized Technologies” for Lighting and Photosynthesis

One of the major challenges with contemplating a subsurface lifestyle for future astronauts is the provision of light for both human use and for photosynthetic use for life support related plants. Of course, this is also a problem with properly shielded, bermed, and other surface habitat strategies. We have not addressed issues of power as they are extremely complex and beyond the scope of this project, however, we are sensitized to the difficulties involved. We have surveyed the available technologies for lighting and have conceptually developed an additional novel idea that we were unable to pursue further in this study. The notion that binds all of these options together we have come to call “externalized technology” to mean that it can take place outside of the subsurface habitat space itself up on the surface or through a skylight or drillhole. We briefly describe these below.

Many of the lighting and heating needs for a cave-based habitat could be provided by the recent explosion of developments in light-mining and light-piping techniques (e.g. Swift and Smith, 1995). These methods rely on some way of collecting sunlight via a reflective surface, possibly passing that light through concentrators, and then using either optical fibers or hollow light guides to direct the photons where they are desired. Invented over 120 years ago, but not practical at the time due to the weight and expense of conventional glass mirrors, new materials have propelled this area of photon management into a renaissance. Of course, technical problems that might render such things infeasible include difficulty of keeping collecting surfaces on the exterior free of clinging fine particles, difficulties of dealing with large thermal gradients between the surface and light piping structure and the interior habitat, and meteorological conditions like the periodic massive (often global) dust storms that may unacceptably further attenuate the already reduced sunlight (~40% of Earth's intensity at the top of the atmosphere). Nevertheless, we believe that innovative use of such technologies for the ET cave applications are still worth evaluation.

The simplest cases of direct photon use, natural skylights, are a possibility in shallow caves. Artificial skylights could also be cut into shallowly located caves. Transparent skylight materials would have to be ultraviolet resistant and readily available materials would not provide shielding from the ionizing radiation in the Mars environment. However, if skylights were located in semi-protected areas, e.g. under overhangs, rock shelters, or in canyon or crater walls, then they would receive diffuse visible light with much less direct ionizing radiation input. The biggest difficulty would likely be the huge temperature difference between inside and outside necessitating extremely effective insulation properties of such skylights.

Much of the success of the types of schemes described here lay in advances in material science. Military research is producing radiation resistant coatings for transparent components of battle vehicles and extremely resilient transparent armor materials. For example, ALON (aluminum oxynitride) and magnesium aluminate spinel are ultra hard (4 times greater than glass), transparent armor materials. ALON is being developed by Raytheon Corp. and is already commercially available. Other companies and research groups are creating special coatings that resist UV, IR, and ionizing radiation all in the warfare context that will be available commercially within the next decade.

Because the space available for habitation within the cave does not have access to direct solar lighting and to minimize the space used for non-human uses, we have considered other alternatives to interior artificial or harvested lighting. Natural or created skylights or access shafts can also provide access to the surface where individual plant growth modules can be deployed, an idea advanced by Jim Clawson at Bioserve Inc., Boulder, CO (pers. comm.) Such sealed, self sufficient photosynthetic units could be deployed on the surface and then robotically returned through a skylight or shaft for harvest, replenishment

and replanting. Although even with radiation resistant plants, their genetic material might be adversely affected by intense radiation, seed stock plants could be grown inside the cave habitat area to protect it while the food production plants could be subject to mutagenic levels of radiation as their endpoint is consumption as food rather than as perpetuators of their line. While there is variability in the light intensities that plants utilize as well as the ultraviolet radiation levels that they can tolerate, providing the tailored wavelengths specific to individual crops has been long suggested and can be done relatively easily with light piping through wavelength selective optical fibers or the like.

Besides light provision technologies, the same idea of “externalized technologies” (i.e. things that can be done outside of the cave on the surface) can also include solar panels and other surface functions like extraction of Mars atmosphere to make breathable air and mining the atmosphere or near surface for water. These features can be in proximity to the habitats without taking up valuable interior habitat real estate. The close proximity facilitates routine maintenance, plant-tending activities, and especially response times in emergency situations.

The most innovative and risky notion that we suggested first during the Phase I of this project is a bioluminescent light and oxygen generation system. Such a system would employ photosynthetic organisms in surface mounted batch chambers to produce and sequester biomass and liberate oxygen. That oxygen would then be sent through a tubing system to the incave area for reaction with naturally bioluminescent microorganisms or with a hybrid materials-mounted luciferin/luciferase system. The low bioluminescent light levels emitted from the bacteria or enzyme couplet through transparent tubing could provide overall wall glow in critical habitat areas that should not be allowed to go dark. It would serve as a backup system against the failure of higher intensity lighting systems, and the net biomass could be harvested for use in producing a wide variety of products. Excess oxygen produced by the photosynthetic module could be shunted into the breathing gas preparation facility to contribute to the overall habitat oxygen supply.

We had no time to pursue this, however we did devise a very simple benchtop model of such a bioluminescent, photosynthetic O₂-generating system. In our design, luminescent bacteria (*Vibrio fischerii*) will be combined in a liquid nutrient chamber in the dark. This will be coupled with a liquid nutrient chamber in which photosynthetic cyanobacteria and algae in mixed culture are housed in the sunlight either directly through surface units or with artificially mined and mixed irradiance. A series of small pumps will circulate the nutrients and gases between the two chambers but organisms will be prevented from crossing chambers by a series of micropore and fritted glass filtration units. A small current will be switched on in the dark *Vibrio* chamber to stimulate bioluminescent output by the bacteria. Perhaps someday, such a system may be attempted.

D. Cave Life Support

Current mission scenarios for human exploration of Mars are numerous and quite nebulous on several critical points. The idea of constructing habitats on the Martian surface has been discussed scientifically and in literature for most of the past century. Typically involving surface construction, the highly damaging ionizing radiation has been assumed to be soluble by some combination of radiation shielding and possibly pharmacological amelioration. However, the cumbersome nature of radiation shielding, its labor-intensive construction and requirement for heavy equipment, and the absence of any medical panaceas against radiation damage make human Mars missions still unreachable in the minds of many mission planners. The caves can provide the two most important ingredients: first, a significant shield against ionizing radiation and secondly, a pressure vessel shell that can be modified to hold a breathable atmosphere. In response to the critical nature of these two features provided by caves, the biggest area of activity for this project was in the general area of “Life Support”. All of the technology demonstrations described below come under this rubric.

V. Demonstration Missions

Our original conceptual framework for systematically exploring our enabling technology list was a test of various technology components using mice (*Mouse Mission to Inner Space, MOMIS*) to be followed by a full-scale trial using humans (*Human Mission to Inner Space, HUMIS*). The demonstrations that we planned called for the subscale phase to also function as an educational and outreach focal point. During the several years of this project, we completed the first mission by way largely of limited duration incave testing of individual and combined technology demonstrations involving a number of different mice that we named “Moustronauts”. The second mission is still underway as of this report because of its complexity, the extra safety issues when human volunteer-participants are involved, and vagaries in access to the selected test caves due to weather events and unpredictable bat closures. Lost Cave was flooded in May in a storm event that set new 24 hour rainfall records in 130 years of recorded history of the area thus aborting our upcoming test.

A. Mouse Mission to Inner Space (MOMIS)

Particularly because of its appeal for educational outreach, we have developed a preliminary version of some aspects of a Mars cave habitat using mice in small, contained habitat units. Aside from allowing us to test some of our notions, e.g. the idea of using argon gas in breathing mixtures because of its relative simplicity of acquisition from the Martian atmosphere, the Mouse Mission to Inner Space has proven to be highly popular with educators and the press. We have leveraged this interest into a number of educational spin-offs that have required minimal input on our part but have resulted in two active high school

projects, two science fair projects and associated press attention and broadcast media.

B. Human Mission to Inner Space (HUMIS)

At the mid-contract site review in Bend, Oregon, concern was expressed that actual implementation of the human field demonstration might prove to be infeasible or too costly in both money and investigator time. Admittedly, it has been massively time-consuming, complex, and difficult. However, we believe that much of the cooperation that we have received from federal managerial agencies (e.g. Carlsbad Caverns National Park, USDA Forest Service, Bureau of Land Management, etc.) has been prompted with their fascination with our field demonstration projects. Additionally, we have received numerous contributions of assistance and equipment from other organizations and individuals to whom the field demonstration concept has appealed. The other aspect that justified proceeding with at least some of the activities involved in the field demonstrations, was the tremendous potential for educational and public outreach. A massive technical report, no matter how well-written it may be, is not appealing to the public or to school children or the press. We have tried to strike a useful balance between the demonstration efforts and the technical development portions of the project. The inspirational value of the HUMIS component can be seen in the fact that a cave astrobiology exploration college level class at Penn State under their Space University program was modeled after our efforts and was mentored by us during the Spring Semester of 2004.

HUMIS is currently still under development and trials are rescheduled for implementation during mid-fall of 2004 into early 2005.

C. System Integration

Extensive research has already been done to define the requirements and technology elements necessary for self-sustaining outposts on Mars (e.g. Stoker and Emmart, 1996), much of which is directly applicable to cave habitats. In this project, we have developed a baseline conceptual infrastructure model for a Mars cave habitat and life support system taking into account the unique requirements, assets and constraints imposed by the use of caves. This model can be used to define interface boundaries for system mass and energy flows and environmental control to allow the development of a simulator in an Earth cave to be used as a total system demonstration of the overall architecture of missions performing science and exploration including resource extraction and life detection experiments.

The components of a real Mars Cave Life Support System model (MCLSS) would include a crew-deployable, inflatable habitat with airlock, an inflatable greenhouse module with airlock, and primary systems for the production of oxygen, buffer gas, water and energy storage compounds from Mars resources. Subsystems will include, temperature and humidity control, CO₂

removal, recycling of urine and wash water, solid waste management, fire detection and suppression, trace contaminant control, and energy storage and heating.

The Earth cave feasibility demonstrator has been designed to at least approximate the mass flows predicted by the baseline Mars cave habitat model, but will use prepared gas and water sources and externally supplied power. Urine and wash water cannot currently be recycled in the simulator so will be piped out and solid wastes will be stored and packed out. Solid waste management for Mars cave habitats will undoubtedly utilize insulated microbial digesters similar to septic tanks or composting toilets on Earth but with wastewater recycling and recycling of solids for use in the greenhouse. No provision has been made for solid waste processing in the Earth cave demonstrator except for mass flow accounting of the water content and solids packed out. Possible benchtop development of an engineering scheme for reducing volume of urine to sludge for cave use previously suggested by Thompson and Boston (1997) is being pursued in a joint project between the National Park Service and our laboratory as the subject of an undergraduate Honors Thesis in the Chemical Engineering Program at New Mexico Tech. where the PI of this project is a professor.

The Earth cave demonstrator will be operated in several caves (described below). One of these contains a poisonous atmosphere consisting of high concentrations of carbon dioxide gas, therefore crew members must either remain inside the habitat or use breathing gear when working outside the habitat elsewhere in the cave as a reasonable simulation of the deadly nature of the Mars environment.

For the HUMIS mission, “Ground Control” consisting of generators, gas, humidity, temperature and barometric pressure monitors, associated computers, and physiological monitoring capabilities (e.g blood pressure and heart rate instruments) will be attended continuously during simulations. Live video imaging and recording will take place throughout the duration of the speleonaut tenure in the caves. Continuous voice communication capability will be maintained.

D. Cave Test Sites

During this project we have conducted tests in a number of caves and will be using several more as we complete the HUMIS mission. These caves are briefly described below.

Lost Cave, NM: We obtained permission from Jim Goodbar, Cave Specialist for the Carlsbad area Bureau of Land Management, to use Lost Cave at the edge of the city of Carlsbad as the site for our initial human habitat tests. This cave offers relatively easy access with no public visitation and is allowing us

to refine our habitat system and incave human protocols in an environment where we can easily access supplies, equipment, and other development needs as we conduct the testing. Another factor is the benign gas environment that avoids the hazardous CO₂ rich air of HM Cave during the testing and proofing phase. This cave also has an interesting history as it was used in a human isolation experiment conducted by a German team in the mid 1990's. The human subject was confined in the cave for a period of 6 months to study her responses to isolation and disruption of normal Circadian rhythms. This cave was badly flooded in spring of 2004 and it remains to be seen whether it will be accessible in the near future for our HUMIS trials.

HM Cave, Arizona: HM Cave in the Payson region of Arizona, was accidentally discovered during survey and test drilling preparatory to road building. It is under USDA Forest Service management. The project engineer realized that cavity had been penetrated, halted work, and called in the forest service cave resources manager, Jerry Trout. Mr. Trout then contacted us because he is familiar with our studies of microorganisms in caves and extreme environment work.

This cave is particularly suited for a Mars cave simulation and is our goal for the final test phase of our HUMIS mission. The atmosphere has been measured to have around 7% CO₂ and requires full breathing gear. The partial pressure of 7% carbon dioxide at that altitude is approximately 60 millibars. The partial pressure of CO₂ on Mars, assuming a mean global average of 7 millibars, is 6.7 millibars although it constitutes the bulk of the Martian atmosphere (95%). We did not directly measure the oxygen content of HM Cave but it has been reported by the others to have been a few percent below the atmospheric nominal 20.9%.

Since its discovery, it has been sealed by an iron tube and airlock arrangement, then buried under several feet of dirt and forest floor litter for concealment. We have accessed it only once for sample acquisition and reconnaissance in the immediate vicinity of the 20 ft. deep entry culvert. Two other scout parties have visited for mapping purposes associated with diverting the plans for road-building away from the cave.

The cave entrance is away from the main public thoroughfare but yet close enough to roads to simplify logistics involved with any simulation. Other than the initial limited entries by initial teams, the cave is entirely unexplored. This is a good feature for a simulation for exploring and outfitting a habitat cave on Mars.

Lavatubes, New Mexico and Oregon: Lavatube caves located at El Malpais National Monument, NM and near Silverton, OR have been used for MOMIS mouse mission work and for habitat simulation of individual technology components. We are conducting scientific work at the NM site and have good relationships with the National Park Service office that manages this monument. The Oregon caves have been used as lunar habitat simulations headed by the Oregon L5 Society in the late 1980's and are available through contacts of NIAC team member, R.D. Frederick. Some tubes are more suitable than others due to

logistical considerations, distance from road access, relative smoothness of interior surfaces, size and configuration. Presently, we know of no lavatube caves that are sealed and containing non-atmospheric air compositions, but are alert to any possibilities.

La Cueva de las Barrancas, NM: This deep cave (320 ft. entrance rappel) in the Guadalupe Mts. of southeastern New Mexico is the clear choice for a Mars cave science simulation and we have used it to develop protocols for dealing with biologically sensitive materials. It is pristine, large, complex and possesses many geological and microbiological sites of interest including tiny pools, moist flowstone, moonmilk, fungal filaments on speleothems, unique mud formations resembling miniature villages of onion ziggurats and pagodas, at least one detection of H₂S coming from deeper levels of the cave, and more. And this is all found within the few hundred feet that we have so far explored!

One of the primary foci of this Phase II work has revolved around the self-deploying robotic communication system. This system has tremendous potential for caves and mines on Earth as well as extraterrestrial applications. Commercial markets for such systems exist in private, military, academic, government agency, and recreational areas. We have addressed the communication issues solely as the robotic devices upon which we imagine such a system would be mounted are outside of the scope of this project. Microrobots suitable for this type of application were inspired by an earlier funded NIAC Phase I study (Dubowsky, 2000) and our requirements expressed in this study also led to another recently completed NIAC Phase I study (Dubowsky and Boston, 2004). We have acted in the capacity of surrogate microrobots and hand deployed the units in Barrancas and other selected caves for test purposes.

Cueva de las Barrancas is officially reserved for science in a signed agreement between the USDA Forest Service, the cave's discoverer (Cave of Mars NIAC team member Jim Werker), and the science investigation team (P.J. Boston, PI). The management plan (Werker and Werker, 1997) calls for complete control of activities within the cave and all necessary precautions to maintain its biologically uncompromised status.

Lava Tubes on Mars (requested images): Malin Space Sciences received our requests for specific, high resolution Mars lava tube images and produced two special images for us. In the late summer of 2003, Malin Space Science Systems, (MSSS) Added a section to their Website requesting targets of Mars from the public. Certain restrictions were applied, both scientific and logistic. Only the narrow angle camera was available, and only sites not previously imaged were to be considered. And of course, a good scientific reason for the acquisition was required.

We made a total of five target requests on two different occasions. Both were on Olympus-Mons, and both were imaged before with lower resolution instruments. In November and again in May, the MOC Imaging Team informed us that they acquired two of our requested images (below). These two frames and their

context images are also being integrated into the Caves of Mars Educational Resource Website as part of the “Find the Lava Tube” activity, and we will use one of them as the main photo on the COM Poster (see Education and Outreach section, below).



Figure 3: The first strip, MOC R11-02729 shows details of a chain of collapse pits near the Northern rim of the giant shield volcano. Also visible are interrupted leveled lava channels, show areas that collapsed, punctuated by sections that did not, and presumably may house lava tube caves. Also visible are odd cloud-like features pointing down slope out of the Northern rims of the larger pits

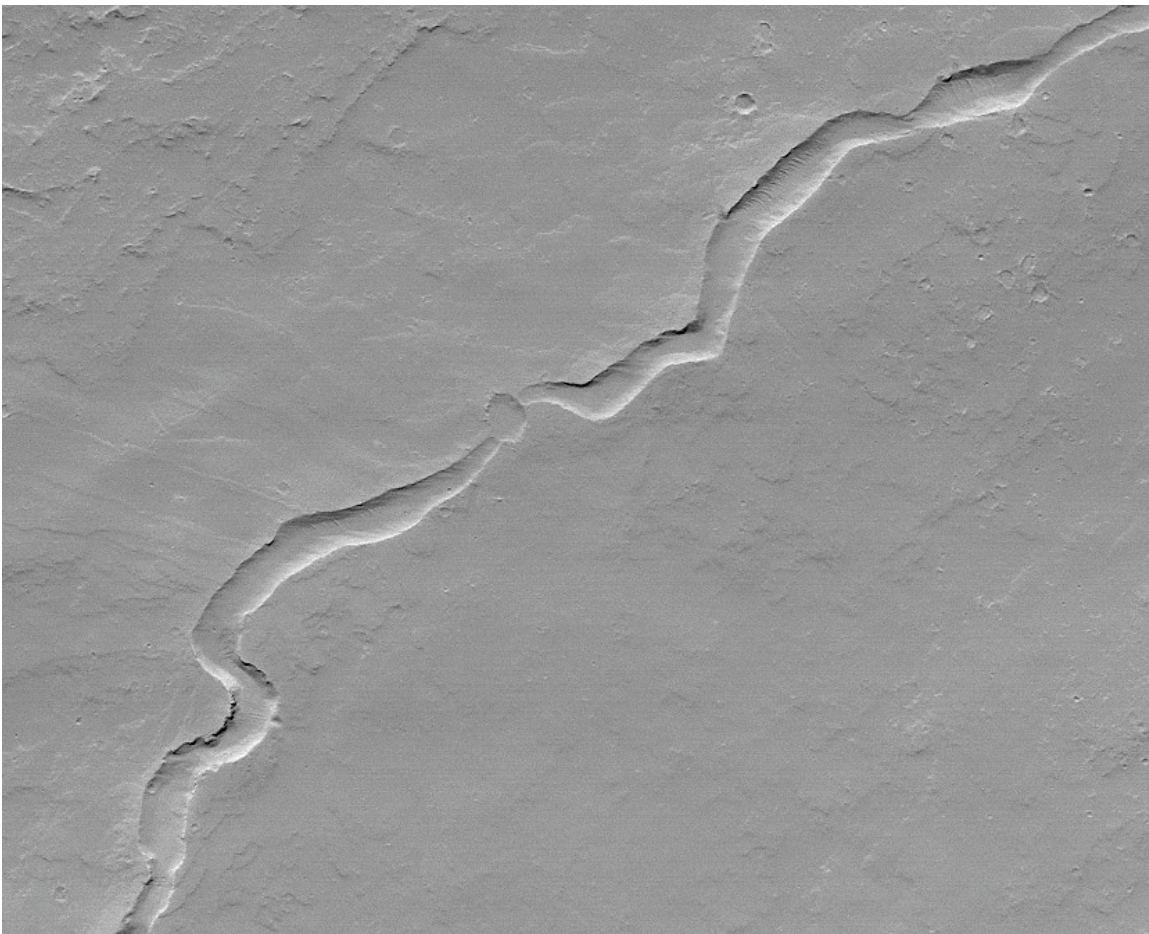


Figure 4: The second strip, MOC R17-02181 was an area imaged earlier by the Mars Odyssey orbiter, of the Eastern flank of Olympus. In the original visible-light THEMIS image, (Frame V01028006), a well-defined leveled channel is visible with several non-collapsed portions. This image “zeros in” what appears to be the eruptive center of this particular flow. The non-collapsed portions are off-frame on either side of the strip. Both strips were shot a 3 meter resolution, and are about three km wide.

VI. Technology Trials

A. Inflatable Habitats

Shirtsleeve indoor environments are desirable for all human habitations on other planets and a cave habitat is no exception. Unique features of the cave environment can be developed further to provide a comfortable shirtsleeve habitat environment. These unique features include the advantage of being able to use non-transparent, inflatable materials to line the cave as an air-containing pressure vessel, specific challenges of fitting airlocks to the variabilities of shape found in natural caves, the need to provide power, and the provision of light via natural sunlight capture and redirection and/or artificial lights.

In work prior to the NIAC Phase I project, we targeted inflatable cave liners as a key technology that could enable extraterrestrial human use of caves (Boston, 2000b). In our NIAC Phase I work, we strengthened this conviction. Additionally, we have developed a series of sophisticated modifications that may be possible as new intelligent textiles, sensing composites, and self-repairing materials become available.

- *Problem:* Create inflatable liners to be placed in natural caves to make them sealable pressure vessels for habitat, workspace, and life support enclosures.
- *Constraints:* Must be easily deployed, lightweight and low bulk, easily replaced, easily repaired, and robust under abrasion and puncture conditions.
- *Proposed solution:* Because cave habitats do not have to hold interior pressure against the near vacuum of the Mars surface atmosphere, they are much more amenable to lining with inflatable structures than freestanding surface structures. The cave itself provides the primary containment strength. The liner serves merely to provide an airtight sealing layer to prevent leakage through cracks, fissures, and any pore spaces that may be in the parent rock of the cave. Additionally, liners will provide a “friendlier” surface than bare rock can provide. Inflatable structures are ideal for this use because they can be topologically simple yet moldable to the complex surfaces found in caves. They are lightweight and low bulk when constructed with optimized folding patterns like pleating or other non-stressing folds. Inflatable materials can also be replaced by inflation of a new unit inside an old unit without requiring the dismantling of the old structure. It can simply remain on the outside of the new unit, or be removed piecemeal after the new unit’s inflation.

A special design consideration was shape vs. functionality of use. Particularly, a simple cylinder is the easiest to fabricate but concerns about use of this shape in large cave passages where the unit is much smaller and doesn’t touch the walls drove us to a hemi-cylindrical liner shape.

Based on extensive consideration of options that we identified in Phase I, the solution that we actually have settled upon for HUMIS is a very lightweight, flexible, tough inflatable module that is deployable even under difficult real world conditions. As of this writing, the prototype for cave use is being fitted with a drilled plexiglass plate and fittings for the inlets for breathable air, communications, and instrumentation that will be powered from outside sources.

We chose to contract fabrication of the inflatable liner as a custom-made unit from Rader Awning Company in Albuquerque. They have extensive experience with fabrication of inflatable structures (including hot air balloons for the famous Albuquerque Annual Balloon Fiesta) and inflatable special purpose buildings (e.g. those used at Sandia National Labs). They use many fabrication techniques but the method identified to provide the lowest leakage rates for our application is a radio frequency heat-sealing technique. This technique is used on vinyl-coated nylon textiles of various weights. We chose a 7 ounce/square yard fabric which tested well in small scale prototypes. The finished inflatable unit used this material.

The very lightweight fabric chosen for our Earth cave test unit is obviously not the material that would be chosen for a real extraterrestrial module. As in so many of the critical enabling technologies identified in this project, the availability of highly engineered materials will facilitate the implementation of our ideas. The present suite of off-the-shelf materials offers a mixed palette for the construction of in-cave inflatable liners. On the one hand, the need for ultraviolet resistance and resistance to high-velocity impacts coming from micrometeorites is minimized by the protection afforded by the cave itself. On the other hand, abrasion-resistance is important in rock environments both during the installation phase, where considerable mechanical abrasion may occur as liners are maneuvered into position and during daily operations where myriad minute movements within the liners will produce microabrasive events at contact points, 1) between cave and liner exterior and, 2) between liner interior and inhabitants and machinery.

Although we fully realize that new materials are coming online all the time, it is instructive to assess current advanced materials that have some potential for our inflatable habitat applications. Leading candidate materials currently available include Turtleskin © (Warwick Mills) fabricated from Kevlar© and Vectran© fiber and used for the Mars Pathfinder crash bags. In addition, similar materials are being used for airship fabrics. The same manufacturer has created related materials that are waterproof and that are extremely puncture-resistant for critical applications like repelling jabs from needles for biologists working with AIDS or Ebola virus. Weight to strength ratio is very good and abrasion resistance is superior. The Vectran fiber itself is a high-performance thermoplastic multifilament yarn spun from Vectra ® liquid crystal polymer (LCP). Vectran is the only commercially available melt spun LCP fiber yet available. It exhibits exceptional strength and rigidity. It is also five times stronger than steel and ten

times stronger than aluminum on a wt/wt basis. It is highly chemically resistant to acids and alkalis, absorbs very little moisture, possesses a low coefficient of thermal expansion (CTE), has excellent flex/fold characteristics, a high dielectric strength, outstanding vibration damping characteristics, and high impact resistance. Puncture and cut resistance exceed that of all other fibers known. Importantly, Vectran retains all these stellar qualities at both very high and very low temperatures.

B. Airlocks

Airlocks are a critical component of any pressurized structures on Mars or the Moon. The subject of airlocks has consumed much of our attention during this project and undergone numerous revisions. The laundry list of properties that we specifically require for our cave airlocks includes:

- Shape-conforming to highly irregular openings
- Easily deployable, Insulating, leak-tight
- Low thermal expansion
- Easily usable by humans in space suits
- Robust performance under dusty, cold, and ultradry conditions
- Foamed in place rigid, standardized airlock door and frame assembly

We originally envisioned a standardized, rigid airlock door and mount assembly that could be custom-fitted to individual cave openings by means of a moldable, shape-conforming technique and further work convinced us that this was a feasible option with the beauty of relatively easy deployment and limited modification of cave entrances. Based on our initial work, we prefer the relative simplicity of a method that relies on hardening foam to fill in space around the rigid doorframe. The identity of such foam is not clear and present foams used industrially lack many of the desirable properties. Such a foam must possess flexibility, high insulative value, possible but not essential transparency or translucency, and ease of application by hand methods in the cold Martian near-vacuum environment.

In the absence of perfectly suitable foam, two options present themselves. The first is the future development of the foam of our dreams for this application and the second perhaps more realistic option is to look at the possibilities for using the foam as an interim construction technique to emplace the rigid airlock module then to be followed by application of a more permanent material that might not be foam to seal and strengthen the initial installation. Such secondary coating and rigidifying materials can also provide a number of other properties that may be important to the structure, namely: 1) additional insulation value, 2) impregnation with materials that inhibit the growth of fungal and bacterial organisms, 3) coatings with various optical properties, 4) an embedment material for piping to conduct warming geothermal fluids and cooling fluids, and 5) even a medium for optical fibers or other light piping devices that bring natural Martian sunlight into the cave environment. Ideal properties of rigidifying foams, semi-

solids, or plastic materials include retention of limited elasticity to allow for thermal expansion and contraction without cracking. However, even if some cracking occurred, since the original inflatable liner is primarily responsible for atmosphere containment, this should not present an immediately hazardous situation until repairs could be effected.

The final design for Mars and Moon caves that we believe is workable involves a metal or advanced composite doorframe and door assembly with a series of telescoping metal members jutting out around the edge whose length can be easily adjusted to meet the rock wall (Figure 3). The flexibility of such an arrangement to meet the myriad shapes and sizes of natural cave openings is a very attractive feature. These metal members can then be bolted in place and the foam applied to bury them constructing what might be termed “hi-tech aerospace adobe”. This will provide increased strength, rigidity, and a type of “rebar-like” structural support for the foam during soft application and after hardening. At the end of the process, a secondary coating material could be hand daubed, sprayed, or even painted on.

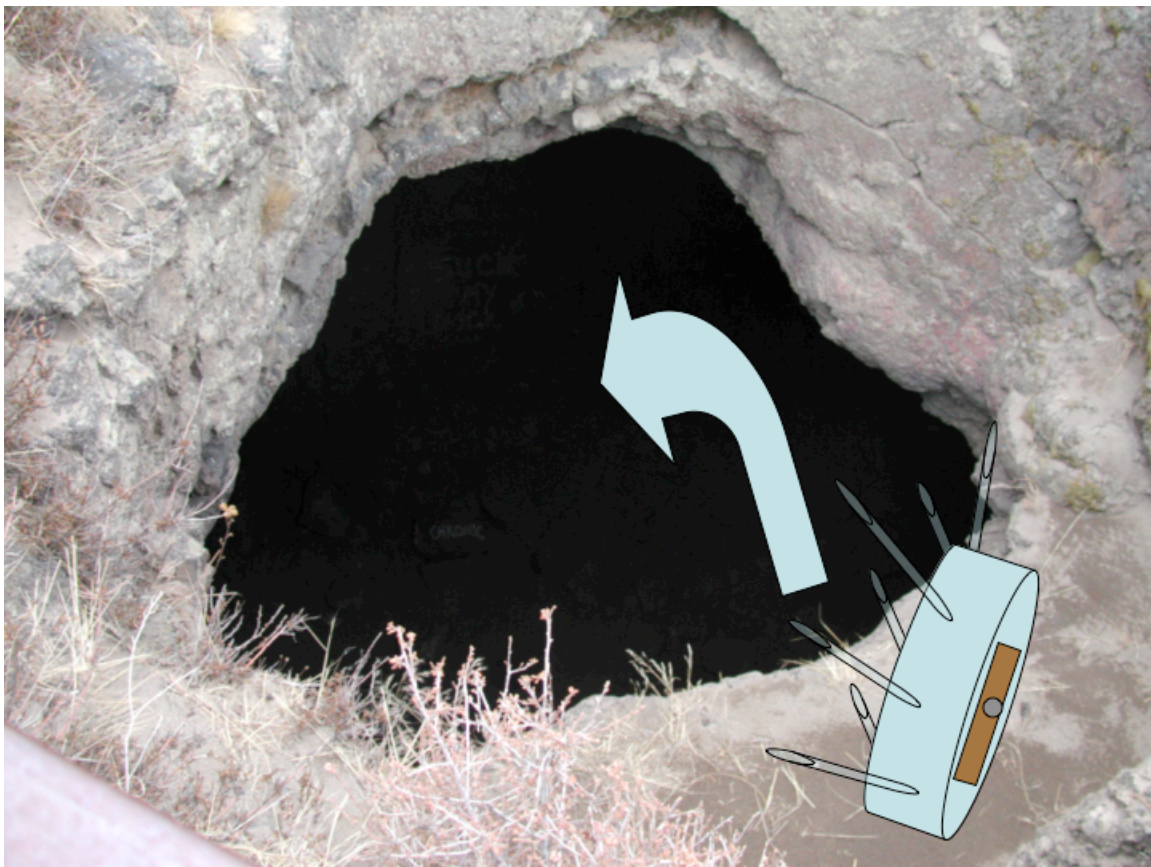


Figure 5 : Rigid airlock assembly with telescoping legs about to be fitted into cave entrance. Once in place, space around the assembly will be filled with rigidifying foam to seal it in place.

As an alternative to rigidifying foam, we have considered using flexible, blanket-like material to provide the initial emplacement “scaffold” that can be secondarily coated with the rigidifying foam after the standard airlock component is fitted into place. However, this seems a much more unwieldy technique and may present problems with adhesion to the cave wall materials and inflatable structure materials. On the other hand, if such a technique were to be pursued we believe that recent advances in creating *flexible* aerogel materials for both high temperature (500°C) and cryogenic applications are encouraging indications that such materials could stand up under Martian conditions. Aspen Industries (Marlboro, MA) is offering these non-shattering shape conformable aerogel blankets commercially. This may provide one possible avenue to achieve some of the properties that we desire. Aerogel properties and state of the art issues are discussed in detail in our Phase I study (Boston et al., 2001b).

Separate from the ultimate extraterrestrial application, we required an effective but inexpensive and easy to operate airlock arrangement for the HUMIS habitat. Sealability is a critical design factor in the non-breathable atmosphere of the human mission candidate cave (HM Cave, AZ). The major design challenge has been to accommodate both easy deployment and secure sealing. Easy deployment of the habitat by suited speleonauts is a non-trivial requirement. Recent experience by Boston (April 2002) in a space suited surface habitat trial in Utah demonstrated painfully the limitations of cumbersome gear when trying to accomplish very ordinary motions and manipulations. For the HUMIS habitat airlock, we first considered plastic, snap-lock components for rigid members of the inflatable, its interior accoutrements and the rigid frame of the airlock, and the frame of its door. In light of cost and the requirements of our trials, our original intent of a rigid door and frame unit gave way to a much lighter and more easily deployed door design that uses the same material as the main inflatable. The initial airlock design was deemed to involve too many seams, thus presenting an unacceptably high leak rate for the structure. Further modifications of the shape to be an extension of the primary structure has eliminated this consideration. Methods of assuring the seal around the inflatable fabric insertion were the primary concern, but we selected a single multiple-fold and back seal arrangement common on many dive bags. The speleonaut enters the airlock, folds the outer flap over in a 3-fold configuration secured with a flat clamp and then back-folds in a 3-fold secured by a second clamp. This is a much simpler and lighter weight option than our original design.

C. Air Provision System for Mars and for HUMIS

On Mars the breathing mixture can be produced by a variety of methods depending on available resources and power sources (McKay et al., 1986). Oxygen could be produced by reduction of atmospheric carbon dioxide using a recycling reverse water gas shift reactor in conjunction electrolysis and process gas recovery to achieve high yields. This process requires thermal and electrical

power and hydrogen supplied as a slowly expended working reagent. Alternatively, oxygen can be produced by electrolysis of water obtained from the Mars atmosphere using temperature swing adsorption pumps, or from water ice possibly occurring in the Martian caves. Since carbon dioxide (95.3%), nitrogen (2.7%) and argon (1.6%) account for most (99.6%) of the Mars atmosphere, buffer gas can be obtained simply by removing the carbon dioxide component thus leaving a nearly pure 60/40 mixture of nitrogen and argon. Whether such a mixture provides breathable gas is debatable, see Section D. immediately following this section for pertinent experiments. Preparation can be achieved using compression and cooling to liquefy the carbon dioxide or by using temperature swing adsorption pumps. The latter can be driven at relatively little energy cost using the natural diurnal temperature swings that are typically 70°C on Mars, or operated inside caves using active heating and cooling.

The breathing mixture for the Earth cave demonstrator is produced using separate pure gas sources remixed to provide a 22/78 percent mixture of oxygen and buffer gas but where the buffer gas consists of either pure N₂ or a 60/40 mixture of nitrogen/argon consistent with their naturally occurring ratio in the Mars atmosphere if appropriate permissions are received (see human experimentation remarks in the next section). During egress from the habitat to do work elsewhere in the cave, crewmembers will use breathing gear supplied with the same gas mixture as used in the habitat. The hypothesis that argon is a safe alternative to nitrogen as a buffer gas is discussed below.

The monitoring of breathing gases is done with multiple redundancies. The triplicate oxygen sensors are set so that below 18% O₂, tanked oxygen will be fed into the system. Two Vaisala carbon dioxide sensors are inside the habitat and additional sensors feed readings outside of the cave to Ground Control. Emergency breathing gear in case of system failure is stowed both in the habitat and outside in the cave environment to meet any emergencies.

The subsystems needed on Mars for CO₂ removal, humidity control, and trace contaminant control are simulated in the Earth cave demonstrator by using a combination of controlled leakage from the habitat with conventional dehumidification and a carbon dioxide scrubbing system devised for the habitat based on well known principles.

CO₂ Scrubbing Issues: We wrestled extensively with the issue of CO₂ scrubbing within the habitat. No off-the-shelf units are available that meet our needs. In consultation with other engineers who have developed systems for submarines, their recommendation was to fabricate a relatively simple system from basic components that uses Lithium Hydroxide or a similar strong base. There are many chemical constituents that are capable of removal of carbon dioxide gas from breathing mixtures but all of them have some drawbacks, often currently this is cost. Another major difficulty with most scrubber materials is the need to have maximum surface area of granular material exposed without

excessively large volumes. One can imagine that powdering the material might be beneficial however that causes packing problems and reduces the effective surface area.

A pumping system that recirculates the habitat air through a triple array of plexiglass tubes that are packed with the LiOH and an activated charcoal prefilter was our design solution. A series of two graduated particle filters will remove motes to keep the system from clogging at the front end.

To orient the reader to the relevant mass flow at issue with carbon dioxide removal from air, the daily consumption for humans of major breathing constituents are:

Air (total)	1.55kg
Oxygen	0.84kg
CO2 removal	0.71kg

A person at rest exhales at least 10 liters per minute of air, which contains 3.6%-4% CO₂ (vol) in their exhalation and they exhale at least 0.4 liters CO₂ per minute or 24 liters per hour. This amounts to 576 liters per day per person CO₂ exhaled (pv=nrt). In other terms, 0.82 liter CO₂ is produced per liter of O₂ inhaled. The total figure is 4,032 liters CO₂ exhaled per person-week.

Considering different absorbers have different absorption values, if it takes on average 0.17kg of absorbent per person per hour, then

1 person-week = 24X7 = 168 hours

= 28.56 kg

= 57.12 for 2 people-weeks

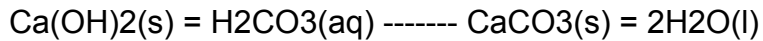
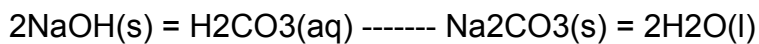
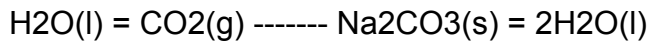
= 114.24 kg

For health considerations, the recommended CO₂ level in the atmosphere is 0.5% by volume. Ambient outside atmosphere has 0.33% by volume. Some Earth caves have as high as 20% CO₂, Frassassi Cave in Italy for example. The HM Cave chosen for the final Mission to Inner Space has been measured at 7%. So there are both internal sources of CO₂ (human respiration) and external sources (high CO₂ atmospheres in some caves).

After considering many models for providing breathable air, we have settled on a system similar to a submersible that has been operating for the past few years. The DeepWorker 2000 submersible uses "rebreather" technology to chemically remove carbon dioxide from a pilots' expired breath and a pair of high pressure cylinders to replenish the oxygen gas metabolized by aerobic respiration. This lab allows students to calculate the volume of carbon dioxide

gas that can be removed from DeepWorker's cabin by the absorbent chemical "Soda-Lime." Soda-Lime, which is a mixture of caustic soda and lime [NaOH and Ca(OH)₂], is a chemical scrubber used to remove carbon dioxide from the air that has been expired by the pilot. SodaSorb[®] (the brand of soda-lime used by DeepWorker) is manufactured by the W.R. Grace Company in the United States. SodaSorb[®] consists of 70-80 percent Ca(OH)₂, 16-20 percent H₂O, 1-2 percent NaOH and 0-1 percent KOH. The greatest benefit of Sodasorb is its relatively low expense and good packing and distribution properties.

The mechanism for this exothermic reaction is:



There is a net production of three H₂O molecules for every molecule of CO₂ absorbed. Some chemical absorbents employ an indicator that changes color when the reactant is exhausted. The ethyl violet indicator in SodaSorb[®] changes from white to purple when the chemical can absorb no additional CO₂.

When a person breathes, 0.82L of CO₂ is exhaled for every liter of O₂ inhaled. An O₂ generation system should either produce a larger volume of O₂ than the volume of CO₂ consumed or make-up for the difference with a supplemental O₂ supply. A gas "regulator" is used to deliver gas to the DeepWorker's cabin at the proper rate. Pressure gauges monitor the supply of O₂(g) in DeepWorker's twin cylinders.

The temperature of the absorbent influences the effectiveness of the reaction. SodaSorb[®] works much better in the relatively warm cabin of DeepWorker than it would at cold temperatures and our cave environments are all within the optimum temperature range.

The system design relies on physical distribution to allow adequate airflow to reach the maximum amount of absorber chemical. Twin units are available to avoid unacceptable buildup of carbon dioxide due to the non-linear response curve of the absorber. One unit can run until it is beginning to degrade in performance as revealed by the Vaisala CO₂ monitors that we are using and then can be automatically or manually switched to the second system allowing swap out of absorber packets from the first system. Below are three figures that illustrate the overall system design.

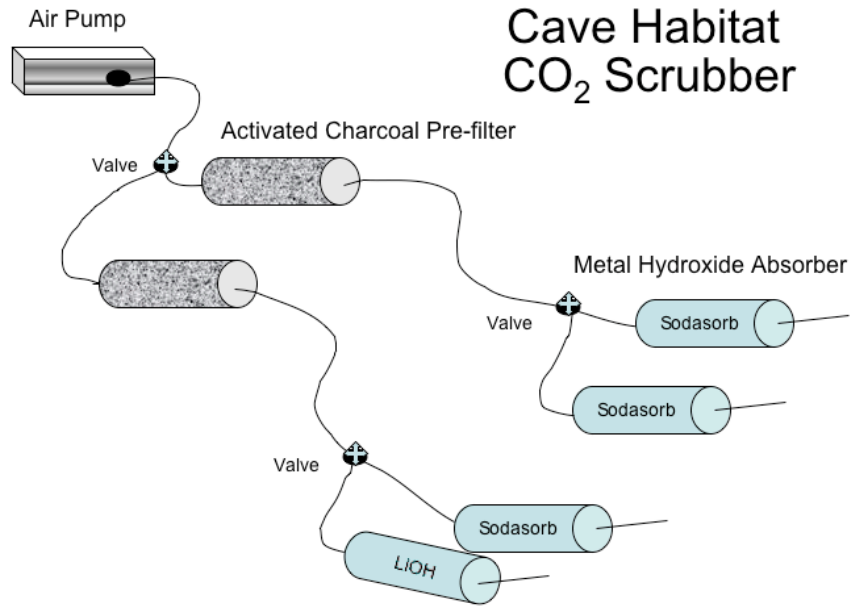
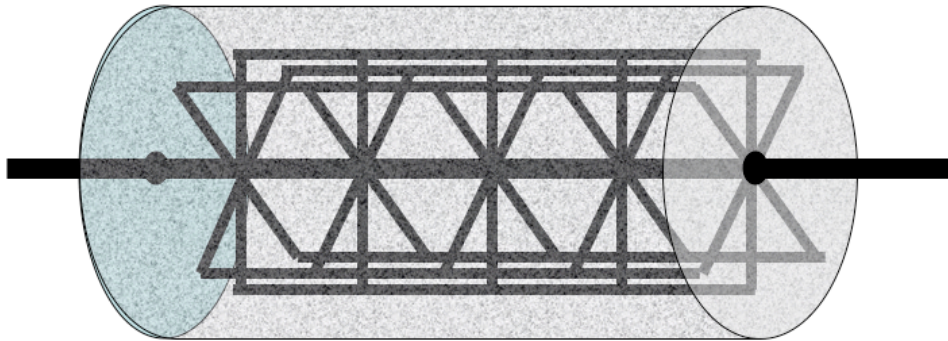


Figure 6: Overall configuration of carbon dioxide removal unit.

Pre-packed Scrubber Columns

Permeable tubing gantry attached to the main flowthrough tube
Plexiglass outer shell for monitoring of indicator color change



Sodalorb or similar commercial absorber for relatively high temp
LiOH as a backup for low temperature excursions

Figure 7: Internal airflow distribution in a single cartridge.

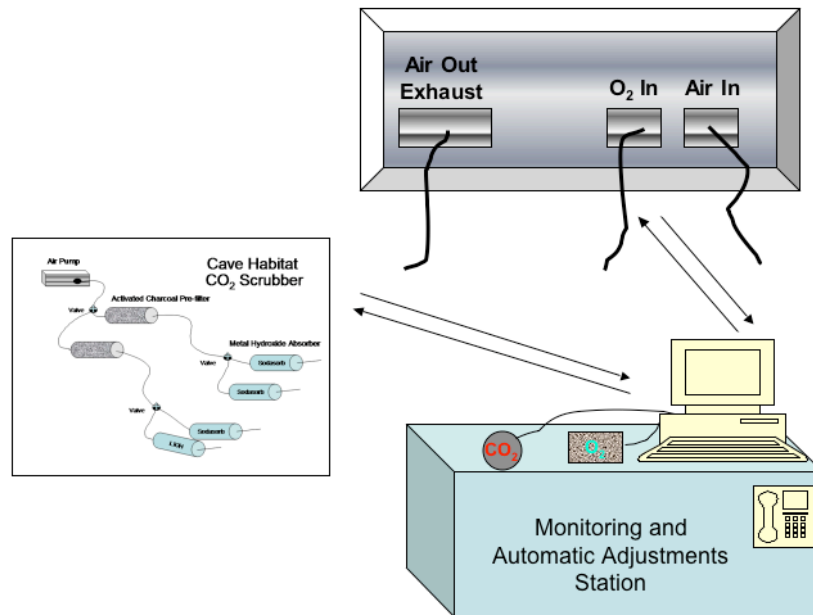


Figure 8: Control schematic of carbon dioxide removal unit.

Optimal moisture content of the absorber granules is 12 to 19%. The process of reducing 5% CO₂ from the breathing mixture for two hours will generate approximately eight ounces of water. This is excess water that must be conducted out of the granule canister. A properly designed canister will allow the hot gas to exit the canister before condensation occurs. Water traps are used to reservoir the excess water or drains can be installed to "bleed" the system. Heat from the canister is a positive indication that the absorber is working. A cold canister is a bad indication. We are using conventional Drierite packed water filtration canisters to control the moisture issue.

An indication of too high levels of carbon dioxide can be a strange smell and taste but the content must be above 0.08% by volume to do this, well above the nominal safety level of 0.05% level that we have as a benchmark. However, the human nose can serve as yet another level of redundancy beyond the instrumental monitoring of carbon dioxide that is routine with the HUMIS system.

D. Mars-derived Breathing Mixture Experiments

We included extensive information about argon's biological affects and properties in Appendix C of Boston et al. (2001b). The only danger from exposure to argon is lack of exposure to oxygen! Thus, there is no immediately identifiable reason why argon or argon/nitrogen mixtures could not be as good an inert component of breathable air as nitrogen is on Earth.

- *Problem:* Need to facilitate human operations in Mars caves without resort to pressure suits and desirability of obtaining the components of breathable air from the Martian environment.
- *Constraints:* Must cause no harm to astronauts and exert minimum interference on cave biogeochemistry
- *Proposed Solution:* The only way to obviate the need for cumbersome pressure suits is to increase the atmospheric pressure within the cave environment. If a cave could be pressurized to at least 150 kPa, then astronauts could operate at the ambient cave pressure. They would need to breathe pure oxygen at such a low pressure, but could breathe a mixture if the cave pressure could be brought higher (1000 kPa is sea level pressure on Earth).

Potentially oxygen could be added to the biologically inert gases in the created cave atmosphere provided that it was a cave totally devoid of any chance of even cryptic lifeforms being present and used exclusively for human habitation and resource gathering. Conversely, neither oxygen nor any other metabolically active gas should be added to the environment of a research cave. The potential disturbance to the natural state would be too great. These caves need to be pressurized with a totally inert gas mixture, if at all.

Research needs to assess the feasibility of using argon containing breathing mixtures include:

- 1) the requirements and methods necessary to adequately seal the cave section of interest for pressurization with Ar/N₂
- 2) developing methods to obtain a reliable supply of inert gas (presumably argon or a nitrogen/argon mixture)
- 3) developing an airtight, thermally insulated caving suit and closed breathing apparatus,
- 4) demonstrating that the inert gas and the increased pressure has acceptably low impact on the cave environment, and
- 5) demonstrating the absence of deleterious effects on vertebrates and humans exposed to external argon gas or exposed to inhaled argon gas

The first three items in the research needs list above are not within the scope of this project, however, the 4th can be addressed as a byproduct of our fundamental cave research activities and the 5th was investigated as a pilot project under this NIAC effort.

To set the stage for the argon breathing experiments conducted as part of this study, it is important to have a general grasp of the Martian atmospheric composition and the work that has been previously done on noble gases as components of breathing mixtures. The Mars atmosphere is mostly carbon dioxide (95%), but contains two potential gases that could be obtained as by-products of other atmospheric processing activities: nitrogen and argon. Argon is biochemically inert. Nitrogen is clearly not inert in many circumstances,

especially in terrestrial microbial nitrogen fixation processes, and should probably not be used in research caves. The Mars atmosphere is 1.6% argon and 2.7% nitrogen. These concentrations should be sufficient if large-scale atmospheric processing is practiced at a research base to supply all volatiles including CO₂-derived propellant.

Compression of the Martian atmosphere and subsequent separation of major constituents by cold traps at target temperatures can yield a mixture of CO₂ (95% of Mars air) and CO condensing at a temperature of approximately -20°C and a residual of other gases, primarily N₂ and argon (2.6% and 1.7% of Mars air respectively) (French, 1989; Finn et al., 1996; McKay et al., 1993).

Separation of N₂ and argon is an energy consuming process involving significant additional processing. If argon could safely comprise a significant component of a breathing mixture, then provision of breathable air for Mars cave habitats, surface excursion vehicles, and space suit EVAs would be greatly simplified (Bauman et al., 1979; Boston, 1986; McKay et al., 1986). Oxygen derived from water or other materials mineable from the Martian atmosphere or lithosphere could be added to the basic N₂/Ar mixture to provide breathable air.

Argon is a better thermal insulator than air. In fact, deep divers use it as an inflation gas in dry-suits for that reason. This effect (about 50% less thermal conductivity than nitrogen), could come in handy in a cold Mars cave in both breathing mixtures and filler gases for other purposes. For example, the N₂/Ar mixture could be used alone to provide pressurization for larger expanses of enclosed cave to provide storage and work space that could be accessed by humans using oxygen breathing gear but otherwise in a “shirtsleeve” environment.

Work with breathing gas mixtures for deep-ocean diving can help elucidate some of the issues arising from the use of an argon-pressurized environment. Very little previous work appears to have been done explicitly on argon but is usually bundled with general studies on inert gas breathing mixtures (e.g. Aldrete and Virtue, 1967). We have only located one reference that mentions the breathing of argon as a possibility for Mars (Buravkova and Pavlov, 1999). We note that the astronauts don't *necessarily* have to breathe an argon mix if oxygen breathing gear is used.

Inert gases have narcotic properties associated with their physical solubility in lipids. In general, all gases induce narcosis if they penetrate cell lipids in a molar concentration of about 0.03-0.07 moles per kg of membrane. Some inert gases (e.g., xenon) have solubilities large enough to invoke surgical anesthetic properties at Earth atmospheric pressure. It is unclear, and probably totally unexplored, whether argon at sub-atmospheric partial pressure would have any solubility-induced effects on terrestrial microbiology. However, these effects can be very easily tested in a laboratory situation.

Suggestions that argon at conventional Earth surface pressures be tried as a constituent of a breathing mixture has been suggested in the past (Bauman, et al., 1979; Boston, 1986; McKay et al., 1986), but not experimentally tested to date. Some work with argon at high pressures as a component of breathable diving mixtures has been done (e.g. Edmonds et al., 1983; Fowler et al., 1985; Bennet, 1993). Several Russian investigators have also more recently suggested argon as a constituent of breathing mixtures for astronauts (Pavlov et al., 1997; Burakova and Pavlov, 1999).

The research questions that we pursued during this study include:

- 1) Will invertebrates like crickets or small mammals like mice exposed to argon and argon/nitrogen breathing mixtures thrive?
- 2) Will humans notice any deleterious or annoying effects from breathing these mixtures?

We began a series of experiments to test the effects, if any, of a breathing mixture containing a significant proportion (40%) of argon. Denise Murphy, summer intern high school student from Ontario, participated extensively with these cricket and mouse experiments.

First experiments were conducted on ordinary house crickets, *Acheta domesticus*. Pairs of female crickets (to avoid fighting) were housed in a small anaerobic/ chamber connected to a custom-mixed gas cylinder. The gas mixture was 40% N₂, 40% argon, and 20% O₂. The experiments were conducted at normal pressure in Boulder, CO, (approximately 830 millibars). Exposed animals were observed behaviorally for normal eating and movement patterns. Experiments lasted for 4 days during which the crickets were breathing this mixture, followed by return to ambient atmosphere and observation of the exposed and unexposed pairs for subsequent deleterious effects. These simple experiments demonstrated to our satisfaction that no obvious ill effects were experienced by the crickets and that it was safe to move on to more lengthy and elaborate experiments with mice.

The first mouse experiment was conducted on two female mice (Sally and Roberta) and a pair of age-matched female control mice, (Argo and Quasi Modo). The experimental mice were set up in a clear, sealed mouse cage, complete with food, water, and bedding (Figure 7). A high tech laboratory animal housing company (Animal Care Systems) in Littleton, Colorado, donated the basic unit for the mouse experiments that was subsequently modified to meet our experimental needs as can be seen in Figure 7. The system was run relatively well-sealed with inlet tubing and outflow tubing.

The breathing mixture flowed through the chamber to yield an internal pressure of approximately 850 millibars, slightly in excess of ambient in order to prevent any back leakage from the outside atmosphere. All mice were observed

visually 4 times a day, while eating, sleeping, grooming, chewing and exhibiting other active behaviors. Both mice were behaving normally seemingly unaffected. Unfortunately, at the 20 hour post closure point, we noticed that too much vacuum grease had been applied as a seal around the lid of the cage and began dripping down the walls. The experiment was halted at the two day point to clean away the grease and lower the amount of mouse bedding inside upon the recommendation of the veterinarian on staff with Animal Care Systems, Inc.

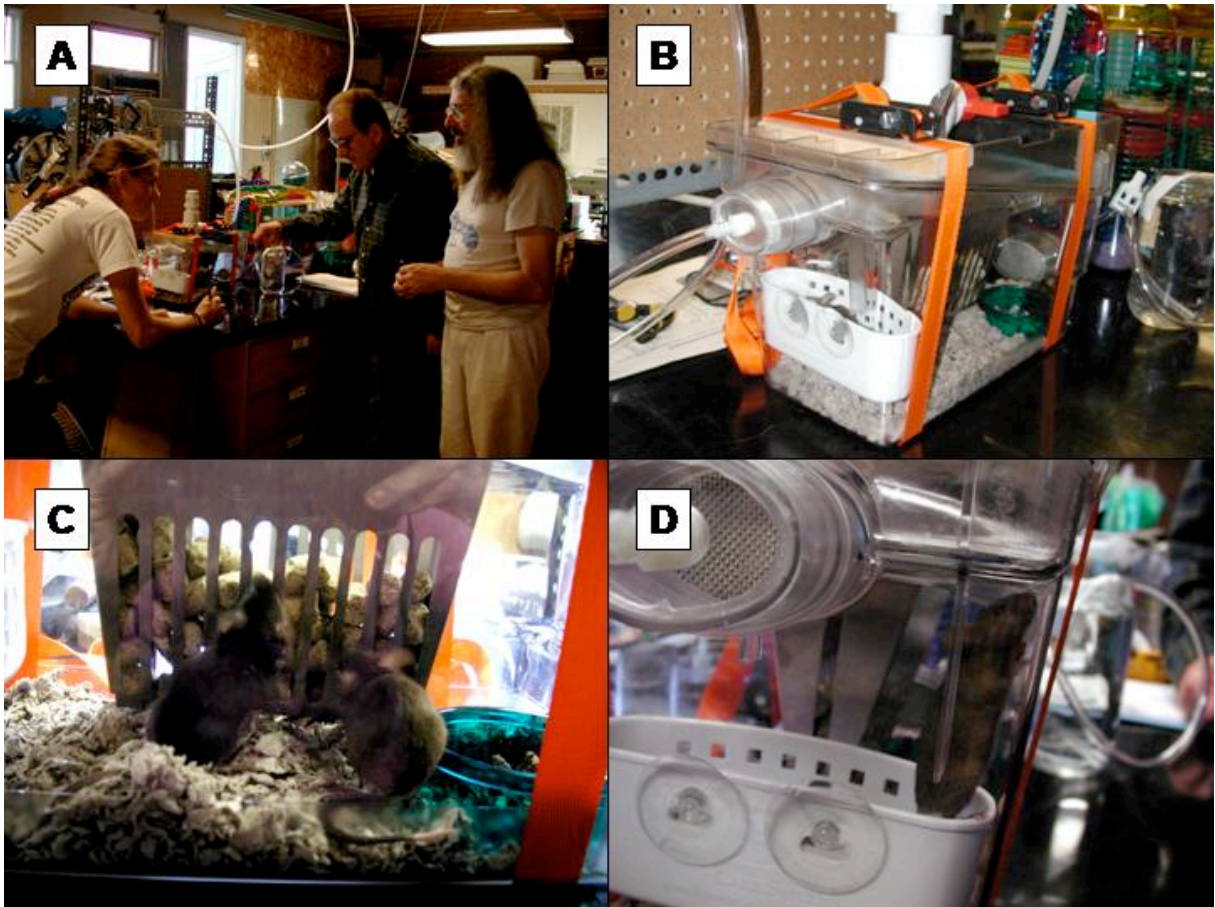


Figure 9:

A. Experimental apparatus and control cage being monitored during initial few hours of experiments (left to right, Denise Murphy, Tom Meyers, and Steve Welch).

B. Experimental apparatus showing air intake. Mousetronaut Roberta is exploring a small nesting box underneath the air intake.

C. Both mice exhibited normal eating behavior for the duration of experiments

D. Both mice showed normal periods of activity and resting.

After the grease was cleaned away and the bedding was decreased, Sally and Roberta were put back into the experimental cage and the experiment began again. The breathing mixture was introduced to yield an internal pressure at the same value as the first attempt (~850 millibars) and their activities were

monitored as before. Both experimental and control mice showed similar levels of activity and normal resting and activity periods (see Figure 8). This experiment ended successfully on 14 September, 2002 after completing 16 days of continuous exposure to the gas mix plus the prior 2 days before the grease episode. Both mice, now reunited with their control partners, seemed unaffected and went about their usual highly active lifestyle. We monitored them, their health, and their lifespans until they died of natural causes at the ages of 17 to 23 months. The experimental mice actually lived longer than their control counterparts and all lived well within the normal expectations for mouse lifetimes.

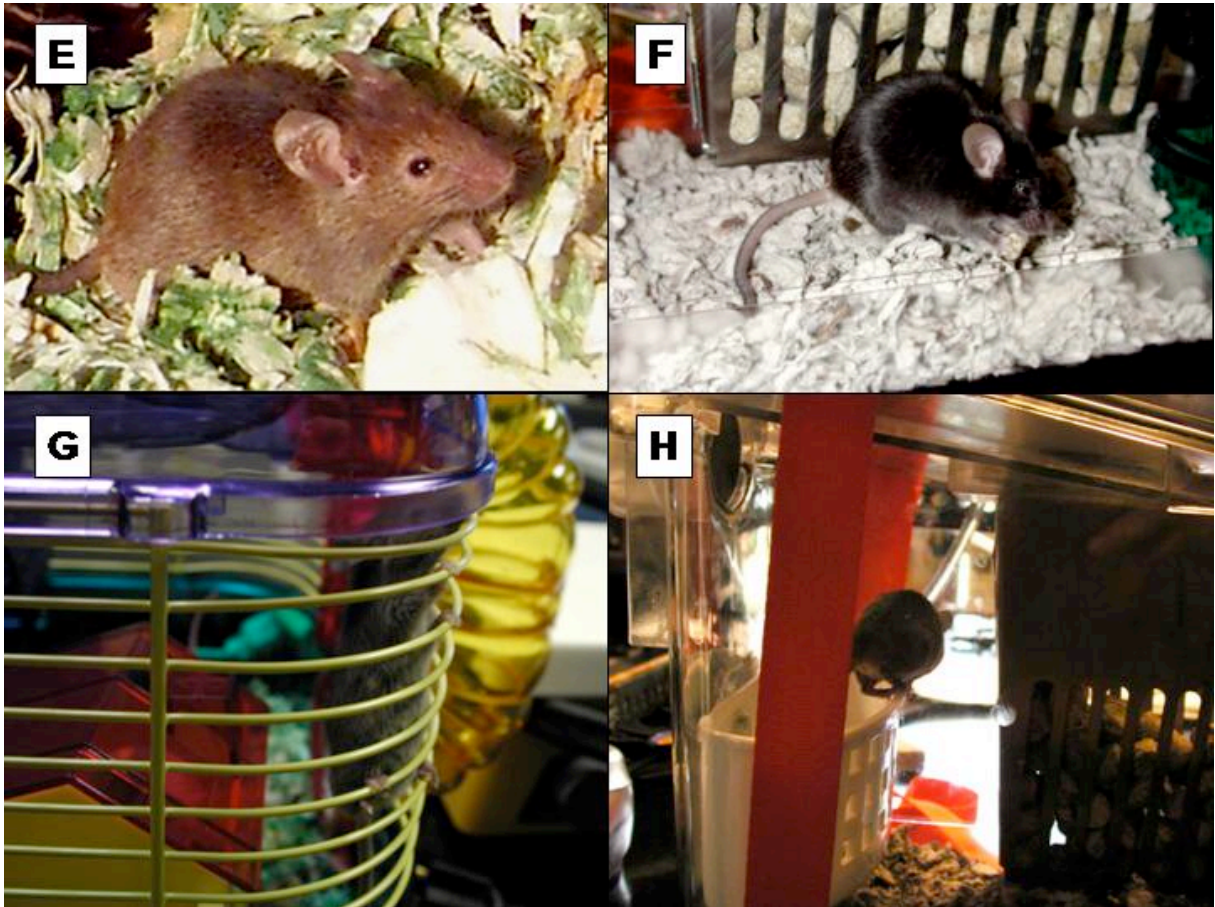


Figure 10:

E. Control Mousetronaut Argo eating.

F. Experimental Mousetronaut Sally eating.

G. Control Mousetronaut Quasi Modo showing acrobatic talents.

H. Experimental Mousetronaut Roberta exhibiting normal acrobatic exploratory behavior.

Although the two completed experiments were short lived and used small numbers of animals yielding data that can not be claimed to be statistically significant, they served their purpose in demonstrating that there are no immediate short term adverse affects that breathing a mixture of 40% argon, 40% nitrogen and 20% oxygen has on crickets and mice. The long term effects on our populations seemed to be negligible but obviously cannot be quantified based on this proof-of-concept pilot study. We believe that this small study justifies additional experiments on both mice in larger numbers and potentially the effects of argon on a complex, nervous system mediated but untaught behavior like spider web-building.

In addition, the effects on humans are of immediate interest. We have applied for permission to study the response of human volunteers to an argon containing breathing mixture. The experimental plan was formulated in compliance with the Title 45, Public Welfare under the Code Of Federal Regulations of the Department Of Health and Human Services of the National Institutes of Health's Office of Protection from Research Risks. The pertinent section is Part 46: Protection of Human Subjects, as revised 13 November, 2001 and implemented 13 December, 2001. The written proposed procedures were submitted through the Institutional Review Board of the Office for Protection from Research Risks, National Institutes of Health, Department of Health and Human Services. As of this writing, six months after filing, the proposal is still pending.

E. Flat Crops

In the limited environment of a cave habitat, the provision of growing space for food is as much of a problem as it is in any space habitat. An idea that we pursued as a potential partial solution to this agricultural space dilemma was the notion of "flat crops", that is, photosynthetic organisms that can grow essentially in a "two dimensional" fashion not requiring any significant depth of medium for growth. Of course, algae and cyanobacteria and many other single-cell protein schemes were proposed during the early days of spaceflight as potential food production schemes (Boston, 1985) however, these proved not to be satisfactory for many reasons. We have been studying two plants, common duckweed which is a very tiny group of higher plants, and waterfern which is also a floating species often found intermixed with duckweed in ponds. Of the two groups, duckweed seems to be more more promising. Much of the following brief synopsis is taken from a master's thesis by Landesman (2000) on duckweed as a nutritional source and as a wastewater treatment plant.

Duckweeds of the family Lemnaceae are small, floating, aquatic plants with a worldwide distribution. They are one of the fastest growing angiosperms and can double their biomass within 2 days under optimal conditions. They have a high protein content (10 to 40% protein on a dry weight basis) although the moisture content (95%) of fresh duckweed biomass is quite high as well.

Potentially, members of the Lemnaceae (of the genera *Lemna*, *Spirodela*, and *Wolffia*) can produce edible protein six to ten times as fast as an equivalent area planted with soybeans. Therefore species of Lemnaceae potentially have a great value in agriculture. Indeed, wild duckweed is even harvested by various groups in southeast Asia and fed to their farm animals to help boost growth rates.

A great deal of work has been done on the nutritional value of species of Lemnaceae, especially *Lemna*, *Spirodela* and *Wolffia*. Duckweed has been fed to pigs, cattle, sheep, chickens, ducks, and fish and can substitute for soybean meal in animal feed rations (Robinette, 1984; Haustein et al., 1994; Johnson, 1998; and Moss, 1999). Its amino acid composition is similar to that of other plant proteins except for having a higher lysine and methionine content, two amino acids normally deficient in plant products. Finally, dried duckweed can provide vitamins, minerals, and pigments such as beta carotene in livestock diets, reducing the need to add these compounds to rations and thus saving the feed producer money.

Much research has been done on the use of duckweed in wastewater treatment systems. As part of a facultative treatment system, duckweed can cover treatment ponds and reduce the growth of algae in these ponds as well as reduce nitrogen in the effluent from these ponds through ammonia uptake and denitrification (Alaerts et al., 1996; Hammouda et al.1995). Duckweed can also be part of constructed wetland systems, either as a component of a wetland receiving wastewater or as plants that polish nutrients from wetland-treated effluents (Ancell, 1998).

Due to their small size and ease of growth, duckweed species make ideal organisms for toxicity testing (Lakatos et al., 1993). A new company in Germany has devised a *Lemna* toxicity test that has been approved by the European Commission (LemnaTec, 1999) and the use of duckweed for toxicity testing is mentioned in Standard Methods (APHA, 1995). Duckweed can be used in both static and the dynamic test procedures (Wang, 1986; Taraldsen and Norberg-King, 1990).

The three dominant duckweed genera (*Lemna*, *Wolffia* and *Spirodela*), will all grow on organic (for example wastewater) as well as inorganic media (for example Hoagland's medium). All three species grow faster on organic as opposed to inorganic media (Culley et al., 1981; Landolt and Kandeler, 1987) with equivalent amounts of nitrogen and phosphorus. This may be due to the ability of duckweed species to take up organic molecules directly from the media in which they grow (Landolt and Kandeler, 1987). Even inorganic media supplemented with glucose will support faster duckweed growth than media without glucose (Hillman, 1961).

In natural environments, several duckweed species are normally found living together. In wastewater treatment ponds, *L. obscura* species are normally

found growing together with *W. globosa* species and sometimes with *Azolla caroliniana* as well which is one of the waterferns that also have interested us. This may be due to selectivity by the grazers. It is well known that some duckweeds are tastier than others. The large amounts of crystallized oxalic acid in *L. obscura* makes them less tasty than *W. globosa* which has much less or no oxalic acid (Landolt and Kandeler, 1987).

Duckweed species can grow very well in lower light levels and it is recommended that they be covered with shade netting in summer to reduce solar insolation that may be too much for them. To maximize growth rate, the plants can be treated almost like microorganisms and harvested at least once a week to keep duckweed populations in the exponential growth phase which also maximizes duckweed's remarkably high protein content.

We conducted preliminary experiments to grow duckweed under various conditions (Figure 9). Duckweed experiments culminated in feeding some of the material to mice as part of the MOMIS mission described in the next section.



Figure 11: Upper left, rice with duckweed additive. Upper right, microscopic image of a duckweed plant showing diminutive leaves and small hanging rootlets. Lower left, pond with high concentration of *Azolla*, waterfern, growing in it. Lower right, pond entirely covered with minute duckweed plants.

F. Results of MOMIS

Our miniature bio-regenerative life support analog, CEMSS (Controlled Environmental Mouse Support System, Figure 10) was subjected to a two day field trial in Skylight Cave, a lava tube near the Central Oregon resort of Black Butte at the end of September, 2002. We used two young female Mousetronauts, Chevy and Pontiac, for this field trial. They were fed standard mouse nuggets during the trial period.

The CEMSS Unit was placed on a scaffold, beneath one of three unique 'hornito' openings within Skylight Cave (see Figure 11). Total height of the scaffold is 4 meters. CEMSS was at the 'second from top' rung so the base was about 10 feet from the cave floor. Variables tracked included oxygen and carbon dioxide levels within the unit as well as temperature and relative humidity (Figure 12 A-D).

Power was provided via photovoltaic solar cells charging a bank of batteries, connected to the CEMSS by an umbilical cord going into the cave. The power system worked well. Two Deep Cycle Marine Lead-Acid batteries powered the system, which were on the surface near the opening. During the trial, the thermo-electric heater was not used, as the temperature stayed in the nominal range without it, (probably due to the small, yet significant heat from the light tubes coupled with the insulation that minimized heat loss). If the temperature drops or rises beyond acceptable limits, the unit switches on and provides heating or cooling as necessary.

Lights took about 30 minutes to flicker on and stabilize, due to the cold. Fluorescent bulbs are optimized to 20°C so the ambient temperature of 15°C caused this effect, but once on, they performed perfectly until we turned them off. Time & fan cycles behaved equally well.

We had calculated that we could run all the devices even without solar input for 100 hours. The 110 inverter has a 'low power' alarm that kicks on if the input voltage drops below 12vdc. To insure that our calculations were correct, Gus Frederick slept next to it on the first trial night to make sure that it was functioning properly and in case intervention was necessary for mouse safety.

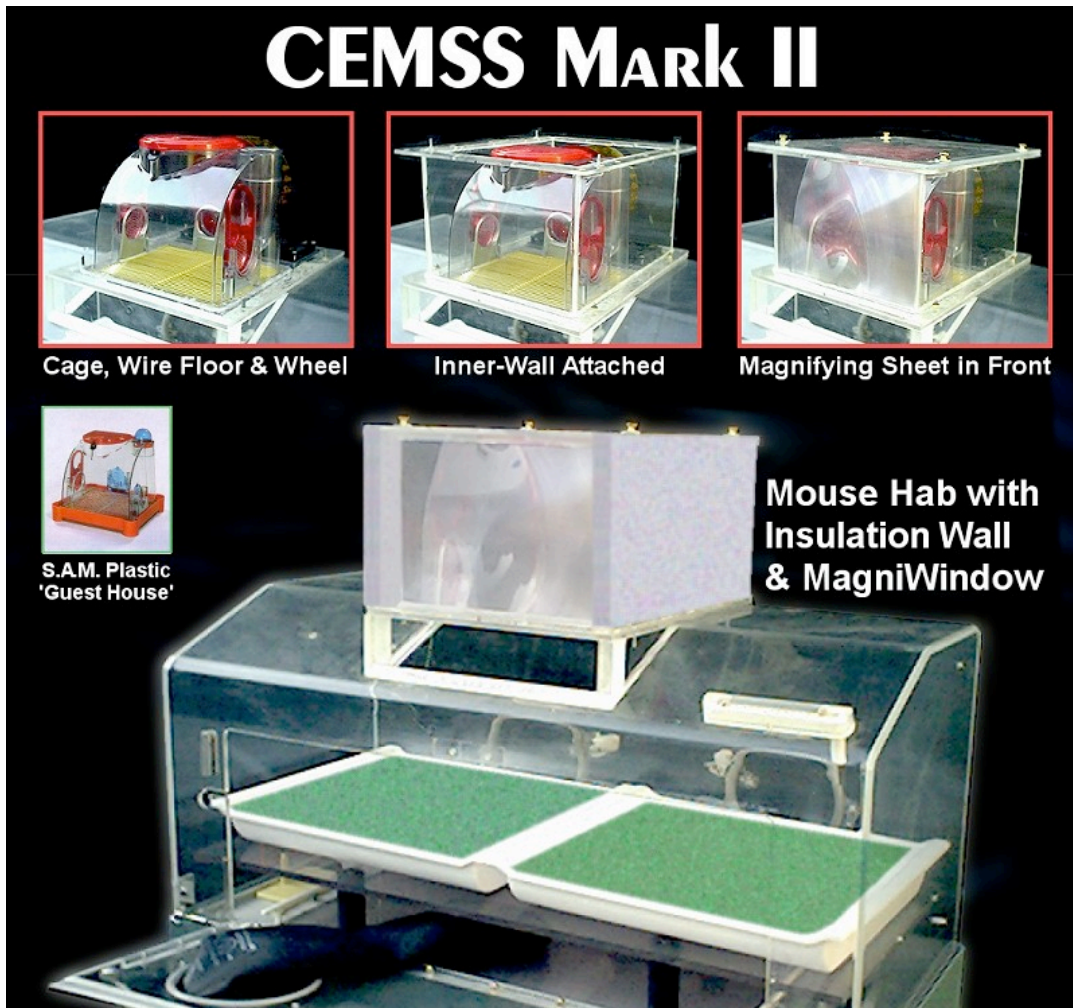


Figure 12: The CEMSS Unit that was used in the Skylight Cave trial. An insulation blanket surrounded the unit during operation to enhance temperature stability.

A small weather station and computer data logging equipment was included to record environmental conditions on the surface and within the cave itself. Alas, only the cave portion of the weather data was collected, as the external “out of cave” temp & humidity sensor failed. The CEMSS interior temperature was amazingly stable (Figure 12A). It maintained 20°C in the Mouse habitat and 30°C in the plant chamber, regardless of the biting cold.

In the plant growth chamber of the CEMSS, the living duckweed and waterfern convert CO₂-rich "mouse-breath" into breathable oxygen. A series of timed fans and vents insure a constant airflow.



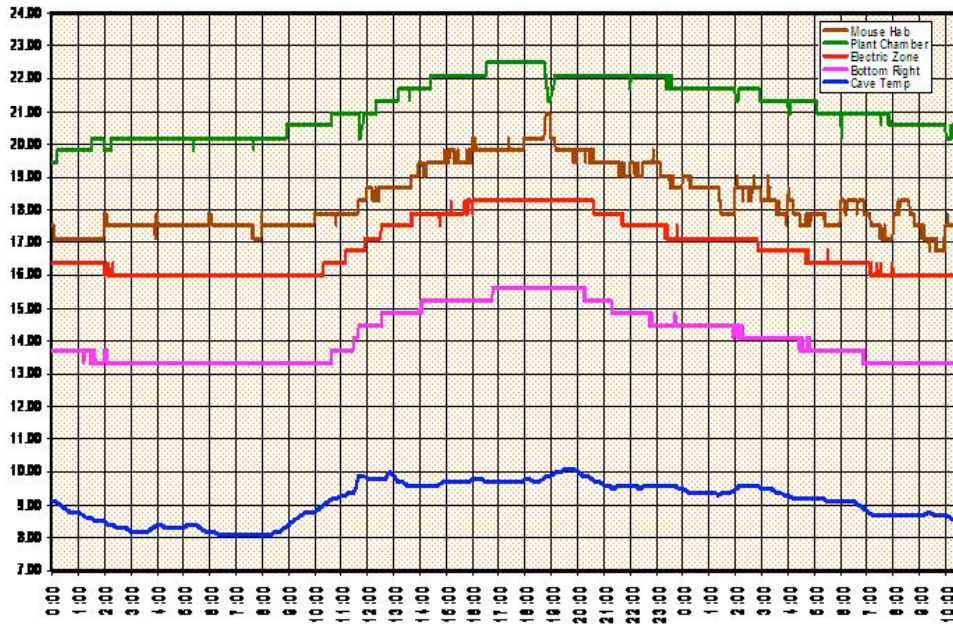
Figure 13: Skylight Cave, OR. Floor to opening (rim of hornito) dimension is about 6 meters. This was the site of the scaffold assembly and CEMSS unit.

As this was primarily a systems based test, we were particularly interested in the CO₂/O₂ fluctuations. As seen in the graphs in Figure 12 C and D, there was a lot of short timescale variability reflected in the spikiness of the data. We conclude that we need more air ‘mixing’ (ie more fans and (or) fan cycles) to reduce the variability. The CO₂ sensor was placed near the bottom of the plant chamber, while the O₂ sensor was at the very top of the unit over the mouse hab. The reason for this placement is that the CO₂ tends to sink, while the O₂ tends to rise particularly when assisted by the fan cycles.

Of most concern, the O₂ levels dropped during the two days, (Friday evening to Sunday before noon) from normal ambient (~21%) to 16% (Figure 12D). The O₂ levels did initially increase, but then slowly went down. We are speculating that there was a burst of growth and resultant oxygen production when I placed the plants in the lighted growing trays after they had been in their dark holding tanks. Over the two days, plant activity was not sufficiently high to

CEMSS Temperature

Degrees C - September 28-29, 2002



CEMSS Relative Humidity

Percent - September 28-29, 2002

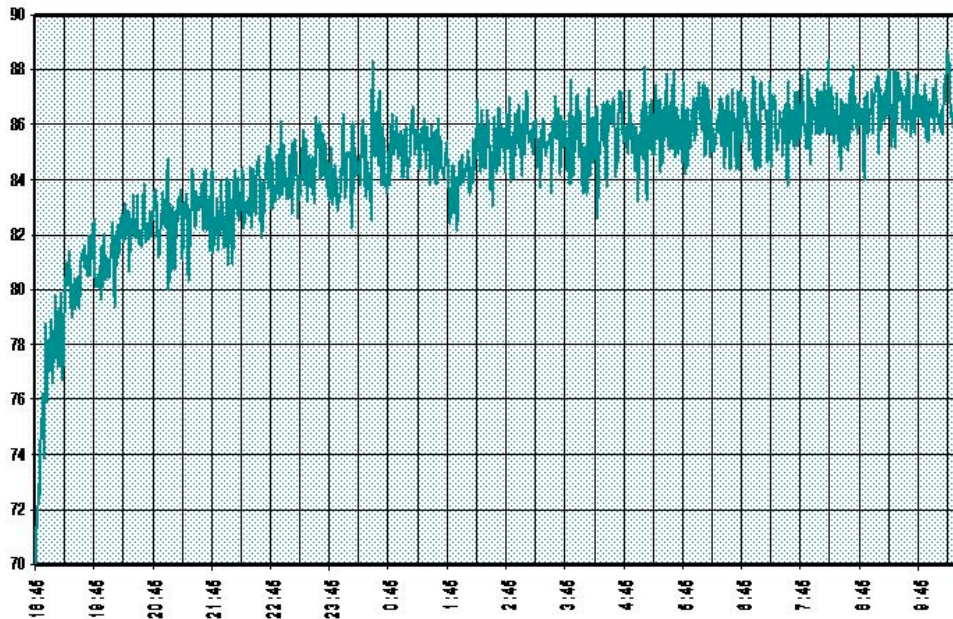
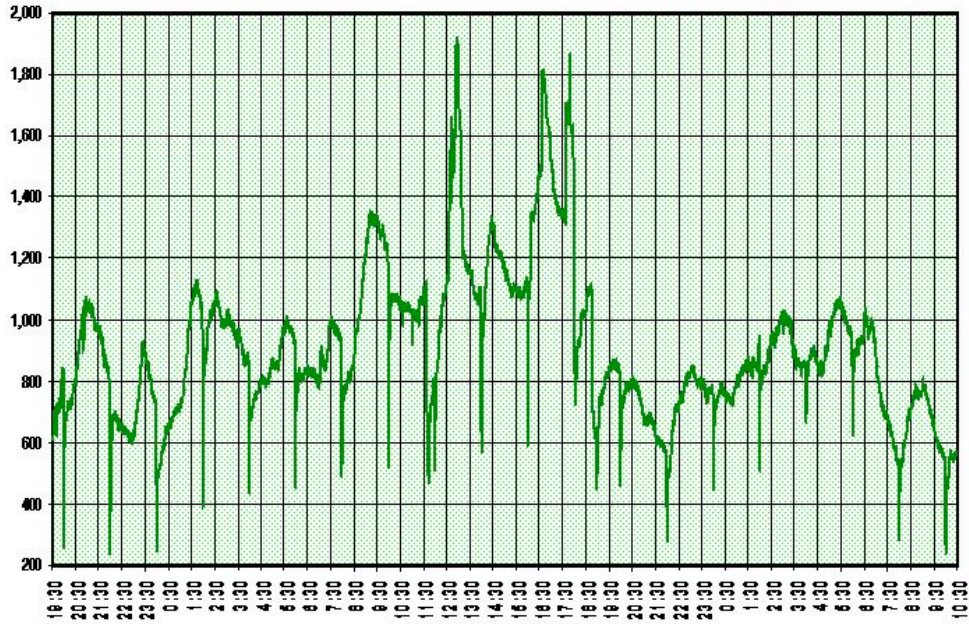


Figure14: A: Temperature profiles remained very stable despite cold in-cave conditions. B: Relative humidity is excessive and a target of further unit refinements.

CEMSS CO₂ Levels

ppm - September 27-29, 2012



CEMSS O₂ Levels

Percent - September 27-29, 2012

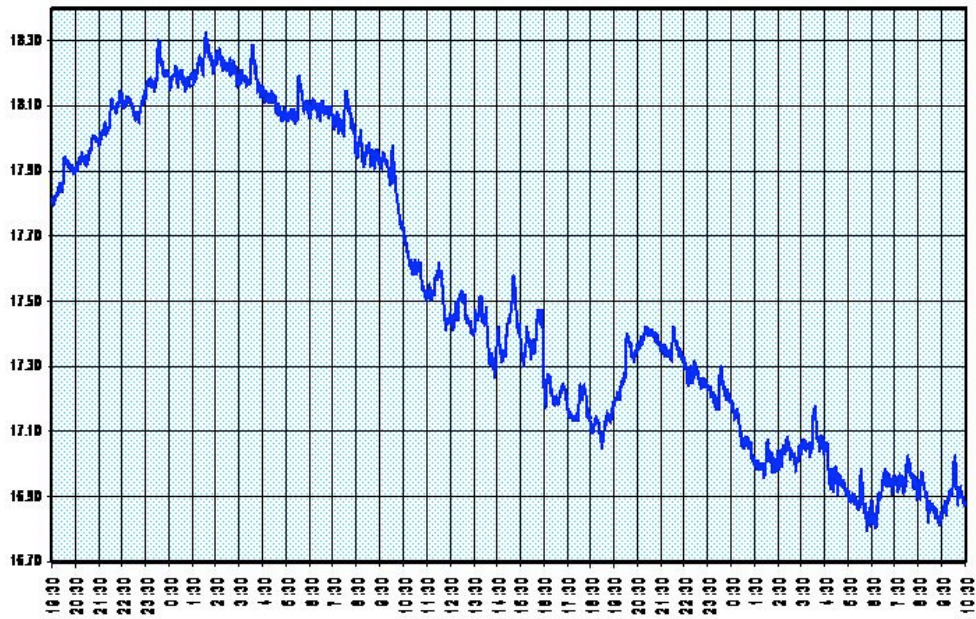


Figure 14 continued: C: CO₂ profile shows response to fan mixing air between habitat and plant chambers. D: O₂ profile shows decline of oxygen over the 2 day duration.

balance the system. This is probably partly because the duckweed took a beating from last month's heat, so it was not up to normal performance. We are considering methods of providing backup oxygen when the levels drop to 17%. This can be accomplished by means of a small (20 lb) oxygen bottle with an interface to the Vernier monitoring system. Obviously, maintaining the plants in more active condition prior to introduction will also be important. During future longer term trials, it will be instructive to see if the amplitude of the variation is damped over time or exacerbated.

Local media coverage of the incave trial was good. Three radio stations carried the story and we made the front page of the *Bend Daily* twice! The stories were also picked up by AP and were used by numerous other regional papers as well as the CBSNews Website and the Portland ABC TV affiliate, KATU.

G. In Cave Communication Test System

The development of robots that wiggle, crawl, fly, ooze, and swim have been undertaken by several other NIAC investigators (e.g. Kroo, Dubowsky, Colozza, and Pell) and others in the field. We hope that someday the fruits of their labor will provide us with such devices. We are building on their conceptual results in our planning activities. Although it is beyond the scope of our proposal to actually use these sorts of devices, as we know more about what the robotic teams are conceptualizing and developing, we utilize them to envision increased efficiency, safety, and sensory reach of our human explorers. The current immaturity of the microrobotic technology and its relative delicacy in real-world applications are issues that we believe will be resolved by market and technology drivers in other spheres (Brooks and Flynn, 1989; Brooks, 1997; Miura et al., 1997; Tilden, 1997, 1998, & 2001).

However, the idea of a robotically mounted and deployed communication system to serve navigation, rapid survey, data monitoring, data transmission, mapping, and telecommunications functions is unique to our cave application and worthy of further development. Below is a description of our Phase I approach.

- *Problem:* Cave communication and telemetry present unique problems, even on Earth. To support human or robotically-assisted human exploration of the subsurface environment of other planets, we will need to devise a communications infrastructure that can function in this unique environment and still possess sufficient bandwidth for video and telemetry from multiple sources.
- *Constraints:* The cave environment is not optimal for wireless communication technologies presently in service. We must devise a communication system that can deal with very limited line-of-sight distances for potential wireless optical technologies, and an extremely

sub-optimal environment for RF communications. This communications subsystem (infrastructure) must be easily deployed, lightweight and low bulk, easily replaced, easily repaired, and robust in dirty and unpredictable underground situations.

- *Proposed solution:* Self-deploying in-cave cellular network
 1. Utilizing existing or emerging communication standards to reduce development costs and risks
 2. Self-deploying and configuring, possibly using autonomous robot technology
 3. Self “Feeding”, capable of visiting recharging stations
 4. Self-repairing
 5. Nodal repeating line of sight (multihop) wireless network technology
 6. Communication types
 7. Explorer to explorer
 8. Explorer to surface team
 9. Telemetry
 10. Explorer video (“helmet cam”)
 11. Explorer telemetry (suit monitoring, health, etc.)
 12. Exploration and science telemetry
 - 13.** Mapping assistance (“underground GPS”), if possible

Building further upon our previous work, in this project we have refined our notion of what is feasible for incave applications of a node to node wireless system. We do know that cave communication and telemetry present unique problems, even on Earth. To support human or robotically-assisted human exploration of the subsurface environment of other planets, we will need to devise a communications infrastructure that can function in this unique environment and still possess sufficient bandwidth for video and telemetry from multiple sources.

The cave environment is not optimal for wireless communication technologies presently in service. We have been concentrating on a communication system that can deal with very limited line-of-sight distances for potential wireless optical technologies, and an extremely sub-optimal environment for RF communications. This communications subsystem (infrastructure) must be easily deployed, lightweight and low bulk, easily replaced, easily repaired, and robust in dirty and unpredictable underground situations.

The proof of concept test of our wireless cave network 802.11b prototype took place at Robertson’s Cave located approximately 15 miles from Hillsboro, New Mexico (Figure 13). This cave was chosen because it is easily accessible but not visited very often. It is primarily horizontal in extent but with several major bends in the main passage. The parent rock is limestone with interbedded secondary chert layers. It was formed at a previous water table level and then

left high and dry by downcutting in the adjoining canyon and limited tectonic uplift of the entire region in that part of New Mexico. Equipment was unloaded at a Forest Service parking area approximately a mile from the cave and carried in backpacks.

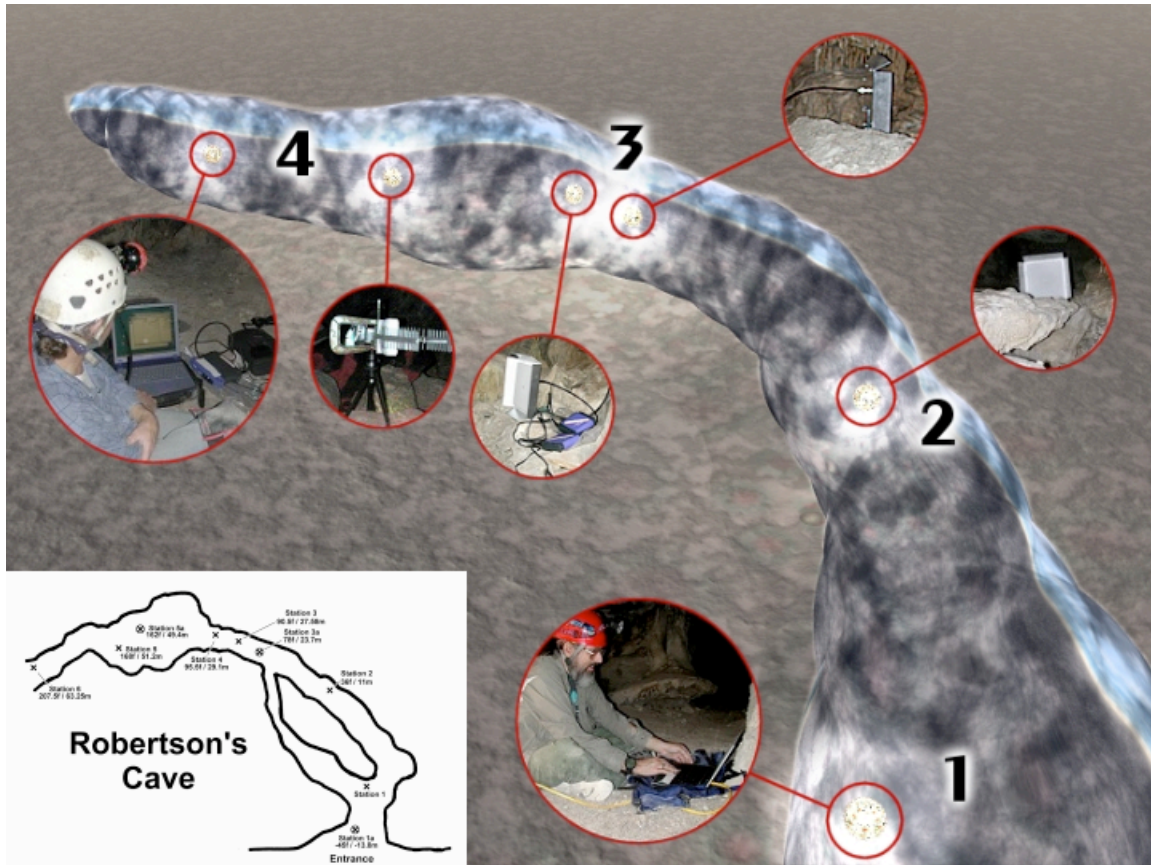


Figure 15: Robertson's Cave 3D volumetric representation with Communication Test Stations indicated. Cave map insert based on our field sketches.

Equipment Description

The test equipment consisted of:

- 1) A Toshiba Portege 2000 PC notebook computer running Windows XP operating system near the mouth of the cave, connected via its internal 10/100 BaseT Ethernet adaptor through a 50 foot Ethernet cable to;
- 2) A Linksys 802.11b/g Router/Access Point (model WRT54G) located a bit further into the cave. The router was running in 802.11b (11Mbps) mode connected to an external 16 dB gain Yagi antenna (wireless link segment A) that was pointed further into the cave towards ;
- 3) A repeater station consisting of two Linksys 802.11b wireless bridges, (model WET11) connected to each other with a short Ethernet 10/100 BaseT cable. Each of the 802.11b bridges had a 15.5 dB gain antenna

connected to it, one pointing “in-cave” (wireless link segment A), and one pointing “out-cave” (wireless link segment B). The “in-cave” antenna was pointed towards the network endpoint;

- 4) The network endpoint station, or simulated data collection site. This site consisted of another 16 dB gain Yagi antenna connected to a Linksys 802.11b/g Access Point (model WAP54G), which was in turn connected via a short Ethernet cable to a second laptop, a Sony VAIO, running the Windows 2000 operating system.

For simplicity during this test, the wireless networking equipment was powered by three small 500VA APC uninterruptible power supplies (model Back-UPS 500), each containing a 12 volt, 7 Amp-hour lead acid battery. These UPS’s weren’t too heavy (about 13 pounds each), and had sufficient capacity to power the 802.11 gear for several hours—more than we needed to conduct this simple test.

In order to avoid interference, link segment A used 802.11b channel 6, and link B used the non-overlapping channel 11. At the repeater station, we kept the link A and link B antennas separated by at least 5 feet and pointed in the opposite direction, in order to reduce a problem called “receiver desensitization”. Receiver desensitization occurs when the receiver on one 802.11 device is made less sensitive by its automatic gain control (AGC) protection circuitry. The AGC circuitry prevents the relatively high power signal from the nearby transmitter on another 802.11 device from damaging the sensitive input circuitry of the receiver. This desensitization is a form of interference, and can occur even when the receiver and transmitter are operating on non-interfering channels if the antennas are too close together. Recommended spacing for between antennas on 802.11b is a minimum of five feet (Reid and Seide, 2003).

We placed the cave entrance station first, with the laptop located at station #1 (see Figure 13), and the router 36 feet further into the cave at station #2, connected via the 50 foot Ethernet cable. We then proceeded in to the repeater location, station #3 and #4. It was desirable that the first wireless link to be not too far, but not line-of-sight, since the biggest question we were hoping to answer was whether the cave walls would severely attenuate (adsorb) the 2.4 GHz 802.11b signal or act as a wave guide, and reflect and direct the RF energy down the cave. We went around one bend in the cave, in order to make this “easy”, but not line-of-sight first hop (the link A segment), and we found a good place to setup the repeater. After setting up all the repeater components, we then proceeded further into the cave, past two bends this time, and set up our endpoint equipment for the first test at station #5. At the first test endpoint we powered up the endpoint laptop, and the Link B Access point, and then came back to the cave entrance, powering up the all equipment as we came out.

We ran the first test with the endpoint at station #5, (see below) and then, after measurements indicated that the link B segment had essentially perfect

signal strength with the endpoint at station #5, we moved the endpoint past another bend in the cave, and set up the endpoint equipment at the final testing point, station #6, where we conducted the remainder of the experiment.

For all testing, we used the simple Web-based configuration and diagnostic tools that came with the Linksys 802.11 hardware. In addition, in order to get some real-world basis of comparison for actual throughput, we also transferred an 8 megabyte file from one laptop to the other and timed it.

The night before our hikes to the cave, we set up the equipment above-ground, and verify that the two-hop link could be established and maintained with the software and hardware. At this time, we determined that when all signals were at maximum, and the diagnostic software reported both links running at full speed (11 Megabits per second), the end to end transfer rate (using an 8.1 Megabyte test data file) was about 3.2 megabits per second—our file was transmitted in 20 seconds on the average, with times varying from 18 to 23 seconds. There was no apparent reason for the variation (see conclusions, below), but this variability pointed out the need for more sophisticated link speed measurement software. We have since acquired an improved configuration.

Test 1 was conducted with the endpoint located at station #5. The diagnostic software used a web browser interface, and we could monitor all the Linksys equipment from either end of the network setup. The end-to-end link came up as soon as the last piece of equipment was powered up, which was a good thing. With the Test 1 setup, link segment B was consistently at maximum signal strength, and 11 Mbps. Unexpectedly, the shorter and less obstructed link segment A was usually also at nearly full strength (80 to 100%, averaging about 90%), but occasionally it would drop down to the slower speeds or occasionally lose contact altogether for a second or less. We experimented with antenna placement and even horizontal vs. vertical polarization, but couldn't seem to either stop or induce these occasional dropouts. We are speculating on the cause of this phenomena but have no good answers at this point.

With this Test 1 setup, the transfer rate for the 8.1 megabyte file was quite close to the above-ground transfer rate, with results ranging from 20 to 25 seconds for the file transfer, averaging 23 seconds, or about 2.8 Megabits per second.

Test 2 was conducted with the endpoint 40 feet further into the cave, and around another bend at station #6. Here we began to see a less than perfect connection, with the B link indicating about 60 to 80% of full strength, and the link B occasionally dropping down from the 11 Mbit per second figure to one of the 802.11b fallback bit rates, usually 5 Mbps. We continued to see occasional dropouts now from both the A and B links. The dropouts increased in duration and frequency with this setup, and at this point saw or imagined some correlation

to between them and movements by the humans in the cave, especially when people were near the repeater station.

With Test setup 2, the transfer rate for the 8.1 megabyte file fell off somewhat, with transfer times ranging from 25 to 35 seconds, averaging 28 seconds, or 2.3 megabits per second.

We maintained this two-hop wireless link for approximately two hours of continuous testing and experimentation of antenna placement and orientation—it seemed perfectly robust and reliable, with the observed momentary dropouts lasting at most a second or two, and having no ill effects on file transfer or web connectivity. After an hour of measurements, we terminated the experiment, and declared it a successful proof of concept.

This experiment proved to our satisfaction that the concept of using 2.4 GHz, 802.11b (or g) wireless networking for cave networking and communications is worth further exploration and development. There are at least two unexpected findings of our initial in-cave tests, and we plan to investigate these further in our future experiments. First, we saw greater attenuation of the 2.4 GHz signal in the shorter, one-bend link A segment than in the Link B segment. The Link A segment was closer to the mouth of the cave and drier than the Link B segment, where the cave walls were damp to the touch in many places. So, we conclude that the cave acts as a better waveguide for 2.4 GHz signals when it is wetter. If this conclusion is accurate, it may indicate that 2.4 GHz 802.11b/g will not be as suitable as 5 GHz 802.11a for use on Mars, where presumably the caves will be dryer (note that extreme dryness may not be the rule for all caves of interest on Mars). This deserves further investigation (see “Future Plans” below), and we do intend to conduct some 5GHz experiments in the future.

Secondly, in retrospect, we think perhaps the variable signal strengths and momentary dropouts we observed may be due to receiver desensitization effects caused by people near the repeater antennas. That is, a human in the path of the 2.4 GHz transmitter of one link might scatter enough of the signal such that the other link’s AGC is activated, causing momentary loss of signal. If true, this could be easily eliminated by increasing the distance between the down-cave and up-cave repeater antennas. For this experiment, we were only a couple of meters apart, but with a longer Ethernet cable between the link A and link B bridges, we could increase this to several meters. For the case in which small microrobotic units are the deploying agents, the large obstructions of human bodies will not be an issue.

A better but more expensive solution for receiver desensitization could involve alternating left and right circularly polarized directional antennas at the repeater stations by using helical directional antennas. This would have the effect of almost completely stopping one link’s RF energy from leaking over to

the other link's receiver, no matter what kind of scattering was occurring in the tight confines of the cave. While inexpensive helical antennas aren't available commercially, we could build them from instructions available on the Internet, and we may try this if time and money permits.

Future system modifications will use better wireless test and diagnostic software, in order to obtain quantitative readouts of signal strength and attenuation. We will also adapt some custom battery packs CSR developed for a previous cave experiment to power the in-cave wireless networking equipment for any operational tests. We will also expand our testing to 802.11a and see if its 5 GHz radio frequency makes a difference in propagation characteristics terrestrial caves. Finally, we hope to set up a small operational demonstration wireless cave network system. We will probably use the 802.11b Linksys equipment used in this test, although if an 802.11g bridge becomes available (for use at the repeater station, we might increase the speed of the connection by using the theoretical 54 Mbps of 802.11g. We would use this demonstration system to demonstrate how we can get video, audio, and scientific telemetry out of a "real" cave science site.

VII. Planetary Protection Protocol Development

One of the most difficult issues that we face working in pristine, biologically sensitive Earth caves is avoidance of contaminating our sites by our very presence. The huge amount of skin cells, hair fragments, and dust that we shed just by moving through an area is enough to disrupt the ultra low nutritional condition of many caves (Moser et al., 2001; Boston et al., 2004). The exercise of performing scientific work under these constraints is a good dress rehearsal for eventual human operations at extraterrestrial biologically sensitive sites. We use a version of a protective suit and breathing gear during science trips to the caves of interest in this study and the others that we are investigating. While not as cumbersome as today's spacesuits, hopefully the lighter weight and less restrictive Tyvek clean suits that we use are a reasonable facsimile of what is being envisioned in lighter more flexible suits for the future (e.g. Hodgson, 2001; Newman, 2001).

“Planetary protection issues: what are the external challenges to the biological environment by pathogenesis or by competition for resources?”

The above quotation from the *NASA Astrobiology Roadmap* document succinctly conveys the problem of protecting the possible biota of another planet from harm. The minute a human investigator enters a cave on Earth, the potential exists for deleterious impact on the indigenous biota (Boston, 1999a & b; Moser and Boston, 2001). In caves that are readily open to the surface, this impact is perhaps less significant because such a system naturally receives considerable and on-going influx of materials from the surface. But in caves that are largely or

entirely sealed, the problem of contamination, changing the environment and breaching the integrity of the system are critical (Figure 14). As we work to solve these issues for caves on Earth, our experiences can serve as a model for similar problems that we will face as we explore extraterrestrial bodies.



Figure 16: A conceptual idea for using sterilized microrobots as cave explorers to minimize contact of human explorers with potentially biologically sensitive extraterrestrial sites. The unique demands of extremophile organism research in Earth caves can provide invaluable insights about how to operate on future robotic and human missions to extraterrestrial bodies for life detection.

VIII. Education and Outreach

The Caves of Mars education Website is an important component to our outreach strategy. By way of it, we can send learners and teachers alike to a multitude of worlds of information. The cross-curricular aspect of the basic subject allows for a wide range of interests and angles. The project website dedicated to our NIAC Phase II activities is available at <http://www.highmars.org/niac/niac01.html> Updates to the site are made every month or when major events or other activities take place. Webmaster is Gus Frederick, gus@norwebster.com

During the two years that this project has been active, outreach to the public in general and the education community in particular has been extensive. Regular media releases and media-targeted Web-based resources have been provided to a global cadre of newsfolk. We have and continue to build working relationships with a number of journalists.

Interest in the Martian Cave concept has been taken up in the popular press from Der Spiegel to the Bend, Oregon Daily Bulletin, we feel in no small part from our efforts. Prior to field trials, media releases were sent out to individual journalists that had showed an interest in space and science in the past. These were followed up with phone calls, and offers of media-ready content. This also facilitated our inclusion in other distribution areas, such as wire services. For example, the Associated Press picked up the story of our “Mouse Mission to Inner Space” story and widely distributed it in multiple venues.

Specific Websites have been setup to provide the media with ready-made camera-ready illustrations and photographs. Members of our team have worked in these same trenches, so we know what they need to make that deadline.

Specific presentations were also made, primarily targeted to the K-12 education community. Multimedia presentations were made to the NSTA regional conference, the Oregon Science Teachers annual conference and we participated in several online interactive video workshops, hosted by the Oregon Access Network. This service connects all of Oregon High Schools by interactive two-way video.

NASA Education officials at Headquarters, NASA JPL as well as other NASA Centers, stress the importance of not reinventing the wheel, and making use of as many of the NASA-developed education activities, lesson plans and resources as possible for all NASA missions and studies. We have attempted to link with relevant parts of other NASA educational activities whenever feasible. The Astrobiology Institute’s web-based materials, curricula, and student activities sections are particularly salient as are portions of the HEDS educational resources.

However, obviously many aspects of our extraterrestrial caves project are unique and worthy of independent development therefore, we have explored educational and outreach possibilities not included elsewhere within NASA educational resources. Our main focus has been a collection of the best Caves of Mars-related activities, lesson plans and resources. This is being compiled and will be available soon in the education section on our Caves of Mars website.

Overview: A key component to the Caves of Mars, (COM) project Web site, (*System Feasibility Demonstrations of Caves and Subsurface Constructs for Mars Habitation and Scientific Exploration; NIAC CP-01-01*) is a suite of educational resources relating to many of the key concepts being examined. Team members have researched and identified a number of NASA-created online curricula and resources that either directly relate to our work, or lend themselves for use by way of minor modifications. Additionally, several new curricular resources have been developed that have grown out of and directly relate to many of the key concepts of our NIAC work.

To disseminate these resources, as well as information on the project as a whole, a website has been developed. Key aspects of the project have their own sections, including a dedicated section assigned to educational outreach.

Focus: The main focus of the COM education component is to provide educators with a suite of *immediately useful* educational tools and resources to teach and learn about caves on Mars. While many educational resources exist dealing with either caves or Mars, little is available on the subject of Martian Caves. We are working to rectify this situation. While we have links to many relevant existing resources dealing with Earth-based caves, as well as resources for Mars, the main content of this site is a growing number of original curricular content packages focused on key portions of the project. Below are short descriptions of the first three such packages.

- **CEMSS:** As a result of our popular “Mouse Mission to Inner Space” trials to test the proto-type self-powered cave life support system, the CEMSS project, (Controlled Ecological Mouse Support System) has spawned a cross-curricular project template, developed for High School level. Working in conjunction with Mr. Steve Holman, a high school teacher in West Salem High School in Oregon, the CEMSS concept has evolved to a new level, with the base educational portions being field tested in an active classroom setting. Mr. Holman, and a half dozen of his honor biology students have taken on the CEMSS project much like an after-school club. By designing, testing and eventually running the experiment on their own, these students will have a first-hand real world experience to report on.

The very nature of the system is such that the experiment can be run in multiple modes: Plants only, plants with mice, mice only, etc. The modular nature of the CEMSS unit itself is conducive to trying different arrangements. The integration of inexpensive education-based data acquisition hardware and software likewise adds a unique technological aspect of the process, and allows for the teaching of data analysis concepts. The cross-curricular approach encourages a team setting, with different interests and learning styles being applied to different aspects of the project.

- **Backyard Lava Tubes:** To illustrate what a lava tube cave is and how it is constructed, another resource is being developed that shows how one can create a model of a lava tube cave using common, easy-to-obtain materials. Unlike the CEMSS project, which by its very nature is more structured, technical and team-oriented, the BYLT activity is geared more towards the individual learner with an artistic bent. It offers an illustrated step-by-step process on making a cave model with spray foam and water balloons. It is suitable for students from middle school up, or as a teacher-led activity for earlier levels. The use of the canned spray foam to layer the water balloons simulates multiple flows of lava as the foam first expands and hardens. Final decoration and presentation allows for much artistic “wiggle-room” while illustrating graphically basic geologic processes that form these features, both here and on Mars.
- **Find the Lava Tube Activity:** Another important aspect of lava tubes on Mars will be identifying and locating them. This activity will use orbital images of Mars from MOC and other orbiters as well as aerial and orbital images of known lava tube areas on Earth and their associated “ground truth” images to show students what to look for. This will involve learning how to navigate the MSSS and Odyssey online Image Galleries, how to interpret NASA’s planetary data system, (PDS) imaging as well as some basic digital image enhancement techniques, with the NASAView cross-platform PDS manipulation software.

The latter portion of the activity will use as a sample image, the strip that the MGS team imaged at our request through the MOC Public Target Request Site Program. The frame, (MOC No. R11-02729d), is a strip just down slope from the North caldera rim of Olympus Mons, and shows a 3-meter-per-pixel resolution image of a series of collapsed flow features and interrupted leveed channels, and its context frame, (MOC No. R11-02730d). With the associated image data, the students will be directed to examine different techniques for enhancing and interpreting the image by selectively increasing contrast, determining the sizes of various features and developing an over-all explanation of those features.

Caves Of Mars Website Flyer For Educators: A Caves of Mars flyer for educators is in production. We plan to have it available soon so it can be included with the posting of our final report on the NIAC website.

Members of our Education and Public Outreach team are also space education resources specialists. They have long-established contacts with the following space and education organizations. These groups have ongoing requests for space science resources to provide to the educators who attend their workshops, professional development courses, conferences and other events. In addition to the flyers, these groups have either linked to our website, or we will be contacting them about linking:

- The Space Foundation's summer Space Discovery Graduate Courses & their Discover Space children's website
- The Challenger Center for Space Science Education
- The Mars Society & their Education Web
- National Space Society
- Civil Air Patrol-Aerospace Education
- Space Frontier Foundation
- National Science Teachers Association
- National Association of Biology Teachers
- American Association of Physics Teachers
- Denver Museum of Nature & Science and a number of other museums
- Home schooling networks

Caves Of Mars Poster: Since classroom teachers especially appreciate posters, we plan to have a Caves of Mars poster available on our website soon, that can be downloaded and printed. Total size will be 11" x 17" and could be easily printed on two 8 1/2" x 11" sheets.

The Mousetronauts Program: One of the features of our NIAC work that has attracted intense interest from students, educators, the public, and particularly the media, is the series of Mousetronaut experiments. Students can

participate either through observing the Mousetronauts on a scheduled mission in their MouseHabs (closed environment life support systems), or by the students actually constructing a MouseHab and running their own experiments in the classroom setting. Students in Oregon during the 2003/2004 school year constructed their own MouseHabs and were involved in demonstrations as part of our Caves of Mars presentations at the Mars Society Conference in Eugene, OR, August 2003.

Mars Society Conference: We participated in a major opportunity to showcase the NIAC Caves of Mars Education, Public Outreach and Media efforts at the Mars Society Conference in Eugene, Oregon from August 14 thru 17, 2003. In addition to the students mentioned above with their MouseHabs, we gave two presentations on our NIAC Caves of Mars research in the general sessions and for educators and students attending the conference. Of special interest was a half day workshop for educators given by NASA-Ames Education Specialist Don Scott which utilized some of our NIAC Caves of Mars concepts.

NIAC Project Appearing In Children's Book: Our cave research including the NIAC project work appears in a children's library book about caving by Laurie Lindop entitled *SCIENCE ON THE EDGE: CAVE SCIENCES* from Millbrook Press of Brookfield, CT.

Cave Preservation Education: Reaching students, educators and the public about the importance of preserving caves on Earth for future generations of scientists and explorers is a high priority in Caves of Mars Education and Public Outreach efforts. This aspect was thoroughly addressed at both sessions at the Mars Society Conference mentioned above and at the Cave Conservation and Restoration session at the National Speleological Society meeting which took place in Porterville, California, August 4-8, 2003. P. Boston gave a talk entitled "What Mars Can Teach Us about Caves on Earth."

Learning Levels & Audience: As much as possible, we are building the COM Education Resource Site to include activities that cover all grade levels, kindergarten through high school. Our intended audience includes a wide range of learning levels. Another audience we hope to involve is the growing home school community. These folks make extensive use of Web-based education.

Content Delivery: Where possible, all content will be on our server. To accomplish this, we are re-formatting many of the existing NASA lessons and activities to keep the same look and feel of the over-all site. These sites of course will be fully referenced as to origin, and will include links back to the original versions. Other resources, such as many of the activities from the Lunar and Planetary Institute will be direct links back to the LPI site, or as in the case of the various Mars orbiter image galleries, back to those servers.

Project lesson guides and many secondary resources will also be available, mainly in the Adobe Acrobat format, and in the case of tabled data, in comma delimited variable, (CSV). The Acrobat files will provide a quick and easy way for teachers and students to “print and go” many of the lessons. Images for those activities making use of them will be in the common .GIF and .JPG format as well as the NASA .PDS format for Mars images, which contain data relating to the specific images.

For the majority of the resources, any common Web browser will work. Supplementary applications such as the free Adobe Acrobat reader will be linked in with basic instructions for its use. The NASAView PDS application will be available via our server or the original NASA site. Where possible, the site design and content will be such that slower connections can easily access this. Additionally, we will attempt to insure that it is “Bobby Compliant” for access by visually impaired users and other disabled learners.

Caves Of Mars Applying For Official Approval Of Technology-Related Activities: We will be submitting our technology-related lesson plans and activities for official approval by the review board comprised of the following organizations: International Technology Education Association, Council for Technology Teacher Education, and National Council for the Accreditation of Teacher Education. Approval is based on lesson plans and activities meeting the Technology For All Americans Project Standards. This approval provides greater dissemination of our activities worldwide.

The National Science Education Standards On Our Website: Among the resources on our Education page, we list Education Standards. We conducted a length search of not only the National Science Education Standards (NSES), but also technology and geography standards. We compiled a list of all the Standards that our NIAC Caves of Mars research could address.

In addition to the National Research Council-National Academy of Sciences' NSES, we included American Association for the Advancement of Sciences' Benchmarks for Science Literacy and the Geography Education Standards from National Geographic. We also used the NASA Space Science Curriculum Standards "Quilt."

It was a time-consuming task to go through these long documents, but it helped us really focus on what activities and resources would be most helpful to not only the classroom teacher, but also community youth groups and home schoolers.

Reaching Home Schooling Students: Members of the EPO team also have a number of close contacts with home schooling networks in Virginia and Colorado. These groups have national networking ties as well. We will be in contact them to ask them to link to our site. There are also two major publications

-- Home Schooling Magazine and Home Schooling Today Magazine. We are pursuing having them publish a listing and description of our website and its resources.

The Standards As A Resource For Other NIAC Contracts: This list of Standards we compiled is also an excellent resource for other NIAC and NASA grantees, especially those whose research involves Mars. Since teachers are required to address the Standards in their classroom activities, it is important to use them in guiding the selection and development of lesson plans, activities and resources.

Space Grant Consortium – Penn State: We mentored the course for the Space Grant Consortium class "SCIENCE, TECHNOLOGY, AND SOCIETY - The Idea of Space Colonization" (STS 497F) offered in spring 2004 at Pennsylvania State University, State College, PA.. The course is run in a seminar format, with lectures alternating between two co-instructors (Ricardo Silva and Brock Pronko) and relevant space experts. We advised on the final project, a simulated space mission in a Pennsylvania cave akin in some aspects to our NIAC project. The link to the course:
<http://www.astro.psu.edu/users/cwc/sts497i-03/>

IX. Conclusion

The Caves of Mars project detailed in this report has tackled a huge number of items on a master laundry list of necessary investigations and feasibility studies to give credence to extraterrestrial cave use and study. Mission planners cannot take options seriously unless the necessary background work is in place. While we have simply scratched the surface on many of the issues that we consider in this report, we hope that we have helped to lay a solid foundation that can be built upon in the future by ourselves and colleagues. The Solar System is a remarkable place filled with many wonders and we believe that it is time that caves took their place alongside the other spectacular natural phenomena worthy of exploration, study, and human utilization.

Acknowledgements:

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X. References Cited and Further Reading

- Adeel A, Siddiqui MA. 1983. On acoustic characteristics, complexity and behavior of *Grylloides sigillatus*, Orthoptera, Gryllidae. *Entomon* 8: 369-372.
- Adler, M.A., ed. 1996. *The Prehistoric Pueblo World, A.D. 1150-1350* University of Arizona Press, Tucson, AZ.
- Alaerts, G. J., Md. Rahman Mahbubar, and P. Kelderman. 1996. Performance analysis of a full-scale duckweed-covered sewage lagoon. *Wat. Res.* 30:843-852.
- Aldrete, J.A. and Virtue, R.W. 1967. Prolonged inhalation of inert gases by rats. *Anesth Analg* 1967; 46: 562-565.
- Alexander, Richard D. & Simons, L.W. (1961) "Aggressiveness, Territoriality, and Sexual Behavior in Field Crickets," *Behaviour*, 17, 130-223
- Al-Nozaily, F., Alaerts, G., and Veenstra, S. 2000. Performance of duckweed-covered sewage lagoons-I. Oxygen balance and COD removal, URL: <http://www.elsevier.nl/locate/jnlr/00309> *Water Research* 34:2727-2733.
- Al-Nozaily, F., Alaerts, G., and Veenstra, S. 2000. Performance of duckweed-covered sewage lagoons-II. Nitrogen and phosphorus balance and plant productivity. URL: <http://www.elsevier.nl/locate/jnlr/00309> *Water Research* 34:2734-2741.
- Amy, P.S. and Haldeman, D.L., *Microbiology of the Terrestrial Subsurface*, CRC Lewis Publishers, Boca Raton, FL, 1997.
- Ancell, M. E. 1998. Constructed Wetlands for Agricultural Wastewater Treatment. M. S. thesis, Dept. of Civil Engineering, Texas Tech University.
- APHA. 1995. *Standard Methods for the Examination of Water and Wastewater*. A.D. Eaton, L.S. Clesceri, and A.E. Greenberg (Eds). 19th edition. American Public Health Association, Washington, D.C.
- Arnold, D.E. 1971. Ethnominerology of the Ticul, Yucatan potters: Etics and emics. *Amer. Antiquities* 36:20-40.
- Arnold, D.E. and Bohor, B.F. 1975. Attapulgitite and maya blue: An ancient mine comes to light. *Archaeology* 28:23-29.
- Balasubramanian PR, Kasturi Bai R. 1992. A study on the utilization of digested biogas plant slurry for aquatic plant biomass production. *Polln Res*, 11 (1):1-11.
- Balasubramanian PR, Kasturi Bai R. 1992. Biogas plant slurry utilization through *Wolffia* aquatic plant culture. *Env Eco*, 10 (2):247-251
- Bate J. 1971. Life history of *Acheta domesticus* (Insecta Orthoptera Gryllidae). *Pedobiologia* 11: 159-172.
- Bate J. 1972. Variation in fecundity of *Acheta domesticus* (Insecta Orthoptera Gryllidae) in relation to season and temperature. *Pedobiologia* 12: 1-5.
- Bateman PW, MacFadyen DN. 1999. Mate guarding in the cricket *Grylloides sigillatus*: influence of multiple potential partners. *Ethology* 105: 949-957.

- Bauman, L., Boston, P.J., LeCompte, M. and McKay, C.P. 1979. *The Preliminary Report of the LASP Mars Study Project*. Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO.
- Bennet, P.B. 1993. Inert gas narcosis. In, P.B. Bennett and D.H. Elliott, eds, *Inert Gas Narcosis*. Pp. 170-193. Saunders, London, UK.
- Biradar VK, Mathad SB. 1983. Influence of crowding on reproduction in the house cricket, *Grylloides sigillatus*. *J. Entomol. Res.* 7: 88-90.
- Boston, P.J. 1981. Low-pressure greenhouses and plants for a manned research station on Mars. *J. Brit. Interplan. Soc.* 34:189-192. Reprinted in, P.M. Bainum, ed., *Space in the 1980's and Beyond*. Vol. 53, Space and Technology Series. pp. 253-265. Amer. Astronaut. Soc., Washington, D.C.
- Boston, P.J. 1986. Human factors. In, S.M. Welch and C.R. Stoker, eds., *The Case for Mars: Concept Development for a Mars Research Station*. JPL Publication 86-28. Jet Propulsion Lab., Pasadena, CA and NASA. pp. 77-93.
- Boston, P.J. 1996. Moving in on Mars: The Hitchiker's guide to Martian life support. In, C.R. Stoker and C. Emmart, eds., *Strategies for Mars: A Guide to Human Exploration*. Vol. 86, Science and Technology Series. pp. 327-361. National Aeronautics and Space Administration, and Amer. Astronautical Soc., Univelt Press, Pasadena, CA.
- Boston, P.J. 1999. Is It Life Or Is It Memorex? Why Humans Are Essential For Scientific Research On Mars. A theoretical and practical analysis of the risks and benefits of *in situ* human scientists. . In, J.A. Hiscox, Editor. *Life on Mars*. British Interplanetary Society, London, UK. pp. 105-112.
- Boston, P.J. 2000a. Bubbles in the rocks: Natural and artificial caves and cavities as life support structures. In, R.M. Wheeler and C. Martin-Brennan, eds. *Mars Greenhouses: Concepts and Challenges: Proceedings from a 1999 Workshop*. NASA Tech. Mem 2000-208577. August 2000, Kennedy Space Center, FL. pp. 9-17.
- Boston, P.J. 2000b. Life Below and Life 'Out There'. *Geotimes* 45(8):14-17.
- Boston, P.J. 2004. The caves of Mars: Possible mechanisms, chemistries, and physical characteristics. In review, *Icarus*.
- Boston, P.J. 1985. Critical life sciences issues for a Mars base. In, C.P. McKay, ed., *The Case for Mars, II*. Vol. 62, Science and Technology Series. pp. 287-332. Amer. Astronaut. Soc., San Diego, CA.
- Boston, P.J. 2003. Extraterrestrial Caves. *Encyclopedia of Cave and Karst Science*. Fitzroy-Dearborn Publishers, Ltd., London, UK.
- Boston, P.J., Frederick, R.D., Welch, S.M., Werker, J., Meyer, T.R., Sprungman, B., Hildreth-Werker, V., Thompson, S.L., and Murphy, D.L. 2003. "Human utilization of subsurface extraterrestrial environments," *Grav. & Space Biol. Bull.* 16(2):121-131.
- Boston, P.J., Frederick, R.D., Welch, S.M., Werker, J., Meyer, T.R., Sprungman, B., Hildreth-Werker, V., Thompson, S.L. 2004. Extraterrestrial Subsurface Technology Test Bed: Human Use and Scientific Value of Martian Caves

- Space Tech. & Applic. Forum 2003 Proc.*. AIP #654. Amer. Inst. of Physics, College Park, MD.
- Boston, P.J., Ivanov, M.V., and McKay, C.P. 1992. On the possibility of chemosynthetic ecosystems in subsurface habitats on Mars. *Icarus* 95:300-308.
- Boston, P.J., Northup, D.E., and Lavoie, K.H. 2004. Preserving the unseen as you clean. Chapter in *Cave Conservation Techniques*, edited by V.Hildreth-Werker and J. Werker, National Speleological Soc. In press.
- Boston, P.J., Spilde, M.N., Northup, D.E., Melim, L.A., Soroka, D.S., Kleina, L.G., Lavoie, K.H., Hose, L.D., Mallory, L.M., Dahm, C.N., Crossey, L.J., and Schelble, R.T. 2001a. Cave biosignature suites: Microbes, minerals and Mars. *Astrobiology Journal* 1(1):25-55.
- Boston, P.J., Welch, S.M., Thompson, S.L., Werker, J., Frederick, R.D., Hildreth-Werker, V., and Sprungman, B. 2001b. Extraterrestrial Caves: Science, Habitat, and Resources. Final report for NIAC CP 99-03, Phase I - #07600-045. <http://www.niac.usra.edu/studies/>
- Boston, P.J., Welch, S.M., Thompson, S.L., Werker, J., Frederick, R.D., Hildreth-Werker, V., and Sprungman, B. 2002. Martian cave utilization: System feasibility demonstrations and scientific exploration technologies, http://www.niac.usra.edu/files/library/fellows_mtg/jun02_mtg/pdf/710Boston.pdf.
- Boynton, W. V. and others. 2002. Distribution of hydrogen in the near-surface of Mars: Evidence for subsurface ice deposits. Published online May 30 2002; 10.1126/science.1073722 (*Science Express Reports*.)
- Brooks, R. A. and A. M. Flynn, 1989. Fast, cheap and out of control: A robot invasion of the solar system. *JBIS*, October 1989, pp. 478--485.
- Brooks, R.A., 1997. Evolutionary robotics; where from and where to. *Evolutionary Robotics: From Intelligent Robots to Artificial Life ER'97*, AAI Books, Ontario, Canada. pp. 1--19.
- Buravkova , L.B. and B.N. Pavlov, 1999: The Possibility to Use Argon Breathing Gas Mixture During Mars Exploration. Joint IAF/IAA Symposium on Life Sciences, Amsterdam.
- Burpee DM, Sakaluk SK. 1993a. The effect of pair formation on diel calling patterns in two cricket species, *Gryllus veletis* and *Grylloides sigillatus* (Orthoptera: Gryllidae). *J. Insect Behav.* 6: 431-440.
- Burpee DM, Sakaluk SK. 1993b. Repeated matings offset costs of reproduction in female crickets. *Evol. Ecol.* 7: 240-250. [*Gryllus veletis* and *G. sigillatus*]
- Cade WH, Cade ES. 1992. Male mating success, calling and searching behaviour at high and low densities in the field cricket, *Gryllus integer*. *Anim. Behav.* 43:49-56. [= *Gryllus texensis*]
- Cade WH. 1981. Alternative male strategies: Genetic differences in crickets (*Gryllus integer*). *Science* 212: 563-564. [= *Gryllus texensis*]
- Calos JB, Sakaluk SK. 1998. Paternity of offspring in multiply-mated female crickets: the effect of nuptial food gifts and the advantage of mating first. *Proc. R. Soc. Lond. Ser. B-Biol. Sci.* 265: 2191-2195. [*Grylloides sigillatus*]
- Carr, M.H. 1981. The Surface of Mars, Yale University Press, New Haven, Conn.

- Carr, M.H. and Wanke, H. 1992. Earth and Mars: Water inventories as clues to accretional histories. *Icarus* 98(1):61-71.
- Conyers, L.B. and Goodman, D., 1997, Ground-penetrating radar: an introduction for archaeologists: Altimira, p.
- Cowgill, U.M. and D.P. Milazzo. 1989. The culturing and testing of two species of duckweed. ASTM Spec. Tech. Publ. 1027 (Aquat. Toxicol. Hazard Assess.: 12th Vol.):379-391.
- Culley, D.D., E. Rejmankova, J. Kvet, and J.B. Frye. 1981. Production, chemical quality and use of duckweeds (*Lemnaceae*) in aquaculture, waste management, and animal feeds. *J. World Mar. Soc.* 12(2):27-49.
- Culley, D.D., Rejmankova, E. y Frye, J. B. 1981. Production, chemical quality and use of duckweeds (*Lemnaceae*). In: *Aquaculture waste management and animal feeds*. World Mariculture Society. U.S.A., pp. 330-340
- Dixon, K.A., Cade, W.H. 1986. Some factors influencing male-male aggression in the field cricket *Gryllus integer* (time of day, age, weight and sexual maturity). *Anim. Behav.* 34: 340-346. [=Gryllus texensis]
- Doherty JA, Callos JD. 1991. Acoustic communication in the trilling field cricket, *Gryllus rubens* (Orthoptera: Gryllidae). *J. Insect Behav.* 4: 67-82.
- Doolittle, J.A. 1982. Characterizing soil map units with the ground-penetrating radar. *Soil Surv. Horizons* 23 (No. 4): 3-10.
- Dubowsky, S. 2000. "CP 99-01 Phase II - Self-Transforming Robotic Planetary Explorers," <http://www.niac.usra.edu/studies/>.
- Dubowsky, S. and Boston, P.J., 2004. Microbots for Large-Scale Planetary Surface and Subsurface Exploration. Final report for NIAC CP 02-02, Phase I. <http://www.niac.usra.edu/studies/>
- Duke, S.K., 1990, Calibration of ground penetrating radar and calculation of attenuation and dielectric permittivity versus depth: MSc Thesis, Dept. of Geophysics, Colorado School of Mines, Golden, 236 p.
- Edmonds, C., Lowry, C. and Pennefeather, J., *Diving and Scubaquatic Medicine*. (Revised second edition). Chap. 9. Diving Medical Centre, Mosman, NSW, 1983.
- Ehrlich, D.J., and Matsudaira, P.T. 1999. Microfluidic Devices for DNA Analysis. *Trends in Biotechnology* 17:315-319.
- Feldman, W. C. and others 2002. Global distribution of neutrons from Mars: Results from Mars Odyssey. Published online May 30 2002; 10.1126/science.1073541 ([Science Express Reports](#).)
- Finn, JE; Sridhar, KR; McKay, CP. 1996. Utilization of Martian atmosphere constituents by temperature-swing adsorption. *J. Brit. Interplanet. Soc.* 49:423-430.
- Fowler, B., Ackles, K.N. and Porlier, G. 1985. Effects of Inert Gas Narcosis on Behavior — A Critical Review. *Undersea Biomedical Research* 12:369–402.
- Frederick, R.D. 1999. Martian lava tube caves as habitats. Second Annual Mars Society Convention, Boulder, CO, Aug. 12-15, 1999.
- French, J. 1989. Rocket propellants from Martian resources. *J. Brit. Interplanet. Soc.* 42:167-170.

- Gage AR, Barnard CJ. 1996. Male crickets increase sperm number in relation to competition and female size. *Behav. Ecol. Sociobiol.* 38: 349-353.
[*Grylloides sigillatus*, *Acheta domesticus*]
- Ghoury ASK, McFarlane JE. 1957. Reproductive isolation in the house cricket (Orthoptera: Gryllidae). *Psyche* 64: 30-36.
- Ghoury ASK, McFarlane JE. 1958. Occurrence of a macropterous form of *Grylloides sigillatus* (Walker) (Orthoptera: Gryllidae) in laboratory culture. *Can. J. Zool.* 36: 837-838.
- Ghoury ASK. 1961. Home and distribution of the house cricket *Acheta domesticus* L. *Nature* 192: 1000.
- Greeley, R. 1969. On the origin of lunar sinuous rilles. *Modern Geology* 1:75-80.
- Greeley, R., and Batson, R. 1998. *The NASA Atlas of the Solar System*, Cambridge University Press. 369 pp.
- Grin, E.A., Cabrol, N.A., and McKay, C.P. 1998. Caves in the Martian regolith and their significance for exobiology exploration.. XXIXth Lunar and Planetary Science Conference. Lunar and Planetary Inst., Houston, TX.
- Grin, E.A., Cabrol, N.A., and McKay, C.P. 1999. The hypothesis of caves on Mars revisited through MGS data; Their potential as targets for the surveyor program. Workshop on Mars 2001: Integrated Science in Preparation for Sample Return and Human Exploration. 2-4 Oct. 1999. Lunar and Planetary Inst., Houston, TX.
- Hammouda, O., A. Gaber, and M.S. Abdel-Hameed. 1995. Assessment of the effectiveness of treatment of wastewater-contaminated aquatic systems with *Lemna gibba*. *Enzyme Microb. Tech.* 17:317-323.
- Hatt, R.T., Fisher, H.I., Langebartel, D.A. and Brainerd, G.W. 1953. Faunal and archaeological researches in Yucatan caves. *Cranbrook Inst. Sci. Bull.* 33:1-119.
- Haustein, A.T., R.H. Gilman, P.W. Skillicorn, H. Hannan, F. Diaz, V. Guevara, V. Vergara, A. Gastanaduy, . and J. B. Gilman. 1994. Performance of broiler chickens fed diets containing duckweed (*Lemna gibba*). *J. Agric. Sci. Cambridge.* 122:285-289.
- Hebard M. 1915. The American species of the genus *Miogryllus*. *J. N. Y. Entomol. Soc.*23:101-21.
- Hebard M. 1935. Studies in the Orthoptera of Arizona, Pt I. New genera, species and geographical races. *Trans. Am. Entomol. Soc.* 61:111-53, Pl. 4-7.
[*Grylitta arizonae*]
- Hedrick AV. 1986. Female preferences for male calling bout duration in a field cricket (*Gryllus integer*). *Behav. Ecol. Sociobiol.* 19: 73-77.
- Hedrick AV. 1988. Female choice and the heritability of attractive male traits: An empirical study. *Am. Nat.* 132: 267-276. [*Gryllus integer*]
- Hedrick AV. 2000. Crickets with extravagant mating songs compensate for predation risk with extra caution. *Proc. R. Soc. Biol. Sci. Ser. B* 267: 671-675. [*Gryllus integer*]
- Heiligenberg W. 1969. The effect of stimulus chirps on a cricket's chirping (*Acheta domesticus*). *Z. Vgl. Physiol.* 65: 70-97.

- Higuchi H., Adachi, Y, Arimura, S., Kanno, M. And Satoh, T. 2001. The carbon dioxide absorption capacity of Amsorb R is half that of Soda lime. *Anesth. Analg.* 93(1) 221-225.
- Hill, C.A. and Forti, P., eds, *Cave Minerals of the World*, 2nd Ed. Nat. Speleol. Soc., Huntsville, AL, 1997. 463 pp.
- Hillman, W.S. 1961. The *Lemnaceae*, or duckweeds: A review of the descriptive and experimental literature. *Botan. Rev.* 27:221-87.
- Hodgson, E. 2001. CP 00-02 Phase I – A Chameleon Suit to Liberate Human Exploration of Space Environments.
- Hoffman, SJ; Kaplan, DI, eds. 1997. *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*. NASA Sp. Pub. 6107. NASA JSC.
- Horz, F. 1985. Lava tubes: Potential shelters for habitats. In, W. Mendell, ed., *Lunar Bases and Space Activities of the 21st Century*. pp. 405-412. Lunar and Planet. Inst., Houston, TX.
- Hose, L.D., Palmer, A.N., Palmer, M.V., Northup, D.E., Boston, P.J., and Duchene, H.R. 2000. Microbiology and geochemistry in a hydrogen sulphide-rich karst environment. *Chemical Geology* 169, 399-423.
- Huber, F., Moore, T.E., and Loher, W. 1989. Cricket behavior and neurobiology. Cornell University Press, Ithaca, N.Y.
- Huffman III, A.C., 1992, Characterization of three-dimensional geological heterogeneities using ground penetrating radar, MSc Thesis, Dept. Geophysics, Colorado School of Mines, Golden, 189 p.
- Jakosky, B.M., Zent, A.P., and Zurek, R.W. 1997. The Mars water cycle: Determining the role of exchange with the regolith. *Icarus* 130(1):87-95 .
- Jelinek, J. 1975. *Pictorial Encyclopedia of the Evolution of Man*. Prague, Hamlyn.
- Jenner, H.A. and J.P.M. Janssen-Mommen. 1993. Duckweed Lemna minor as a tool for testing toxicity of coal residues and polluted sediments. *Arch. Environ. Contam. Toxicol.* 25(1):3-11.
- Jenner, H.A. and Janssen-Mommen, J.P.M. 1989. Phytomonitoring of pulverized fuel ash leachates by the duckweed Lemna minor. *Hydrobiologia* 188-189:361-366.
- Johnson, J.W. 1998. Livestock Waste Management And Policy Through The Utilization Of Aquatic Feedstuffs. M. S. thesis, Texas Tech University.
- Keller, G. V., 1987, Rock and mineral properties: in Electromagnetic methods in applied geophysics -- theory, vol.1, M. N. Nabighian, ed.: Tulsa, Soc. Explor. Geophys., p.13-51.
- Klein, H.P. 1978. The Viking biological experiments on Mars. *Icarus* 34:666-674.
- Kokh, P. 1996. Searching Mars for lavatubes. *Moon Miners' Manifesto*, #93. Section 6.9.3.2.093, Artemis Data Book.
- Kolecki, J.C., and Landis, G. A., 1996, Electrical Discharge On The Martian Surface: NASA Lewis Research Center.
- Lakatos, G., I. Meszaros, S. Bohatka, S. Szabo, M, Makadi, M. Csatlos, and G. Langer. 1993. Application of *Lemna* species in ecotoxicological studies of heavy metals and organic biocides. *Sci. Total Environ. Suppl.* 1993. 773-778.

- Landesman, L. 2000. Effects of herbivory and competition on growth of *Lemnaceae* in systems for wastewater treatment and livestock feed production. MS Thesis, Univ. Louisiana, Lafayette, LA.
- Landolt, E., and R. Kandeler. 1987. The Family of *Lemnaceae* - A Monographic Study: Phytochemistry, Physiology, Application, and Bibliography. (vol.2 of monograph). In Biosystematic Investigations in the Family of Duckweeds (*Lemnaceae*), vol. 4, no. 95. Publications of the Geobotanical Institute of the E.T.H. Zurich: Stiftung Rubel.
- LaPara, T.M., Konopka, A., and Alleman, J.E. 2000. Energy spilling by thermophilic aerobes in potassium-limited continuous culture. URL: <http://www.elsevier.nl/locate/jnlr/00309> Water Research 34:2723-2726.
- Lawrence J. Baudendistel, P, MD 1987. "Performance comparison between prepacked canisters of Sodasorb versus Baralyme." internal report St. Louis University School of Medicine.
- Lee, M., and Schladow, S.G. 2000. Visualization of oxygen concentration in water bodies using a fluorescence technique. URL: <http://www.elsevier.nl/locate/jnlr/00309> Water Research 34: 2842-2845.
- Lindsley, D. H., ed., 1991, Oxide minerals: their petrologic and magnetic significance: Mineral. Soc. Am., Washington, DC
- Lourandos, H., "Pleistocene Australia," O. Soffer, ed., *The Pleistocene Old World*. Plenum Press, NYNY, 1987. Pp. 147-166.
- Malin, M.C. and Edgett, K.S. 2000. Evidence for recent groundwater seepage and surface runoff on Mars. *Science* 288:2330-31.
- Mathad SB, McFarlane JE. 1968. Two effects of photoperiod on wing development in *Grylloides sigillatus* (Walk). *Can. J. Zool.* 46: 57-60.
- McFarlane JE. 1964. Factors affecting growth and wing polymorphism in *Grylloides sigillatus* (Walk): Dietary protein level and a possible effect of photoperiod. *Can. J. Zool.* 42: 767-771.
- McFarlane JE. 1968. Diel periodicity in spermatophore formation in the house cricket *Acheta domesticus* (L). *Can. J. Zool.* 46: 695-698.
- McFarlane JE. 1984. Studies on group effects in crickets; III Wing development of *Grylloides sigillatus* (Walk). *Can. J. Zool.* 44: 1017-1021.
- McKay, C.P. and Nedell, S.S. 1988. Are there carbonate deposits in the Valles Marineris, Mars? *Icarus* 73(1):142-148.
- McKay, C.P. and Stoker, C.R. 1989. The early environment and its evolution on Mars: Implications for life. *Reviews of Geophysics* 27(2):189-214.
- McKay, C.P., Friedman, E.I., Wharton, R.A., and Davis, W.L. 1992. History of water on Mars: A biological perspective. *Adv. Space Res.* 12:231-38.
- McKay, C.P., Meyer, T.R., and Boston, P.J. 1986. Mars base infrastructure. In, S.M. Welch and C.R. Stoker, eds., *The Case for Mars: Concept Development for a Mars Research Station*. JPL Publication 86-28. Jet Propulsion Lab., Pasadena, CA and NASA. pp. 95-108.
- McKay, C.P., Meyer, T.R., Boston, P.J., Nelson, M., MacCallum, T. and Gwynne, O. 1993. Utilizing Martian resources for Life Support. *Resources of Near Earth Space*. Tucson, AZ: University of Arizona Press. pp.819-843.

- McKay, CP; Toon, OB; Kasting, JF. 1991. Making Mars habitable. *Nature* 352:489-496.
- Miura, H., Yasuda, T., and Shimoyama, I. 1997. Insect-model based microrobot. *Robotics and Autonomous Systems* 21(3):317-322.
- Moser, D., Boston, P.J., and Harris, M. 2001. Sampling in Caves and Mines. In *Encyclopedia of Environmental Microbiology*. Wiley and Sons, Publ.
- Moss, M.E. 1999. Economics And Feed Value Of Integrating Duckweed Production With A Swine Operation. M. S. thesis, Texas Tech University.
- Narula, J.S. 1968a. Studies on the skeleton of the Indian house cricket *Grylloides sigillatus* (Walker) (Gryllidae: Orthoptera): I The sclerites of the head capsule and head appendages. *Bull. Entomol.* 9: 134-146.
- Narula, J.S. 1968b. The female genital system of the Indian house cricket *Grylloides sigillatus* (Walker) (Orth Gryllidae). *Entomol. Mon. Mag.* 104: 23-29.
- Narula, J.S. 1969. The male genital system of the Indian house cricket *Grylloides sigillatus* (Walker) (Gryllidae: Orthoptera). *Bull. Entomol.* 10: 86-91.
- Nedell, S.S., Squyres, S.W., and Andersen, D.W. 1987. Origin and evolution of the layered deposits in the Valles Marineris, Mars. *Icarus* 70(3):409-440.
- Newman, D. 2001. CP 00-02 Phase I - Astronaut Bio-Suit System for Exploration Class Missions.
- Northup, D.E. and Lavoie, K.H. 2001. Geomicrobiology of caves: A review. *Geomicrobiology Journal* 18(3):199–220.
- Nowosielski, J.W., and Patton, R.L. 1965. Life-tables for the house cricket *Acheta domesticus* L and the effect of intra-specific factors on longevity. *J. Insect. Physiol.* 11:201-209.
- Olhoeft, G. R., 1991, Magnetic and electrical properties of martian particles: in Sand and Dust on Mars, R. Greeley and R. M. Haberle, eds., NASA Conf. Publ. 10074, p. 44-46. (invited)
- Olhoeft, G. R., 1998, Ground penetrating radar on Mars: in Proc. of GPR'98, 7th Int'l. Conf. On Ground Penetrating Radar, May 27-30, 1998, The Univ. of Kansas, Lawrence, KS, USA, p. 387-392.
- Olhoeft, G.R., 1975, The electrical properties of permafrost: Toronto, Canada, University of Toronto, Dept. of Physics, Ph. D. thesis, 172p.
- Olhoeft, G.R., 1976, Effects of water on the electrical properties of planetary regoliths, in Colloquium on Water in Planetary Regoliths Proceedings: Hanover, NH, Dartmouth College, p. 139-142.
- Olhoeft, G.R., 1977, Electrical properties of natural clay permafrost: Canadian Journal of Earth Science, v. 14, p. 16-24.
- Olhoeft, G.R., 1979, Impulse radar studies of near surface geological structure, in Lunar and Planetary Science X: Lunar and Planetary Institute, Houston, p. 943-945.
- Olhoeft, G.R., 1986, Direct detection of hydrocarbon and organic chemicals with ground penetrating radar and complex resistivity, in Proc. of the NWWA/API Conference on Petroleum Hydrocarbons and organic chemicals in ground water -- prevention, detection and restoration, Nov., 12-14, 1986, Houston: Dublin, OH, NWWA, p. 284-305.

- Oron, G., Potah, D. y Jansen H. 1987. Performance of the duckweed species *Lemna gibba* on municipal wastewater for effluent renovation and protein production. *Biotech.Bioeng.* 19:258-268.
- Otte, D., and Cade, W. 1976. On the role of olfaction in sexual and interspecies recognition in crickets (*Acheta* and *Gryllus*). *Anim. Behav.* 24: 1-6.
- Patton, R.L. 1975. Wing polymorphism in *Acheta domesticus* (Orthoptera: Gryllidae). *Ann. Entomol. Soc. Am.* 68: 852-854.
- Pavlov, B.N., Grigoriev A.N., Buravkova L.B. and Smolin V.V. 1997. Argon in breathing gases. *Undersea & Hyperbaric Medicine*. Suppl. to 24:54.
- Polyak, V. and Asmerom, Y., "Late Holocene Climate and Cultural Changes in the Southwest United States," *Science* 294:148-151 (2001).
- Reid, N. and Seide, R. 2003. 802.11 (Wi-Fi) Networking Handbook, McGraw Hill. pp 168-169.
- Robinette, H.R., M.W. Brunson, and E.J. Day. 1980. Use of duckweed in diets of channel catfish. in *Proc. Ann. Conf. S.E. Assoc. Fish Wildl. Agencies* 34:108-114.
- Rummel, J.D. 2001. Planetary exploration in the time of astrobiology: Protecting against biological contamination. *Proceedings of the National Academy of Sciences* 98(5):2128–2131.
- Sakaluk SK, Belwood JJ. 1984. Gecko [*Hemidactylus turcicus*] phonotaxis to cricket [*Grylodes supplicans*] calling song: A case of satellite predation. *Anim. Behav.* 32: 659-662. [=*Grylodes sigillatus*]
- Sakaluk SK, Burpee DM, Smith RL. 1992. Phenotypic and genetic variation in the stridulatory organs of male decorated crickets, *Grylodes sigillatus*, Orthoptera:Gryllidae. *Can. J. Zool.* 70: 453-457.
- Sakaluk SK, O'Day DH. 1984. Hoechst staining and quantification of sperm in the spermatophore and spermatheca of the decorated cricket, *Grylodes supplicans*, Orthoptera: Gryllidae. *Can. Entomol.* 116: 1585-1590. [=*Grylodes sigillatus*]
- Sakaluk SK. 1982. Onset of phonotaxis and age at 1st mating in female house crickets, *Acheta domesticus* (Orthoptera: Gryllidae). *J. N. Y. Entomol. Soc.* 90:136-141.
- Sakaluk SK. 1984. Male crickets [*Grylodes supplicans*] feed females to ensure complete sperm transfer. *Science* 223: 609-610. [=*Grylodes sigillatus*]
- Sakaluk SK. 1985. Spermatophore size and its role in the reproductive behavior of the cricket, *Grylodes supplicans*, Orthoptera: Gryllidae. *Can. J. Zool.* 63:1652-1656. [=*Grylodes sigillatus*]
- Sakaluk SK. 1986. Sperm competition and the evolution of nuptial feeding behavior in the cricket, *Grylodes supplicans*. *Evolution* 40: 584-593. [=*Grylodes sigillatus*]
- Sakaluk SK. 1987. Reproductive behavior of the decorated cricket, *Grylodes supplicans*, (Orthoptera: Gryllidae): Calling schedules, spatial distribution, and mating. *Behaviour* 100: 202-225. [=*Grylodes sigillatus*]
- Sakaluk SK. 1991. Post-copulatory mate guarding in decorated crickets. *Anim. Behav.* 41: 207-216. [*Grylodes sigillatus*]

- Sasowsky, I.D., Foos, A., and Miller, C.M. 2000. Lithic controls on the removal of iron and remediation of acidic mine drainage. URL: <http://www.elsevier.nl/locate/jnlr/00309> Water Research 34:2742-2746.
- Schaber, G.G., McCauley, J.F., Breed, C.S., and Olhoeft, G.R., 1986, Shuttle imaging radar: physical controls on signal penetration and subsurface scattering in the eastern Sahara: Institute of Electrical and Electronic Engineers Trans. Geoscience and Remote Sensing, v. GE-24, p. 603-623.
- Schenk, C.J., Gautier, D.L., Olhoeft, G.R., and Lucius, J.E., 1993, Internal structure of an eolian dune using ground penetrating radar, in Lancaster, N., and Rye, K., eds., Ancient and Modern Eolian Sediments: Spec. Publ. Int. Ass. Sediment, v. 16, p. 61-69 p. (invited)
- Sharma K. 1976. Oviposition in the house cricket *Gryllodes sigillatus* (Walker). Indian J. Entomol. 38:236-247.
- Shuvalov VF, Popov VA. 1971. Reaction of females of the domestic cricket *Acheta domestica* to sound signals and its changes in ontogenesis. J. Evol. Biol. Physiol. 7: 523-526.
- Sieveling, A. 1979. *The Cave Artists*. Thames and Hudson, Ltd., London, UK. 221 pp.
- Smith, R.L, and Thomas WB. 1988. Southwestern distribution and habitat ecology of *Gryllodes supplicans*. Bull ESA 34:186-190. [=*Gryllodes sigillatus*]
- Smith, S., and Kwan, M.K. 1989. Use of aquatic macrophytes as a bioassay method to assess relative toxicity, uptake kinetics and accumulated forms of trace metal. Hydrobiologia 188/189: 345-31.
- Sogaard, E.G., Medenwaldt, R., and Abraham-Peskir, J.V. 2000. Conditions and rates of biotic and abiotic iron precipitation selected Danish freshwater plants and microscopic analysis of precipitate morphology. URL: <http://www.elsevier.nl/locate/jnlr/00309> Water Research 34:2675-2682.
- Squyres, S.W., Clifford, S.M., Kuzmin, R.O., Zimbelman, J.R. and F.M. Costard. 1992. Ice in the Martian Regolith. In: H.H. Kieffer et al., (eds.) Mars, University of Arizona Press, Tucson, AZ. pp. 523-554.
- Squyres, S.W., D.E. Wilhelms, and A.C. Moosman. 1987. Large-scale volcano-ground ice interactions on Mars. *Icarus* 70:385-408.
- Stoker, C.R. and Emmart, C. eds. 1996. *Strategies for Mars: A Guide to Human Exploration*. Vol. 86, Science and Technology Series. pp. 327-361. National Aeronautics and Space Administration, and Amer. Astronautical Soc., Univelt Press, Pasadena, CA.
- Subramaniam M, Haniffa MA, Pandian TJ. 1988. Effect of multiple matings on egg production in *Gryllodes sigillatus* (Walker) (Orthoptera: Gryllidae). Entomon 13: 317-320.
- Subramaniam M, Subramoniam T. 1990. Mating behavior and spermatophore transfer in *Gryllodes sigillatus* (Walker) (Orthoptera: Gryllidae). Mitt. Zool. Mus. Berl. 66: 65-71.
- Tankersley, K.B., Munson, C.A., Munson, P.J., Watson, P.J., Shaffer N.R. and Frushour, S.S. 1997. Archaeology and speleothems. In, C.Hill and P.

- Forti, eds., *Cave Minerals of the World, Second Edition*. Pp. 266-270. Nat. Speleolog. Soc., Huntsville, AL.
- Taraldsen, J.E., T.J. Norberg-King. 1990. New method for determining effluent toxicity using duckweed (*Lemna minor* L.). *Environ. Technol. Chemistry* 9:761-767.
- Tauriainen, S.M., Virta, M.P.J., and Karp, M.T. 2000. Detecting bioavailable toxic metals and metalloids from natural water samples using luminescent sensor bacteria. URL: <http://www.elsevier.nl/locate/jnlmr/00309> *Water Research* 34:2661-2666.
- Taylor, A.G. and Gibbs, A. 1998. New views of the Moon: Integrated remotely sensed, geophysical, and sample datasets. September 20, 1998 at the Lunar and Planetary Institute in Houston, Texas.
- Thompson, S.L. and Boston, P.J. 1997. Urine mitigation with concurrent power generation for Lechuguilla Cave. *Carlsbad Caverns National Park*, Carlsbad, New Mexico.
- Tilden, M.W. 1997. Coordinated Covert Detector Ecologies, 4th. EUROPEAN CONFERENCE ON ARTIFICIAL LIFE: ECAL97 PROCEEDINGS, Brighton, UK, July 28-31, 1997, Publisher: MIT Press/Bradford Books. Editors: Phil Husbands and Inman Harvey. Submission number - ecal97_1/97:1:20:18:8-6887-14660.
- Tilden, M.W. 1998. 'Autonomous Biomorphing Robots as Platforms for Sensors', Report Number 'LA-UR--96-3222, U.S. Information Bridge, DOE Office of Scientific and Technical Information (OSTI), <<http://www.doe.gov/EnergyFiles/>>, Jan 21, 1998.
- Tilden, M.W. 2001. "The simply-does-it robotic approach", *Astronomy Now*, Volume 15, Number 6, June 2001, ISSN 0951-9726, Tonbridge, Kent, United Kingdom, Pgs 3, 49, 55-57, <<http://www.astronomynow.com>>
- Walden, B.E. 1988. Lunar base simulations in lava tubes of the Pacific Northwest. AAAS Pacific Region Meeting, Corvallis, OR. June, 1988.
- Walden, B.E., Billings, T.L., York, C.L., Gillett, S.L., and Herbert, M.V. 1988. Utility of lava tubes on other worlds. AAAS Pacific Region Meeting, Corvallis, OR. June, 1988.
- Walker T.J. 1977a. Japanese burrowing cricket widely established in southeastern United States. *Fla. Entomol.* 60: 308-309. [*Velarifictorus micado*]
- Walker T.J. 1977b. Re-examination of monopteroous and "micropteroous" house crickets (*Acheta domesticus*). *Ann. Entomol. Soc. Am.* 70: 602.
- Wang, W. 1986. Toxicity tests of aquatic pollutants by using common duckweed (*Lemna minor*). *Environ. Pollut.* 11B:1-14
- Wang, W. 1986. Toxicity tests of aquatic pollutants by using common duckweed. *Environ. Pollut.* 11:1-14.
- Watson, P.J. 1986. Prehistoric cavers of the eastern woodlands. In, C. Faulkner, ed., *The Prehistoric Native American Art of Mud Glyph Cave*. Pp. 109-116. Univ. Tennessee Press, Knoxville, TN.
- Weissman DB, Rentz DCF. 1977. Feral house crickets *Acheta domesticus* (L) (Orthoptera: Gryllidae) in Southern Calif. *Entomol. News* 88: 246-248.

- Weldon, L.W., Blackburn, R.H. y Harrison S.D. 1973. Common aquatic weeds. Dover Publications Inc. New York., pp. 2- 10
- Werker, J. and Hildreth-Werker, V. 1997. Management Plan For La Cueva De Las Barrancas. United States Department of Agriculture Forest Service, Southwest Region (Region 3), Lincoln National Forest, Guadalupe Ranger District.
- Wong, J., Rossiter, J.R., Olhoeft, G.R., and Strangway, D.W., 1977, Permafrost: electrical properties of the active layer measured in situ: Canadian Journal of Earth Science, v. 14, p. 582-586.
- Wright, R.V. 1971. *The Archaeology of the Gallus Site, Koonalda Cave*. Inst. Aboriginal Stud., Canberra, Australia. 133 pp.
- Wymer, J. J., *The Paleolithic Age*. London, Croom Helm, 1982.

Appendix A:

Void as Object: Scanning Skylight Cave

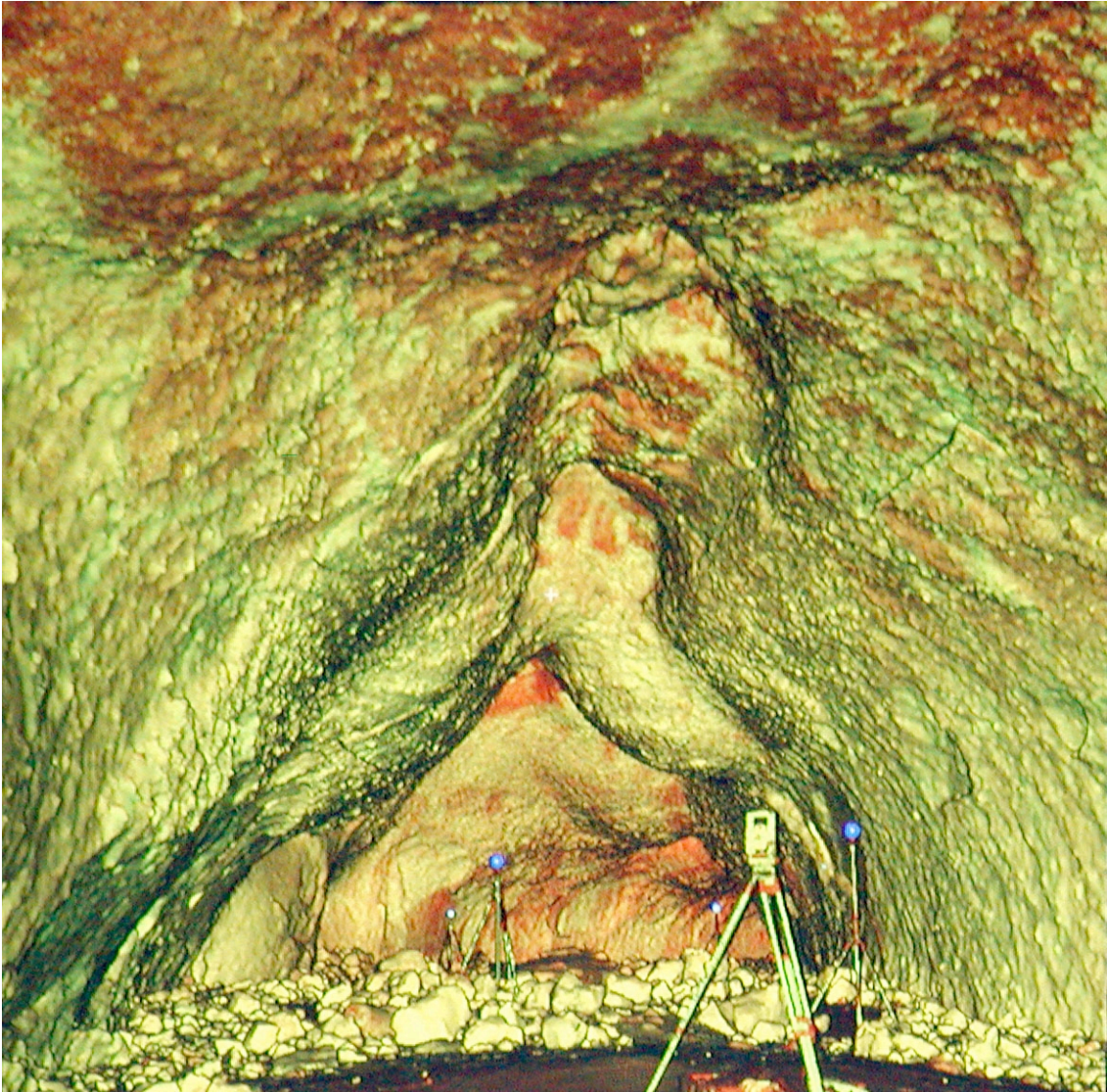
Overview: Cyra Technologies in Oakland, California produces a device called the “Cyrax System,” a state-of-the-art LIDAR scanning system with integrated 3-D modeling software. With it, a user can literally scan a 3 dimensional object or area, and convert that to a digital point cloud, viable in any 3D CAD application. The Cyrax is used primarily for architectural and transportation use, but several experiments were performed in caves to test the viability of capturing natural voids in this manner.

Through a serendipitous encounter, Pacific Survey Supply, one of five engineering firms with a Cyrax, unit was interested in trying the unit out in a lava tube cave. The other cave tests were performed in a limestone, or karst environment. We had already obtained a three-day conditional use permit from the Deschutes National Forest to use Skylight Cave, a small lava tube near Sisters, Oregon for our Mouse Mission to Inner Space demonstration. The crew from PSS went in and scanned the cave while we prepped the CEMSS unit prior to starting our experiment.

The unit includes the central scanner, connected to a laptop computer, and several movable reflective calibration targets. The scanner shoots out LASER light pulses as it tracks around the cave. The distance from the light’s reflection on the cave wall is recorded, and on the fly translated by software into a 3-Dimensional representation of the scene.

The process is repeated from several vantage points, and the resulting point clouds stitched together to form a digital “object file” of the cave’s space. Through additional software, the file can be converted to one of several common 3D CAD formats.

While the over all process of scanning this cave took awhile, (close to 6 hours for an approximately 200 meter cave), the results were astounding. The resulting mesh file would be invaluable for cave survey purposes, especially if the system could be automated and scaled down. Additionally, it could facilitate the creation of custom form-fitted inflatable cave habitats, by integrating the LIDAR scanner and software with a CAD-CAM system.



Cyra Technologies 3D scanning setup in Skylight Cave lava tube.

Appendix B: Remote Sensing of Biological Signatures of Martian Caves

As a way to advance the search for life on Mars, one direction our research has taken is to investigate the feasibility of identifying biomarkers by remote sensing on Mars, that is, remote identification of minerals that have become altered from being in contact with biological processes.

One auspicious location for finding such evidence on Mars is in the vicinity of Martian caves. Compared to the environment on the surface of Mars, caves can offer significantly enhanced environmental protection that may enable microorganisms to flourish. They can completely block the harsh solar UV on Mars and they can ameliorate solar energetic particle (SEP) radiation and galactic cosmic radiation (GCR). Caves can also minimize temperature extremes and keep their internal temperatures close to the planetary mean. In volcanic areas caves may be conduits for volcanic gases including methane and water vapor that may be beneficial for organisms.

External evidence of past or present life in Martian caves may be visible around cave openings, along porous zones, and in debris fields where cave integrity may have been disrupted by weathering, erosion, or meteor impacts. The detection of such evidence might be accomplished by remote sensing from Mars orbit, from low flying craft such as gliders and balloons, or by robotic vehicles on the surface. Ideally, preliminary surveys can be conducted by remote sensing before rovers are deployed.

To pursue this it will be necessary to develop instruments for distinguishing between biologically altered minerals (biomarkers), inorganically and environmentally altered minerals such as desert varnish, freshly exposed or unaltered minerals, and the many potential varieties of each category.

To test this hypothesis, we have defined a methodology for Earth analog investigations that could be the subject of a future research proposal, and we have already investigated certain aspects during the course of this research.

The first requirement is the development of a catalog of biomarker specimens detailing their morphology and mineralogy, their spectral signatures, and other properties as may prove diagnostic. P.J. Boston has already collected some field specimens for this purpose from sites in New Mexico and at the Mars Desert Research Station in Utah.

The second phase requires the selection and study of a desert Mars analog research site that contains caves, both with and without biology, and plain areas without caves. In situ measurements must be taken using portable equipment so as to completely characterize the biological and mineral signatures throughout the site and this data must be correlated with a complete assessment of the biological species in the caves. Using this data as ground truth, remote sensing instruments must then be selected or developed.

Over the past two years we have pursued the development of video remote sensing equipment that we have flown on several experimental gliders. We have begun the investigation of various remote sensing instruments including systems for multi-spectral imaging. Lastly, we have initiated a seminar series on space instrument technology for mineral and biological analysis that will be hosted jointly by Complex Systems, Inc., the Boulder Center for Science and Policy, and by Equinox Interscience, Inc. a space instrumentation company. This will start in the fall of 2004.



21 foot wingspan Mars glider. Payload capacity (remote sensing instrumentation, etc.) of several Kilograms

Appendix C: CAVES OF MARS E/PO MEMBERS TO PRESENT AT SCIENCE TEACHERS CONVENTIONS

Two of our E/PO members have been accepted to present at National Science Teachers Association (NSTA) Regional Conventions in late 2004:

NSTA Regional
November 18-20, 2004
Seattle, WA
Presenter: R.D. "Gus" Frederick

NSTA Regional
December 2-4, 2004
Richmond, VA
Presenter: Barbara Sprungman

CAVES OF MARS Brief NSTA Session Description:

Martian Geology and Biology Activities: The Caves of Mars Project
Learn about geology, astronomy and biology activities and resources collected and created as part of a two-year NASA-funded study on how Martian lava tube caves can provide future human explorers with a sheltered habitat and laboratory.

CAVES OF MARS Longer NSTA Session Description:

Learn about the Caves of Mars Project's Mousetronauts breathing Martian-like air in their Controlled Ecological Mouse Support System -- and how to build one. Other activities include Building a Backyard Lava Tube and Find the Lava Tube using recent orbital images of Mars.

As NASA and its international partners pursue their quest for signs of life, or evidence of former life, by following where the water once was on Mars, lava tube caves are of high interest. Hand-outs will include a list of lesson plans, activities and resources on Martian geology, biology, comparative planetology (Earth & Mars) and astronomy, collected and created as part of this two-year NASA-funded study on how Martian lava tube caves can provide future human explorers a sheltered habitat and laboratory for studying geological (and perhaps biological?) samples.

Also hear how the project's astrobiologists conduct research in southwestern U.S. caves gathering biological samples in their quest to understand how life in extreme environments on Earth could give us clues to life on Mars. They also tested cave communication systems using wireless computers. The project is a NASA Institute for Advanced Concepts (NIAC) Phase II study entitled: System Feasibility Demonstrations of Caves and Subsurface Constructs for Mars Habitation and Scientific Exploration (NIAC contract # CP-01-01).

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