HUMAN UTILIZATION OF SUBSURFACE EXTRATERRESTRIAL ENVIRONMENTS
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ABSTRACT
Caves have been used in the ancient past as shelter or habitat by many organisms (including humans). Since antiquity, humans have explored caves for the minerals they contain and sometimes for ceremonial purposes. Over the past century, caves have become the target of increasing exploration, scientific research, and recreation.

The use of caves on extraterrestrial bodies for human habitation has been suggested by several investigators. Lunar lava tube bases received early attention because lava tubes were clearly visible in lunar images from the Apollo Era. More recently, Mars Observer Camera data has shown us clear evidence of large tubes visible in a number of volcanic regions on Mars.

The budding field of cave geomicrobiology has direct application to questions about subsurface life on other planets. Caves contain many unusual organisms making their living from unlikely materials like manganese, iron, and sulfur. This makes caves and other subsurface habitats prime targets for astrobiological missions to Mars and possibly other bodies.

We present the results of a completed Phase I and on-going Phase II NASA Institute for Advanced Concepts (NIAC) study that intensively examines the possibilities of using extraterrestrial caves as both a resource for human explorers and as a highly promising scientific target for both robotic and future human missions to Mars and beyond.

INTRODUCTION
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. Conditions in the interiors of caves are usually radically different from the surface environment (Boston et al., 2001a). This has enabled microorganisms, larger organisms and even humans to gain protection from surface conditions 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 status of many types of caves on other planets in our Solar System is unclear; however, the basic physical and chemical processes that produce many of the cave types on Earth have counterparts on other bodies (Boston, 2003). Thus, caves are expected to be widely distributed on many other planets, as shown in Table 1. In particular, the Moon and Mars show clear photographic evidence of lava tube caves, as shown in Figure 1. Our future aspirations to explore Mars and the Moon both robotically and with human crews can utilize extraterrestrial caves as both objects of extreme scientific interest and as potential resources to facilitate human tenure on the surface of those bodies (Boston et al., 2001b).

NIAC PHASE I TECHNOLOGY IDENTIFICATION
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, as summarized in Table 2. See the Project Report at http://www.niac.usra.edu/studies/ NIAC Phase I: Identification of Enabling Technologies.

The Phase I list of enabling technologies deemed worthy of further exploration and potential experimentation include:

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 techniques
- Planetary protection protocol development

NIAC PHASE II FOCUS
Over the course of the first half of our Phase II study, we have begun to explore each of the technologies listed above. We have made inroads on feasibility assessments and concept developments for all of these major technologies. In some cases, we have undertaken actual experimentation and development of simple prototype operational systems.

Our conceptual framework for systematically exploring our enabling technology list is an eventual
Table 1. Extraterrestrial Cave Types

<table>
<thead>
<tr>
<th>Site Type</th>
<th>Possible Parent Materials</th>
<th>Possible Formation Mechanisms</th>
<th>Possible Unique Martian Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solutional Caves</strong></td>
<td>Soluble Rock</td>
<td>Dissolution of rock by solvent</td>
<td>Other non-water liquid solvents, e.g. liquid CO₂ on Mars, or liquid N₂ on Titan</td>
</tr>
<tr>
<td>Epigenic Caves</td>
<td>Limestone, Dolomite, Gypsum, and other soluble rocks or minerals</td>
<td>Weak carbonic acid (groundwater or rain and dissolved CO₂), organic acids</td>
<td></td>
</tr>
<tr>
<td>Hypogenic Caves</td>
<td>Limestone, Dolomite, Gypsum, and other soluble rocks or minerals</td>
<td>Strong sulfuric acid (subsurface H₂S dissolving at the water table)</td>
<td>Sulfur-rich crust, e.g. on Mars, may make hypogenic caves more likely</td>
</tr>
<tr>
<td>Other karstic caves</td>
<td>Quartzite, Sandstone, arkoses, opalized silicates, etc.</td>
<td>Water dissolution of parent rock, decementation, tafoni formation</td>
<td>Other non-water liquid solvents, e.g. liquid CO₂ on Mars, or liquid N₂ on Titan</td>
</tr>
<tr>
<td>&quot;Pseudokarst&quot; Caves</td>
<td>Meltable or vaporizable solid</td>
<td>Melting or other phase transition</td>
<td>Scale of tubes larger than Earth</td>
</tr>
<tr>
<td>Lava tubes, bubbles</td>
<td>Basalt, andesite,</td>
<td>Molten rock with differential cooling of outer surfaces</td>
<td></td>
</tr>
<tr>
<td>Sub-ice volcanic caves</td>
<td>Ice masses overlaying volcanic terrain</td>
<td>Lava/ice or lava/permafrost interactions</td>
<td>Lava interactions with CO₂ ice or ice-clathrate interactions, around ice sublimation</td>
</tr>
<tr>
<td>Glacier caves</td>
<td>Ice masses</td>
<td>Thermal and pressure-induced localized melting in water ice</td>
<td>Melting in super-cooled water ice, and other ices, e.g. CO₂, methane, or ammonia ice</td>
</tr>
<tr>
<td>Ice volcanism</td>
<td>Ice crusts with subsurface liquid and/or vapor</td>
<td>None known for Earth</td>
<td>Ice-covered bodies, e.g. Europa, Callisto, and other planet's moons</td>
</tr>
<tr>
<td>Subsidence caves</td>
<td>Permafrost, ice/sediment complexes</td>
<td>Permafrost voids</td>
<td>Ground ice sapping and subsequent collapse and void formation on Mars or cold moons</td>
</tr>
<tr>
<td>Volatile labyrinths</td>
<td>Icy breccia or rubble</td>
<td>None known for Earth</td>
<td>Sublimation or boiling of ground ices, e.g. on perihelion passage by comets</td>
</tr>
<tr>
<td><strong>Tectonic &amp; Fracture Caves</strong></td>
<td>Solid rock &amp; ices</td>
<td>Faulting, rifting &amp; other tectonic movements</td>
<td>Cratering and subsequent fracturing</td>
</tr>
<tr>
<td><strong>Erosional Caves</strong></td>
<td>Solid materials</td>
<td>Weathering effects</td>
<td></td>
</tr>
<tr>
<td>Piping caves</td>
<td>Unconsolidated materials</td>
<td>Subsurface erosion of particles by water, “suffusion” in arid environments</td>
<td>Subsurface erosion of particles by non-water solvents</td>
</tr>
<tr>
<td>Sea caves</td>
<td>Solid rock, welded tuff, ice</td>
<td>Water action (waves, floods) against rock</td>
<td>Massive flood events, e.g. on Mars. Aeolian caves on Venus</td>
</tr>
<tr>
<td>Wind-scoured caves</td>
<td>Solid rock, welded tuff, ice</td>
<td>Wind blasting of abrasive particles against rock</td>
<td>Global or regional dust storms on Mars. Aeolian caves on Venus</td>
</tr>
<tr>
<td>Thermo-kinetic caves</td>
<td>Solid rock</td>
<td>Thermal expansion and contraction, spalling, exfoliation</td>
<td>Thermal; regimes and unique physical effects much hotter &amp; much colder than Earth</td>
</tr>
</tbody>
</table>


Figure 1. Ceraunius Patera. Large Martian volcano showing distinct lavatubes flowing down its surface. Upper tube drains into an apparent lava lake at bottom of slope. Lower left buried tube shows series of collapse pits along the length of the tube. NASA Malin Space Systems image.
Table 2. Innovations Unique to Phase I. 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.

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

human trial in an Earth Cave Habitat that incorporates some of the important features required for a Martian version (Human Mission to Inner Space; Figure 2). In support of that, and 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 (Mouse Mission to Inner Space). Aside from allowing us to test some of our notions (e.g. the idea of using argon (Ar) gas in breathing mixtures because of its relative simplicity of acquisition from the Martian atmosphere, as illustrated in Figure 3), the Mouse Mission to Inner Space has proven very 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.

Figure 2. Human Mission to Inner Space. As a demonstration of several of our identified critical enabling technologies for successful use of Mars caves as habitat, we are developing an Earth cave mission. This mission will take place in a cave with a poisonous, unbreathable atmosphere necessitating full breathing gear. The trial will involve a crew of two who will deploy their cave inflatable habitat, render the infrastructure systems operational, and perform a roster of cave exploration and science tasks in this cave that has no natural opening and is unexplored. Graphic by R.D. Frederick. Inset photo by V. Hildreth-Werker.
Essential Tasks

In developing the ideas that flow from our overarching concept of extraterrestrial cave use, we have identified a logical sequence of goals that must be met. These goals include:

1. Finding Extraterrestrial (ET) Caves
   (remotely and in situ)
2. Facilitating ET Cave Science
   (robotically and for human crews)
3. Cave Life Support
4. Planetary Protection and Operational Protocol Development
5. Educational Outreach and Communication

1. Finding ET Caves

We are not specifically developing new ideas for cave detection, but we are assessing those techniques that can provide information on possible cave location. These include: orbital reconnaissance, aerial reconnaissance, geophysical methods (e.g. ground-penetrating radar, microgravity anomaly mapping, seismic techniques), outgassing sources possibly indicative of subsurface access, situational (i.e. geological settings conducive to subsurface cavity formation), specific on site tools for exploration, use of microrobots (expendable, simple, and numerous) self-deploying communication systems, and robotic mapping networks. Subprojects that have resulted from this work, include development of a glider reconnaissance prototype for future Mars aerial cave detection (in collaboration with PSAI, Performance Software Associates, Inc., in Denver), collaboration on robotic cave mapping techniques using a 3D Lidar Scanner system from Cyrax 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.
2. Facilitating ET Cave Science

Based on our existing experimental and field program in the geomicrobiology, mineralogy, geology, and climatology of caves, we are developing concepts that can facilitate both robotic and human field science.

Spin-off concepts for facilitating such science include proposals to NASA for a Speleoscope instrument (a robotic micro-explorer for inundated sub-human scale passages) in collaboration with Equinox Interscience in Denver, CO, collaboration with SWRI, Inc. (Southwest Research Institute) in Boulder, CO, on Project DEPTHX for exploration of subsurface environments aquatic environments, and development of a small, hand-portable general science instrument for human use in caves.

3. Cave Life Support

Most of the actual experimental work that we have conducted with NIAC sponsorship has been in the area of cave life support issues. These primarily involve interior cave modifications that can render caves habitable for long periods, unusual breathing gas mixtures derivable from the existing Martian atmosphere, and energy acquisition strategies. To accomplish these goals, we have focused on inflatable structures as cave liners and novel airlock designs suitable for deployment in topologically complex cave environs, as illustrated in Figure 4, and human operational considerations in the challenging environment of a cave while wearing protective gear and breathing apparatus, as illustrated in Figure 5.

4. Planetary Protection Protocol Development

We are exploring microrobotic technologies as possible precursors to human involvement at potentially biologically sensitive sites, as illustrated in Figure 6. The use of such devices could make the “chain of asepsis” more secure, that is, put greater barriers between humans and putative biological materials that might be discovered. This facilitates both protection of any indigenous biota that may exist and safeguards the health of astronauts, both of which are of critical concern to NASA and the international space community (Rummel, 2001).

Specific critical tasks suitable for miniature robotic bioexplorers and assistants to Mars astronauts include aseptic reconnaissance trips, long term monitoring of sensitive sites, noninvasive in situ techniques. Future astronaut training activities in Earth caves can further refine operational protocols for specific missions.

5. Education and Outreach

The primary educational and outreach efforts to date have focused on the high school age population and the general public. We have had several high school students working on summer projects. During the 2002/2003 school year, a high school class in Oregon developed their own controlled environment mouse habitats. Aspects of this work has appeared in several children’s science magazines over the past year and will be included in a forthcoming children’s book from Millbrook Press, CT, entitled “Science On the Edge: Cave Science”.

Scientific Justification for Extraterrestrial Caves as Mission Targets

Caves provide an unparalleled window into the subsurface (Boston, 2000 a,b). Through this window, aspects of the geology, climate history, deep microbial world, and unique minerals and ores are preserved and observable in important detail not available from surface observations (shown in Figure 7). Caves on other planets undoubtedly will have preserved many of the same phenomena. If life has ever existed on Mars, traces of its presence may well be best preserved in the protective environment of caves. If an extant biosphere survives, it is likely to have survived by exploiting a protected, subsurface way of life (Boston et al., 1992). Compared to labor intensive activities involved in drilling, developing cave detection and exploration methodologies for other planets may, indeed, prove to be MORE cost effective in the long run for extraterrestrial subsurface exploration.

Habitat Issues

The surface of Mars has strong fluxes of high intensity. short wavelength ultraviolet radiation, and background galactic and solar ionizing radiation. These circumstances make the surface extremely inhospitable for the construction of human habitat. Radiation shielding requirements are onerous. The notion of using subsurface habitats on Mars, the Moon, and other planets has been advanced by several authors (see Boston et al., 2001b, for a review). Typically, mound ed earth construction has been cited as a possible solution. However, there is potentially a free resource that exists on the Martian surface – caves. These natural constructs can provide more than adequate radiation shielding and the shell of a pressure vessel that can be sealed via lining and other techniques to provide large and convenient habitat, working space, subsurface greenhouse area, and storage. In contrast to human constructed subsurface space which is labor intensive and costly, caves are often very large and commodious, especially lava tube caves. We already know that these exist on the Martian surface, as shown in Figure 1 (Boston, 2003). The lower gravity of Mars (possibly combined with differences in the lava chemistries) has resulted in lava tubes of scales greatly exceeding those found on Earth (3–10 times the width and several times typical lengths).

In addition to the enormous physical effort required to manually construct subsurface habitat on Mars, it is also a hazardous endeavor in a novel and challenging environment and will eat into the time budget of future astronauts in an unacceptable way. Using existing caves as the primary construction promises to alleviate time, expense, and hazard factors for the astronauts. In the future, extraterrestrial cave operations can be developed and tested in Earth caves of appropriate types. This will also allow for in situ astronaut training.
Figure 4. Airlock View from Inflatable Habitat. Speleonaut returns to the incave, inflatable habitat after a trip into the cave or perhaps onto the Martian surface. Graphic by R.D. Frederick©, 2003.

Figure 5. Operational Protocols. Development of protocols for working in physically hazardous environments like caves while wearing pressure suits present a significant challenge. As a template, we are using our experiences working in Earth caves with poisonous atmospheres (Boston et al., 2001a). Graphic by R.D. Frederick©, 2003.
Figure 6. Planetary Protection. Microrobot inspecting potential biological material in a Mars lavatube cave entrance. This illustrates utility of non-human devices as intermediaries to ensure safety of both astronauts and any indigenous biota. Graphic by R.D. Frederick©, 2003.

Figure 7. Science in Caves. Caves can contain minerals, ice, and other frozen volatile compounds. They can provide closer access to subsurface deposits and also act as storage facilities. Biology and microbiology of native subsurface life forms on Earth is helping to provide a “Field Guide to Unknown Organisms” to help us plan exploration of other Solar System bodies. Caves are wonderful preservation environments for both fossil materials and for preserving signals of climate change. Images: Upper left by V. Hildreth-Werker; upper right by K. Ingham; lower left Scanning Electron Micrograph by M. Spilde and P. Boston; lower right by R.D. Frederick.
Specific Accomplishments in Habitat Issues

Design of Inflatable Habitat and Airlock

Extensive design work on the inflatable incave habitat for the human cave mission has taken place. A series of small-scale inflatable test shapes were constructed and deployed in small rocky vugs in cave walls to observe topological accommodation to uneven rocky surfaces. The design team is considering the problem of simplicity of shape vs. functionality of use. A simple cylinder is the easiest to fabricate, but there are concerns about use of this shape in large cave passages where the unit is much smaller and doesn’t touch the walls. We have settled on a hemicylindrical basic profile with slightly squared join lines along the top to provide additional head room.

Airlock design considerations are still being refined. Our original intent of a rigid door and frame unit has given way to a much lighter and more easily deployed door design that uses the same material as the main inflatable. Methods of assuring the seal around the inflatable fabric insertion are the primary concern. The team produced a series of three preliminary designs to use in fabricating small test units to assess feasibility of the candidate options. This assessment is still actively underway.

Easy deployment 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. We are considering 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. Sealability is also critical in the non-breathable atmosphere (7% CO₂ and 14% O₂) of the human mission candidate cave (HM Cave, AZ). The major design challenge will be to accommodate both easy deployment and secure sealing.

Mars-Derived Breathing Mixture Experiments

For any future missions to Mars, a simple and effective extractive methodology to provide breathable air is to use the Martian atmosphere and modify it to yield breathable air. Simple compression of the atmosphere of Mars followed by physical separation techniques can form a breathable mixture for humans.

The Martian atmosphere is composed of about 95% CO₂, 2.6% N₂, 1.6% Ar, and a few tenths of a percent of other trace gases. Earth’s atmosphere has approximately 78% N₂, 21% O₂, a small amount of CO₂ (0.03%), and many other trace gases. Ideally, breathing mixtures for humans are made up of O₂ plus a buffer gas like N₂ similar to the real mix of gases we breathe in the Earth’s atmosphere.

Compression of the Martian atmosphere and subsequent separation of major constituents by cold traps at target temperatures can yield a mixture of CO₂ and CO condensing at a temperature of approximately -20°C and a residual of other gases, primarily N₂ and Ar (2.6% and 1.7% of Mars air, respectively) (French, 1989; Finn et al., 1996; McKay et al., 1993). However, separation of N₂ and Ar is an energy consuming process involving significant additional processing. If Ar 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). O₂ 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.

Ar 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 N₂) 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 O₂ breathing gear but otherwise in a “shirtsleeve” environment.

Suggestions that Ar 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 Ar at high pressures as a component of breathable diving mixtures has been done (e.g. Aldrete et al., 1967; Edmonds et al., 1983; Fowler et al., 1985; Bennet, 1993). Several Russian investigators have also more recently suggested Ar as a constituent of breathing mixtures for astronauts (Pavlov et al., 1997; Burakova and Pavlov, 1999).

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 whether Ar 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. We designed a simple series of experiments to monitor the activities of different animals while breathing a gas mixture similar to that derivable from Martian atmospheric gases.

The experiments utilized a gas mixture containing a significant proportion of Ar (40%). First experiments were conducted on ordinary house crickets, Acheta domesticus. Pairs of female crickets (to avoid fighting by males) were housed in a small anaerobic chamber connected to a custom-mixed gas cylinder (40% N₂, 40% Ar, 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 of breathing this mixture, with frequent observations 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 conduct lengthier and more 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 (courtesy of Animal Care Systems Inc., see Figure 3B), complete with food, water, and bedding. The breathing mixture flowed through to yield an internal pressure of approximately 830 millibars. All mice were observed visually 4 times a day, including while eating, sleeping, and exhibiting active behavior. Both mice survived seemingly unaffected. Unfortunately, too much grease was administered as a seal around the cage lid. The experiment was halted at the 2-day point to clean away excess grease and lower the amount of mouse bedding inside upon the recommendation of the veterinarian on staff with Animal Care Systems, Inc.

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 (~830 millibars) and their activities were monitored as before. Both experimental and control mice showed similar levels of activity and normal resting and activity periods, shown in Figure 4. This experiment ended successfully on 14 September, 2002, after completing 15 days of continuous exposure to the gas mix. As of this writing (late April, 2003), both experimental mice, now reunited with their control partners, seem unaffected and go about their usual highly active lifestyle. We plan to monitor them, their health, and their lifespans until they die of natural causes.

Although the two completed experiments (crickets and mice) were short lived, used extremely small numbers of animals, and are obviously far from capable of producing statistically relevant data, they served their purpose in demonstrating that there are no immediate short term adverse affects that breathing a mixture of 40% Ar, 40% N2 and 20% O2 has on these species. The long term effects are still unknown and the mixture has yet to be tested on humans.

In the future, we plan to conduct similar experiments on larger numbers of mice. We are also considering experiments to look for any effects of breathing Ar on the complex, nervous system-mediated, untaught web-building behavior of spiders.

In-Cave Communication Test System

We have designed a prototype system to provide node-to-node in-cave communications, as illustrated in Figure 8. A very modest first prototype of this system was successfully tested in early 2003 in Robertson’s Cave, southern New Mexico. Very simply, we used off-the-shelf Orinoco PCMCIA wireless technology connected by laptop computer nodes to provide a proof-of-concept system for testing in real cave environments. Incremental elaboration of the system is underway and further tests in more challenging cave environments are scheduled for next year.
Duckweed Mouse Feeding Experiments

We have been experimenting with the use of two aquatic “Flat Crops” (duckweed and waterfern) as mouse food for incorporation into the Mouse Mission to Inner Space concept, shown in Figure. The species of duckweed that we are using (**Lemna minor**) and waterfern (**Azolla filiculoides**) were selected because of these species’ rapid growth, high nutritional value, water purification capabilities, and small space required for growth. Additionally, the waterfern is an atmospheric N₂ fixer. During a trial period, two mice were fed an exclusive diet of duckweed with small amounts of waterfern, but this proved to be insufficient calorically. Although both duckweed and waterfern have more protein than soy beans, it may not be providing sufficient carbohydrate intake for mice. We are modifying the diet for future trials.

Figure 9. Flat Crops for Martian Mice. Use of “Flat Crops” that grow in shallow water trays, produce nutritionally high quality protein, and are palatable to test mice include duckweed and waterfern. **A.** Growth of duckweed in the prototype mouse habitat; **B.** Enlarged image showing individual duckweed plant; **C.** Collection site of duckweed in an Oregon pond; **D.** Culinary use in a rice dish. Images by R.D. Frederick.

SUMMARY AND PLANS FOR CONTINUED ACTIVITIES

Our NIAC Phase II work is proceeding rapidly. We have taken our original list of possible tasks and winnowed them to a smaller list of accomplishable activities. We are concentrating on those that can demonstrate concepts that we believe to be necessary for the eventual successful exploitation of extraterrestrial caves for human exploration and scientific investigation.

We are working actively to build upon the foundation of creative work that the NIAC program has allowed us to undertake. We believe that consideration of the subsurface of Mars as a potential human habitat, an important scientific site, and possible resource base for future human missions provides the best chance of conducting those missions successfully and productively.
ACKNOWLEDGEMENTS

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REFERENCES


