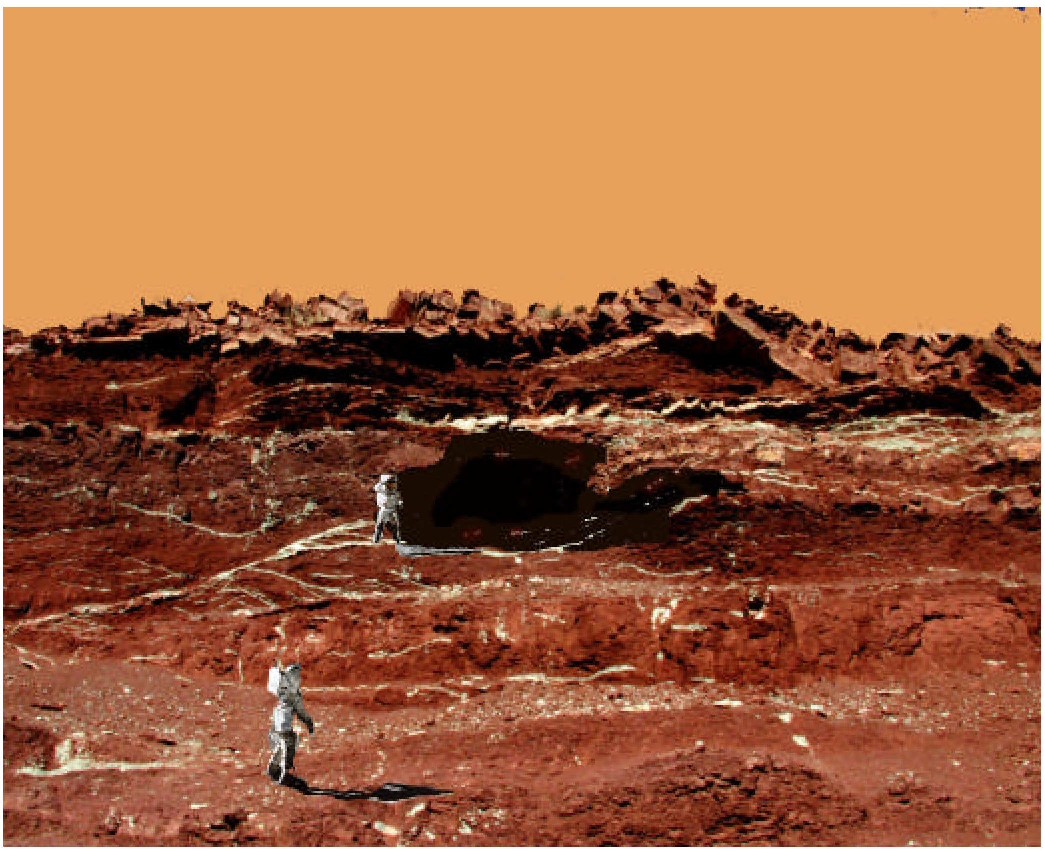
Extraterrestrial Caves:

Science, Habitat, & Resources

(A NIAC Phase I Study)



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NIAC
NASA Institute for Advanced Concepts

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Scientific Exploration and Human Utilization of Subsurface Extraterrestrial Environments:

A Feasibility Assessment of Strategies, Technologies and Test Beds

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This Phase I NIAC study explores 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. However, within this large array of ideas and technologies, some suggestions are unique to this work as far as we can determine. They are listed above in the order in which they are discussed throughout the text.

* TRL = Technology Readiness Level

I. Introduction

A. Why caves?

With all the truly compelling sites on Mars that have been championed as the "best" sites for scientific investigation, 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, although it is a novel concept. We have chosen caves because we are working in the highly understudied caves of Earth and are presented daily with the amazing diversity of shapes, forms, biology, mineralogy, chemistry and formation mechanism of these "big holes in the ground" (Boston et al., 2001; Northup and Lavoie, 2001; Boston, 2000a).

Caves are a relatively untapped source of scientific treasures and unexpected discoveries. Science in caves is a young and emerging field. Biology in caves is even less mature. Microbial environments in caves are the least studied of all, but ironically are one of the most promising and productive from the view of many disciplines; mineralogy, biogeochemistry, geomicrobiology, pharmacology, industrial enzymology, mining, and speleology. We have suggested that the subsurface of Mars, including caves, may have been the last refuge for life on that planet as the climate on the surface became ever less hospitable (Boston et al., 1992).

Caves 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. 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.

1. Science

The science that can be conducted in extraterrestrial caves runs the gamut from geology to biology, however, the latter is the area of greatest operational sensitivity and greatest uncertainty. The high premium placed on life detection 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 innovative field science and active exploration. Nothing of this magnitude has ever been attempted in human history. While some microbial forms in Earth's caves are quite readily apparent (Figure 1), more often they are far more cryptic. Indeed, even with a fleet of scientists of all types and the capabilities of many laboratories at our disposal, we have had significant challenges convincing ourselves and colleagues that some of the materials we work with are actually alive (Figure 2).

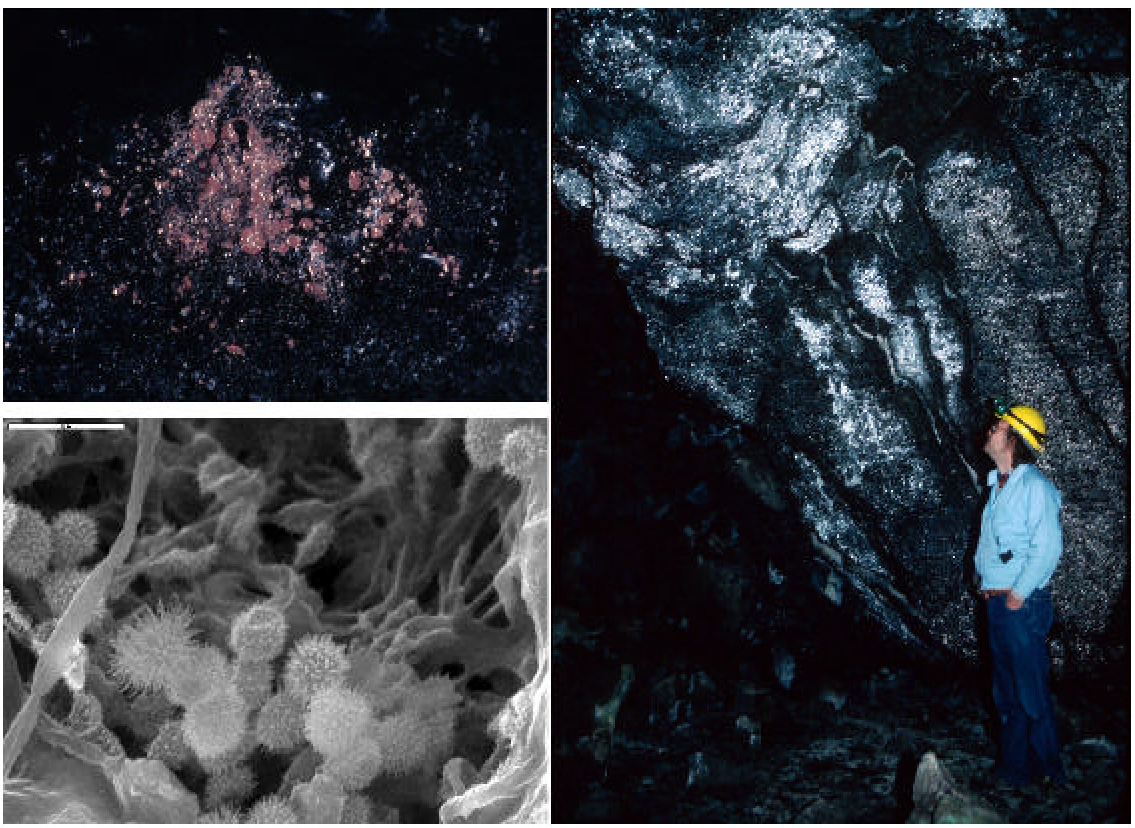

Figure 1: Many Earth caves have visible evidence of microorganisms. Upper left shows pink actinomycetes in Hawaiian lavatube cave. Lower left shows a SEM (scanning electron micrograph) of streptomycete relatives from dirt in a Cape Verde Islands lavatube cave. Image on right shows silvery actinomycetes covering the wall and gleaming in the headlamp of caver. Upper left and right, courtesy of K. Ingham. Lower left SEM courtesy of M. Spilde.

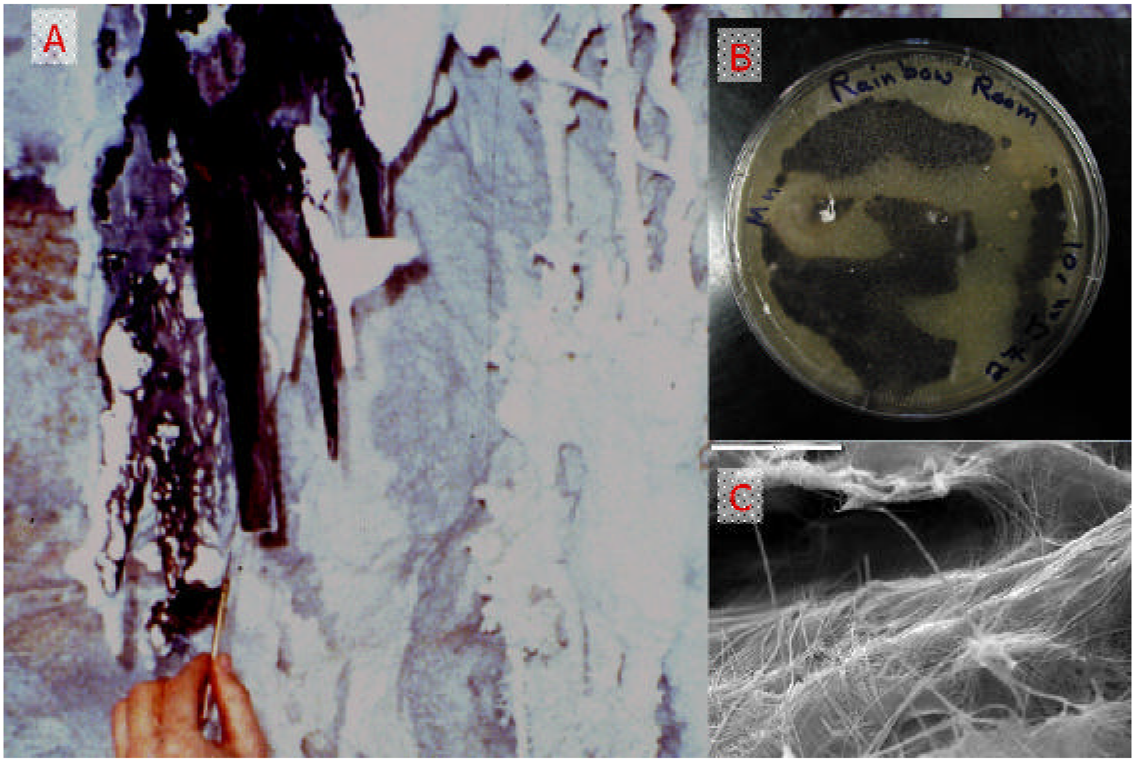

Figure 2: Is the black smear (A) on this white calcite cave decoration (speleothem) alive? Hard to tell, but we have been able to determine that it has a very high manganese content, that we can isolate manganese oxidizing bacteria from the material (B) and that amazing filamentous forms are visible upon examination with SEM. Image C courtesy of M. Spilde.

2. Habitat

The use of caves for habitat is a very ancient idea (Boston, 2000b). The idea of caves as shelter was invented early in the history of life presumably by microbes (!) and then by invertebrates. Microorganisms may have even originated in a subsurface environment according to some suggestions. Early humanoids used caves and rock overhangs as shelters (Johansen and Edey, 1974; Wymer, 1982). There are remains of artificial habitats constructed by *Homo habilis* as early as 2 million years BCE (Leakey and Lewin, 1977, 1992). , 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!

In recent times, the use of caves on extraterrestrial bodies for human habitation has been suggested by a number of groups. Lunar lava tube bases received much of the attention because lava tubes were clearly visible in early lunar images (Horz, 1985; Walden, 1988; Kokh, 1996; Taylor, 1998). 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 3).

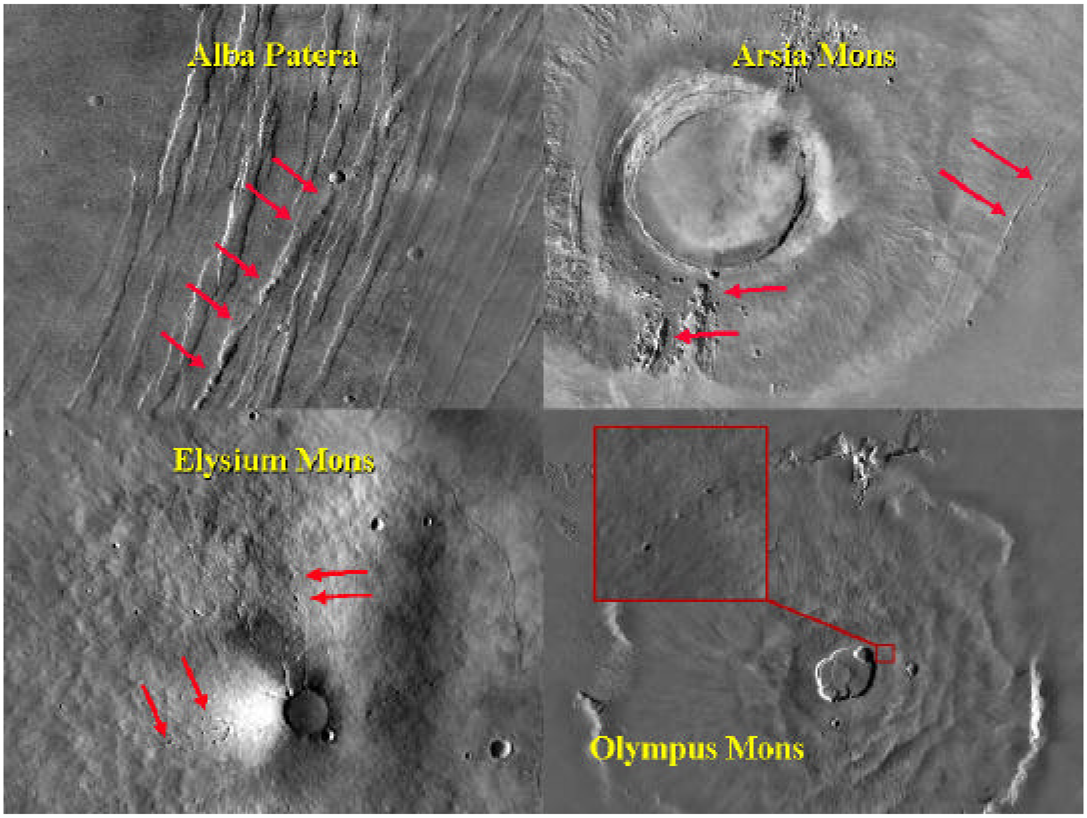

Figure 3: MOC images clearly showing lava tubes and collapse features.

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.

3. Resources

Mining, mineral collection, and other extractive activities in caves are as ancient in lineage as the idea of shelter (Tankersley et al., 1997; Wright, 1971). The proximity to mineral resources not available on the surface lured even ancient humans armed only with burning torches to collect pigments (Hatt et al., 1953), medicinal clays (Arnold and Bohor, 1975) and tradable minerals (Arnold, 1971; Sieveking, 1979; Watson, 1986; Lourandos, 1987).

B. What kinds of caves?

1. Cave types possible on Mars

Caves are NOT rare on Earth, contrary to general assumptions of those unfamiliar with the topic. 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, to melting within a solid as in the case of ices.

The heat flow from the planetary interior drives the type of plate tectonics that we have on Earth, thus resulting in faulting to create these 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 are reasonable expectations. Indeed, there is morphological evidence of these features on the moon, Mars, and Venus (see Figure 3). On planets like Io, i.e. in close proximity to gigantic Jovian planets, tidal flexure causes the volcanism itself and can produce lava tube features and perhaps other tectonic cave types.

Abundant evidence of water-created features exists on Mars (e.g. Malik and Edgett, 2000; Carr and Wanke, 1992; McKay et al., 1992). 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 the chemistries of the solids and liquids involved. The intriguing possibilities for many different kinds of caves besides those we know from Earth have recently been explored (Boston, 2002).

By virtue of its very nature, the environment in a cave WILL differ from the surface. This is why a cave can maintain a cool temperature with saturated humidity of the air and sometimes even permanent ices when there is a hot dry desert on the surface. The thermal regime will be more stable because of insulation of the surrounding material. The galactic cosmic radiation and solar ultraviolet and ionizing radiation environment will be lessened because of the protection of the rocky material. Sealed caves provide the opportunity to amass repositories of frozen volatiles on otherwise dry and cold worlds. Even in Earth caves open to the exterior, permanent ice lenses are found in caves in the temperate latitudes and in very hot summer areas (Figure 4). Formation and preservation of minerals that could not exist on the surface is another potential scientific and resource benefit. We know that there is a fantastic array of minerals that are found in the caves of Earth (Hill and Forti, 1997).

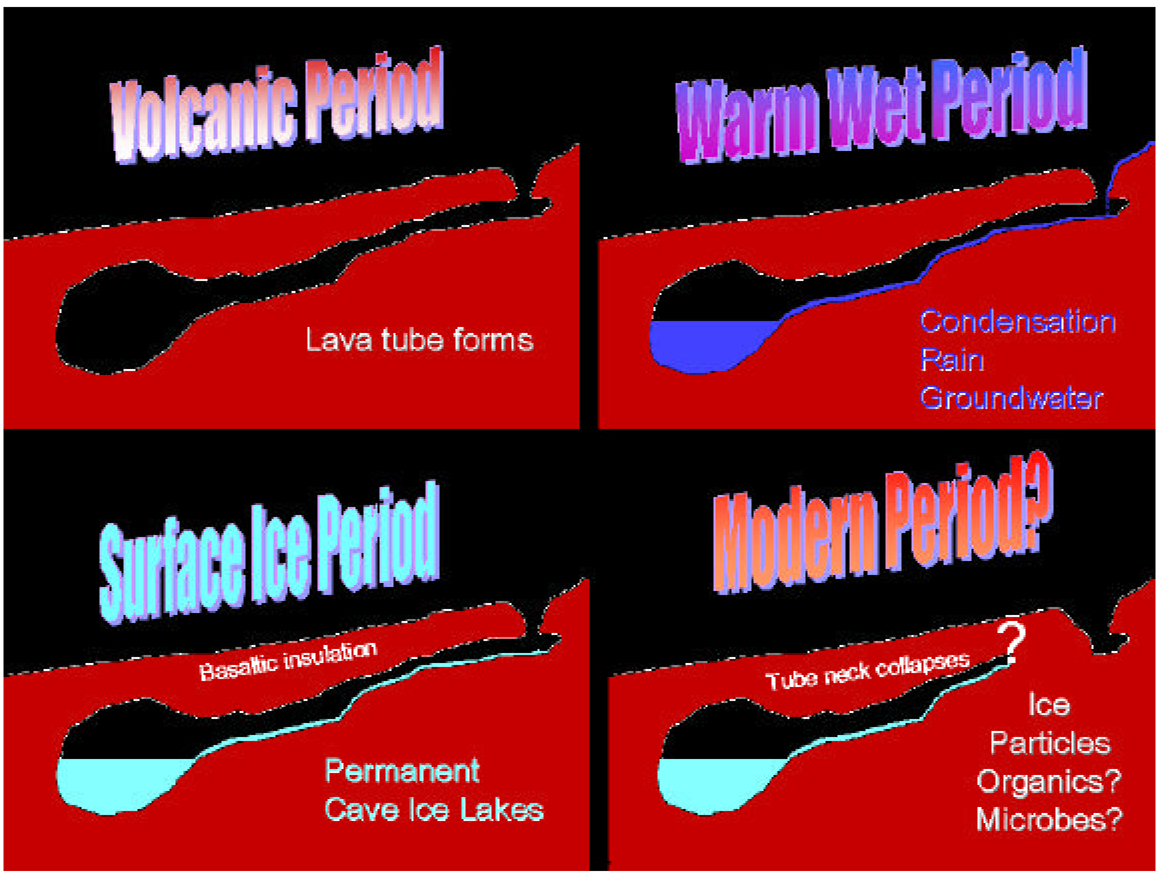

Figure 4: Lavatubes on Earth frequently contain permanently frozen ice even in mid-latitude desert climates. This graphic sequence illustrates a possible scenario for the entombment and preservation of such ices over long periods of time on Mars. Early in Martian history, lavatubes were created. During the warmer and moist period such tubes would have been invaded by water from precipitation. As the climate cooled, these became permanent ice features much as Antarctic lakes are on Earth today. Some tubes may have collapsed at the narrow and thinner shelled end, thus sealing the ices and any trapped particles, organics, and microorganisms inside. Graphic, R.D. Frederick.

2. Comparison to Earth caves

Caves form in MANY different ways on Earth.

Lavatube Caves - On Mars and the moon, the most obvious cave types present are lava tubes. The morphological evidence of lava tubes can be seen easily in lunar images where the strings of collapse features near the tube ends are clearly visible. Features on Mars also resemble these strings of lava tubes radiating out from central volcanic sources as we see them on Earth. The properties and structure of such features depend upon the basic physical conditions within which they form. The most obvious difference between Earth and Mars and the moon is the gravitational situation. Scaling for Mars simply on the basis of gravity, lava tubes can grow perhaps two to two and a half times the size that they can on Earth. However, this is modified by considerations of the inherent load-bearing strengths of the basalts, andesites, or other lava materials involved. On the moon, even larger spans are supportable gravitationally to about a factor of 4 larger than Earth. On the other hand, the lower gravity causes less trenching erosion to occur thus preventing some of the types of tubes that we find on Earth.

There are five main lava tube types on Earth. These depend primarily upon the length of flow and the landforms that the flows penetrate. *Interior tubes* occur mainly in flood basalts and rarely drain, thus they are solid and not of particular interest to our purposes. *Surface tubes* are rather small individual lava streams that frequently harden over and drain to form tubes that resemble the veins on the back of a human hand. These are identifiable as radiating ridges on satellite images. Though they are small on Earth, the scaling factors on Mars and the moon could make them large enough to be useful for habitat. *Semitrench tubes* result from a lava flow through an already existing channel. This type of flow builds up successive crustal walls. Eventually such a channel may roof over if the flows persist for a long enough time. The width of these is dependent upon the original width of the channel, but the length depends upon the usual factors of lava fluidity and gravity. *True trench tubes* form by a process of fluid lava erosion that cuts a channel just as water or ice will do. The subsurface positioning of these tubes can be quite deep. The primary material of the cave is the parent rock lined with a variable coating of lava. The positioning of these tubes with respect to depth on Mars and the moon may be less than that of Earth simply because of the lesser downward force exerted by the eroding lava stream. On Earth, they are harder to detect because the tops of them are often equiplanar with the overall flow surface. Presumably this would also be the case on other bodies. So-called *rift tubes* are highly variable in size and shape because they form by lava infilling an existing valley, canyon, rift, or fissure. Because they are controlled by the overall topography of the area, the low areas often allow the subsequent buildup of many layers of tubes in a complex maze of multilevel tubes.

Solutional Caves - Caves that form by the dissolution of parent rock fall into two dominant categories on Earth: 1) karstic caves in limestone and other calcareous materials or in the soluble minerals like gypsum that form in evaporite basins, and 2) non-karst caves that form in a wide variety of other materials including ice. While the moon has no imagined mechanism to form carbonates and none have been detected, Mars' early history as a wetter and warmer environment has provided ample speculation that carbonate may have formed abundantly during its early history and remains as deposits today. Indeed, one theory for the absence of a dense carbon dioxide atmosphere on today's Mars is the notion that the initial several bar endowment of gaseous carbon dioxide was tied up as carbonates and never recycled by plate tectonics as it has been here on Earth. Large standing water bodies on Mars would have had abundant sulfur on this sulfur-rich planet to form such evaporite minerals as gypsum.

So far, none of these minerals have been detected on the Martian surface. However, attempts to determine the composition of the Martian surface by spectroscopy suffer from several problems. The first is the failure rate of some of the Mars missions that might have helped answer these questions by now, but the second and more fundamental problem for carbonate and evaporite detection is the well-mixed and apparently globally distributed surface fine materials that appear everywhere on Mars. This material is thought to be relatively shallow, but it is certainly deep enough to obscure the underlying materials and preclude the identification of large carbonate deposits in structures that may be ancient lakebeds or on cliffs that appear to have some sort of layering that could be construed as sediments.

If carbonates and evaporites are present on Mars, then early cave formation processes analogous to those on Earth would have unquestionably taken place in the presence of ground water. As Mars grew cooler, drier, and less atmospherically dense, these caves would gradually be less affected by the continuous erosion and recycling processes that Earth caves experience. Thus, the average lifetime of conventionally produced karstic caves on Mars will greatly exceed their counterparts on Earth.

While some terrestrial caves are rather short-lived, in the tens of thousands of years, others are of great antiquity even in Earth's extremely active weathering and tectonic environment. The caves in the Guadalupe Mountains of southeastern New Mexico and Western Texas are reliably dated at a minimum age of 4.5 to 12 million years old based on the minimum ages of secondary clays in their interior mineral deposits (Polyak et al., 1998). The actual age of the caves exceeds this, of course, because they had to form before the secondary deposits were emplaced. Although these are of great age for Earth caves, these are brief spans compared to the apparent antiquity of at least abundant surface waters on Mars. However, some caves on Earth are known to have been formed by episodic flooding events rather than a slower, acidic solution process. Thus, Martian caves may have been formed in the post-surface water era by episodic fluvial events.

The primary mechanism that forms water-dissolved carbonate caves on Earth involves weak carbonic acid formed by atmospheric and soil carbon dioxide dissolution into rainwater and ground water (epigenesis). This is a clear candidate mechanism on early wetter Mars with its carbon dioxide dominated atmosphere. The other mechanism (hypogenesis) involves the dissolution of hydrogen sulfide gas in water, thus forming sulfuric acid. The dissolution of this type occurs at the watertable/air interface in a forming cave and creates extremely large passage because sulfuric acid is much more solutionally aggressive than carbonic acid. The presence of sulfur on Mars is known from the Viking missions and the abundance in those surface materials is an order of magnitude greater than Earth's average crustal abundance. If this apparent sulfur richness is generally true of Mars materials, then sulfuric acid formation may have been a significant cave creating mechanism on early Mars.

Recent void formation in a strictly subsurface context could be happening even on contemporary or relatively recent Mars if liquid water or other liquids are present in the subsurface. Whether such voids will be too deep for human access, scientific instrument access, or even to be found by geophysical techniques remains to be seen.

Features of carbonate cave formation on Mars that do not have a direct counterpart on Earth include the possibility of ground-ice formation of void space. Ice sapping features are clearly visible on Mars. This process occurring on a planet with an extremely dry surface cannot be compared to anything on Earth, although there are void spaces formed in permafrost by melting events. However, permafrost is subject to continual water inundation and refreezing thus minimizing the permanence and growth of void. On Mars, thawing, water flow and subsequent subliming of the liquid into the tenuous atmosphere could create very unusual subterranean passage.

Another particular Martian feature is the presence of carbon dioxide ice at the poles and possibly liquid CO_2 under certain circumstances. The types of solutional cavities that could be created by this material is unknown but could conceivably be modeled based on the known properties of dry ice or even physically modeled at small laboratory scales (Boston, 2002).

Non-carbonate solutional caves form in sandstones, arkoses, quartzites, granites, and many other rock types. Their much lower solubilities and resistance to weak acids make them a more rare occurrence on Earth than the ubiquitous carbonate caves, but nevertheless their presence indicates that carbonates are not essential for cave formation. Typically void is created by the dissolution of the cementing materials between grains rather than in the bulk rock. In the subsurface, microbial degradation contributes to the breakdown of non-carbonate rocks as well as carbonates. Whether there are microbial processes ongoing in Mars' deep subsurface is unknown but could have provided an additional void-creation mechanism.

Non-solutional or tectonic caves can be formed by processes as simple as crumbling of material or non-fluid undercutting in faults, scarps, and other cracks. The cracks and voids can be enlarged when freezing expansion of water ice occurs. As the water either melts or sublimes away, the enlarged crack remains. Auxilliary cracks form from the main crack and are then available for subsequent freeze-thaw cycles. We know that Mars has not only been warmer and wetter in the distant past, but that it also undergoes wide-ranging climatic swings over much shorter time periods as the obliquity and precession variations interact to form a complex cyclicity in the climatic regime. Such cyclicity may have produced freeze/thaw caves over the course of many obliquity cycles as ground ice alternatively forms during cold periods and is sublimed during warm climatic periods. This ground-ice pumping mechanism over Martian geological time has been posited by various investigators (e.g. Squyres et al., 1992) and indirect evidence inferred from various landform types on modern Mars.

3. Science vs. Habitat caves

Caves on Earth differ vastly in their properties. We expect that to be the case on Mars and other planets. Therefore, we have developed checklists of several generalizable features that fit caves specifically for scientific activities, human habitat purposes, or resource gathering activities.

<u>Scientific targets:</u>

- High probability of interesting geological and biological features, e.g. extreme age, isolation from surface, evidence of reduced gases or water
- Big enough for instrumentation or microrobots (not necessarily humans)
- Depth variable, but deep caves could well prove the most scientifically interesting, e.g. for stratigraphy, for mineralogy, or for biology.
- Caves that have no natural openings would be highly desirable because of possible superior preservation of the contents.
- Caves in or near geologically or hydrothermally active areas would be very interesting for many scientific purposes.

<u>Human habitation caves:</u>

- Shallow and easily accessible
- Commodious, walk-in large passages and rooms
- Smooth (relatively)
- Geologically stable
- Formed in relatively impermeable material to facilitate airtightness
- Natural openings would be convenient.

- Suitable types include lavatubes, gypsum boreholes, some carbonate caves, and rock-shelters.
- Location within a lower area like a canyon or crater could provide additional protection from surface conditions.

<u>Resource caves:</u>

- Contain volatiles, minerals, or other materials of use within the cave itself.
- Provide nearer proximity to interesting deposits than surface drilling and mining operations would afford. Can be directly drilled from into deposits.
- Provide access and storage space for geothermal fluids, volatiles, and minerals.
- Roomy enough to support these activities.
- Caves with natural openings would be more accessible but sealed caves could provide greater likelihood of finding entombed volatiles and unreworked minerals.
- Geothermally active.
- Low permeability would potentially allow for filling cave with inert atmosphere compressed from the Mars environment, thus allowing shirt-sleeve environment with only oxygen breathing gear.

C. Where are the caves?

1. Cave prospecting.

A number of techniques can be employed to prospect for subsurface cavities. Some of these can be done from orbital platforms or aerial devices like airplanes, gliders, or balloons (Figure 5). Others must be conducted in situ. Amongst the former, imaging can show both clear cave features like lava tubes and indications of potential subsurface collapse features (Figure 3). Ground-penetrating radar and magnetometry may be useful in some cases. Amongst the latter ground-based techniques, even the lo-tech but time-honored caver tradition of “ridge walking” to look for possible faults and likely hydrological flow patterns resulting in caves can be implemented by robotic devices or ultimately humans (Figure 6). Observation of canyon walls, as depicted in Figure 6, can yield a wealth of cave and rock shelter prospects, by humans or by a variety of rovers and robotic devices.

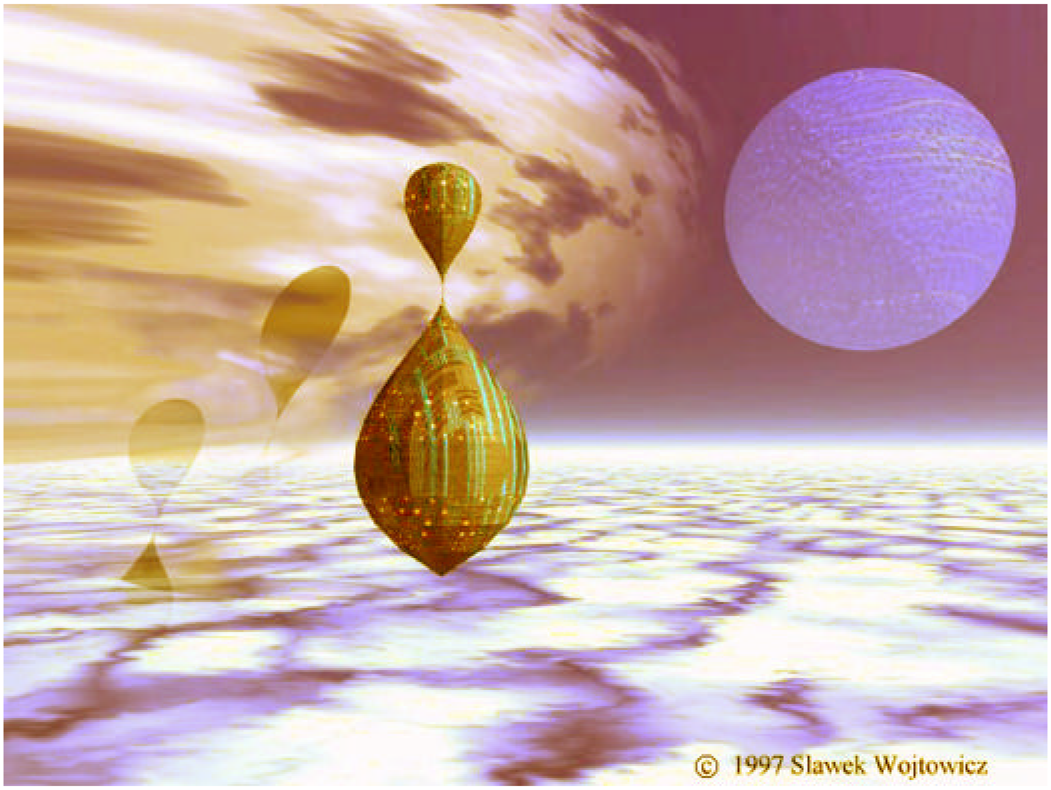

Figure 5: Ballooning over an unknown planet. Such platforms are being suggested for aerial reconnaissance on Mars and could easily use imaging and radar to look for caves.

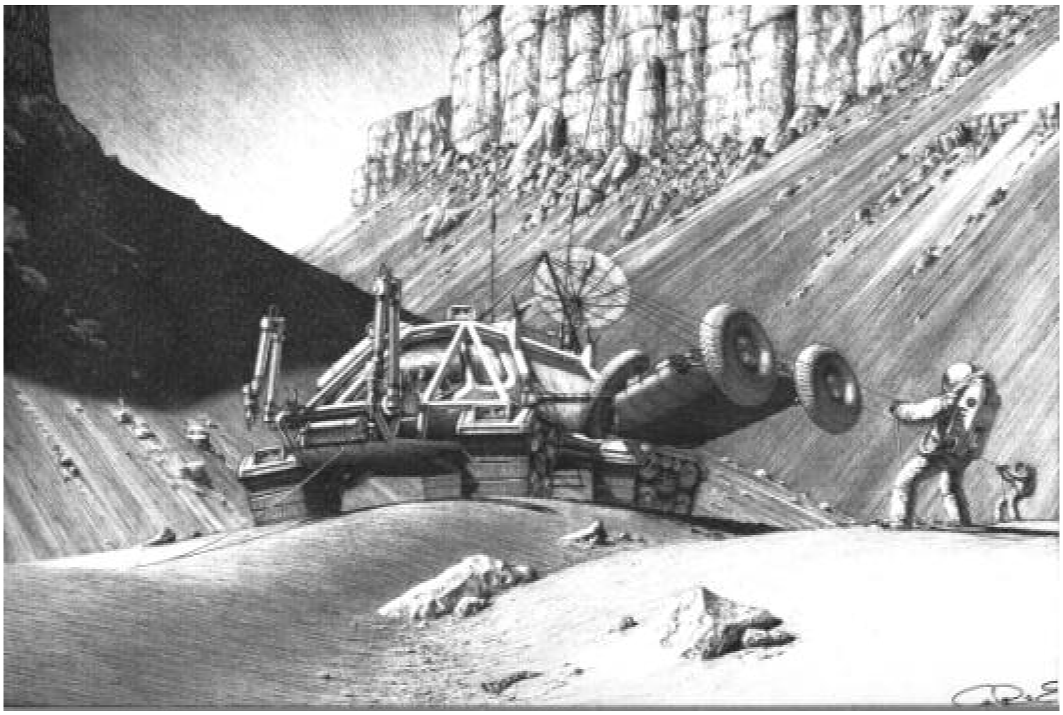

Figure 6: Direct human inspection of canyon walls and outcrops is the time-honored method for finding caves. These techniques could be redesigned for robotic searches. Art courtesy of C. Emmart.

Suitable techniques for cavity detection have been suggested dating back many decades (e.g. Watkins et al., 1967). They include magnetometry, resistivity measurements, ground-penetrating radar, various seismic techniques employing active and passive methodologies, micro-conductivity measurements, and the entire gamut of imaging instruments at all scales from orbital through aerial through rover-based to human exploration. We have compiled a website and reference list in Appendix C to serve as a guide to these techniques for the interested reader.

2. Earth test-bed caves

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 are in the works, but 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. 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, thus requiring full breathing gear for investigators.

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.

3. Planetary protection issues in caves

"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 8). 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.

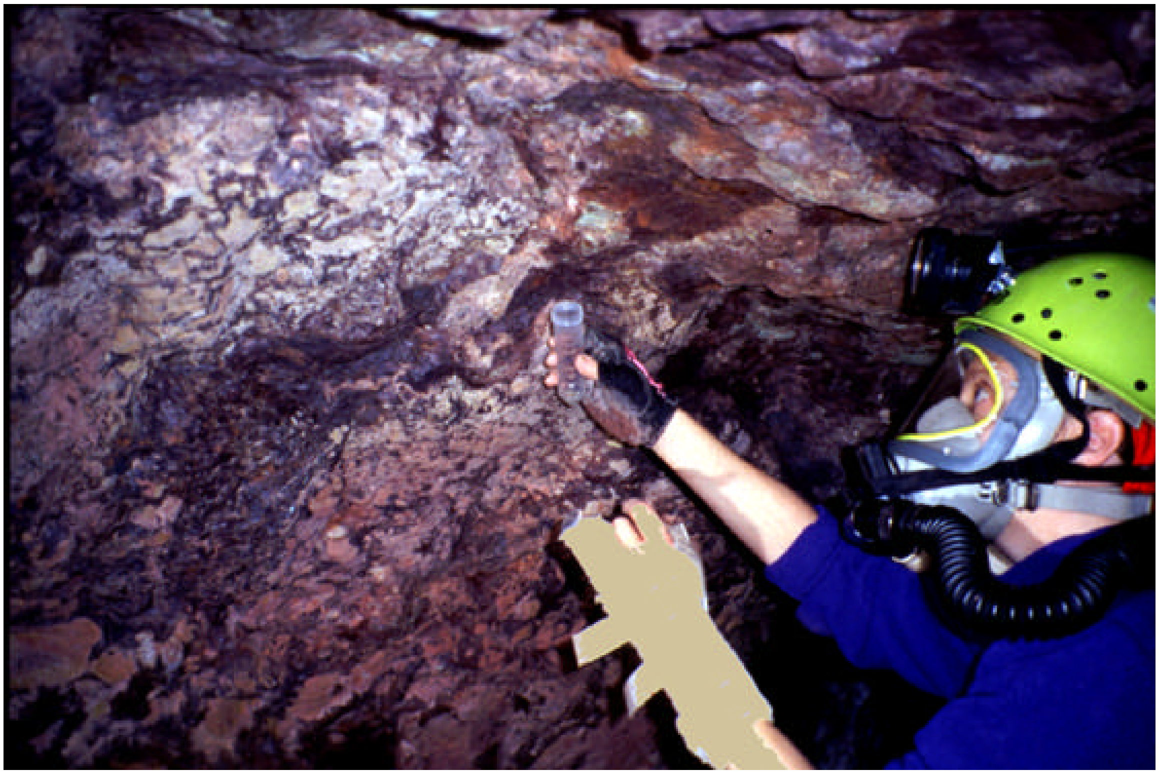

Figure 7: Carbon dioxide levels in the cave air hovering around 7% greet researchers in HM Cave, AZ. This pristine, sealed environment is a highly mineralized microbial environment replete with vividly colored patches of rock breakdown products that are the result of microbial action. Image by V. Hildreth-Werker.

Even the issue of backward contamination, i.e. contamination of Earth by extraterrestrial microbes, is faced by cave investigators! Eye infections, weird skin rashes that won't heal, fungal respiratory diseases and other mysterious maladies are all common occupational hazards of cave researchers.

New minimal impact exploration and analytical techniques developed for Earth caves will be available for further development and application to extraterrestrial caves. Such technologies and special protocols are necessary to minimize the impact of human access on the physical structure of sensitive cave environments, to enable human researchers to operate more effectively and safely in challenging and hostile environments, to develop scientific exploration protocols which do not contaminate or disturb the indigenous organisms and habitats that we are trying to study and to develop protocols which can ultimately become part of the training of astronauts destined for extraterrestrial missions.

We are already making strides in our study of a pristine, unexplored cave (La Cueva de las Barrancas) in the Guadalupe Mts. of New Mexico. We are working in conjunction with the responsible USDA Forest Service management to preserve its unspoiled nature as we study it. Our efforts in this area can serve as a model for human scientific, exploration, and life support applications on other planets and enable us to assess the potential uses of the terrestrial cave environment in astronaut selection and training.

Figure 8: Left image - First Touch. This sterile-gloved hand places a glass slide into a miniscule puddle to encourage growth of native microorganisms onto the surface for later collection and cultivation "in captivity". Right image - Virgin cave passage never before seen or touched by human explorers opens before a team of speleologists and microbiologists as they prepare to don sterile tyvek suits, gloves, helmet covers and booties. Even these precautions are less than those that will be necessary for initial contact with possible extraterrestrial life. The extremes to which this group of investigators goes in its work requires a very slow pace with repeated reassessments of protocol and subsequent adjustments – an object lesson for future astrobiological missions. Images by V. Hildreth-Werker.

II. Science

Conducting science in Mars caves requires the creation of novel methods, devices, and infrastructure not yet within our grasp. We have focused on those that are of critical importance, that are not being worked on by others, and that are neither easily foreseeable as derivative from some on-hand technology but yet do not require the development of something entirely unforeseen.

A. Communication infrastructure

The development of robots that wiggle, crawl, fly, ooze, and swim are being undertaken by several other NIAC studies (list PI's here and website). We hope to use the fruits of their labor to provide us with an idea of potential future capabilities of such devices. We are building on their 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 will utilize them to increase 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 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

Figure 9: An adventurous bugbot modeled after the transforming microrobots of S. Dubowsky (NIAC CP-99-01, “Self-Transforming Robotic Planetary Explorers”). It is finding its way through a cave carefully keeping a line-of-sight to its two nearest neighbors.

1. Wireless Networking Technology Survey

Our communications infrastructure is built around wireless networking technology. We performed a survey of current and upcoming wireless communications technologies to help constrain our thinking with a dose of realism. We assessed them for suitability as the basis (transport component) for this proposed subsurface communications infrastructure.

Three existing technologies look promising from our investigations:

- High-powered directional infrared communication
- 2.4 GHz Wireless Ethernet (IEEE 802.11b) LAN
- A low-power 2.4 GHz proprietary wireless LAN technology, “Bluetooth”

After our initial assessment, we conclude that any one of these technologies could serve admirably as the backbone for a demonstration or breadboard communication system. We plan to propose a live demo of our cave exploration communication infrastructure, based primarily on existing technology and products, in a cave in the US as a component of our Phase II proposal.

Since we started examining wireless communication technology candidates at the beginning of this Phase I NIAC grant, the 802.11b wireless networking standard has rocketed into popularity as the consumer’s choice for personal computer wireless local area networking. In addition, ISPs (Internet Service Providers) in some areas are now providing Wireless WAN (Wide Area Networking) connectivity via directional antennas and/or higher powered 802.11b “cell” technology. This is good for our purposes, as any technology that goes into popular consumer production typically has its cost reduced by orders of magnitude.

2. Near-term “Up and Coming” Wireless Networking Standard, 802.11a

The currently widely deployed 802.11b standard operates at a maximum bit rate of 11 Megabits per second in the 2.4 GHz frequency band, with very limited power. As of mid-2001, products are beginning to be announced using the 802.11a standard, which operates at 5 GHz, with a maximum bit rate of 54 Megabits per second, and with higher power options, more suitable for terrestrial WAN applications.

If 802.11a gains even a fraction of the popularity of 802.11b, this would be very good news for Mars exploration, where the increased bit rate could be especially useful for high resolution imaging. In addition, operation at the higher frequency of 5 GHz may prove to be advantageous (over 2.4 GHz 802.11b) by increasing the underground range for a given amount of power. As part of a Phase II study, we will propose to conduct experiments to measure this possible enhancement of the waveguide effect (which allows microwave communication to operate underground) between 5 GHz and 2.4 GHz.

B. Robotic science

In situ robotic science is valuable in its own right, regardless of its connection to robotic sample return to Earth missions, orbital and aerial data acquisition, or human-conducted science. We envision arrays of robotic investigators of all sizes and modalities of movement assailing scientific targets (especially caves!) on Mars and other planets in the future (Figure 10). The typical cave science areas to be addressed by robotic investigation include mineralogy, paleontology, and biology.

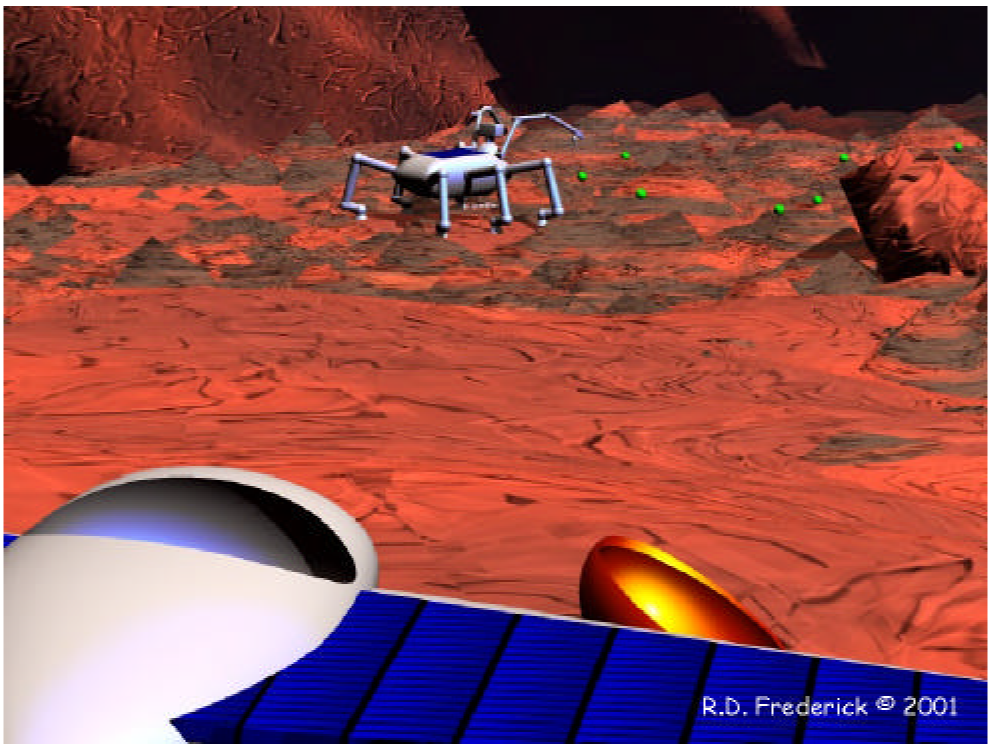

Figure 10: Intelligent robotic rover concept for the NASA Mars Scout Mission Series (http://eisci.com/specproj.html#goose) spun-off from this Phase I NIAC study. A single robotic rover using LEIF (intelligent control system being developed by Equinox Interscience, Inc. http://eisci.com) and nested microrobots based on concepts by M. Tilden at Los Alamos National Laboratories (shown as small green dots) approach a cave entrance preparing to analyze the mineralogy, chemistry, and hopefully paleontology and microbiology.

1. Mineralogy, Chemistry, and Physical Parameters

These are the easiest topics to address robotically in caves. Fairly simple sampling, sensing, and analytical strategies can yield a wealth of information including measurements as basic as temperature and as complicated as spectroscopy, microscopy, x-ray diffraction, and isotopic studies.

2. Paleontology

The magnitude of difficulty increases tremendously when traces of past life are sought. Some measurements may overlap with the physical science suite just mentioned, however, any determination of likely biogenic structures, textures, or microfossils will require a combination of advanced intelligence coupled with ground-based or (ultimately) on site human guidance (Figure 11).

Figure 11: A type of cave formation (speleothem) known as "pool fingers". Was this ever alive? Recent work (Melim et al., 2001) supports that idea. Significant pattern recognition capabilities must be possessed by any robotic devices attempting to pick out features like this from the background milieu of complex lithological shapes. Image by V. Hildreth-Werker.

3. Biology

The level of difficulty in determining biological versus non-biological phenomena is very high and will be challenging for robotic intelligence. Human inspired and episodically guided robotic life detection and analysis presents the paramount challenge for non-human missions to extraterrestrial caves. Many habitats on Earth that we now know to contain a large biodiversity of life appear barren and non-living on first (and even nth!) inspection. Significant cross-correlation of different data types is essential to begin to unravel whether a particular material is of biogenic origin or a pseudobiological feature (Figure 12).

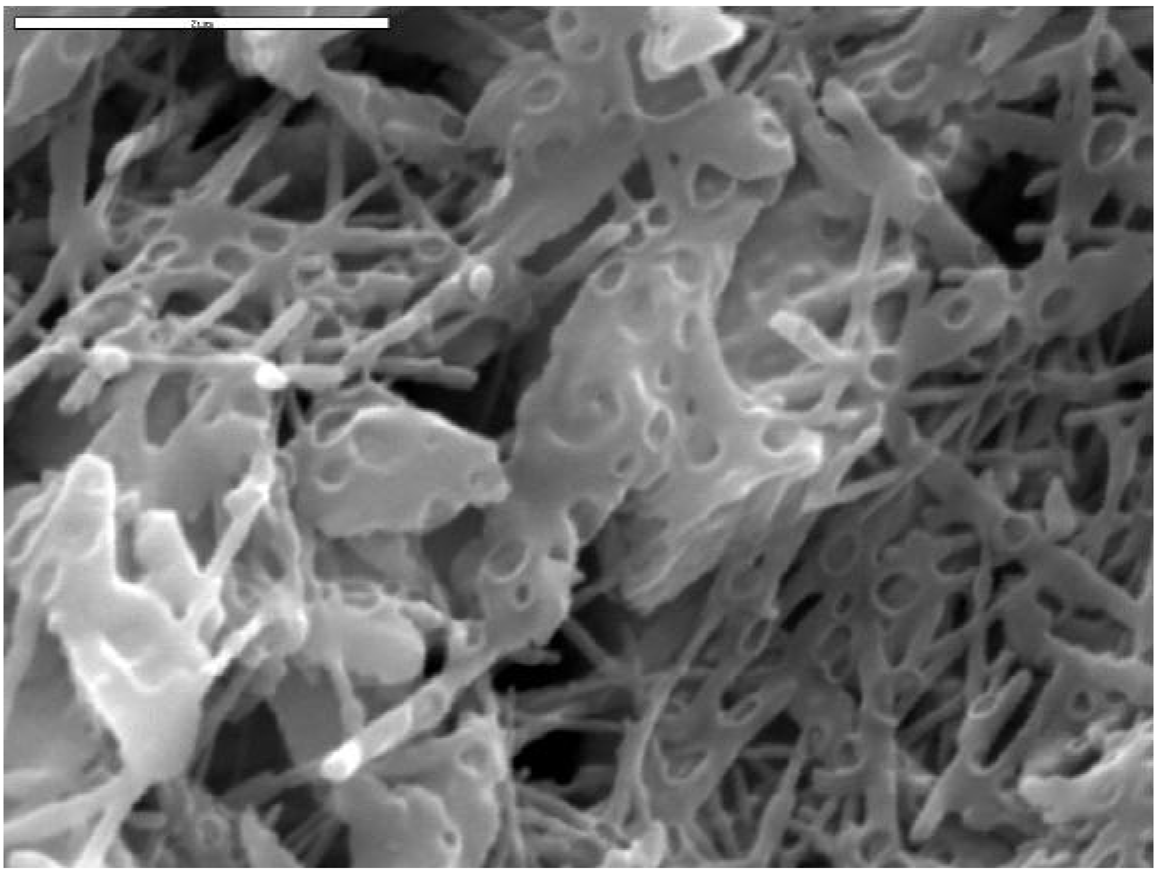

Figure 12: SEM of a cave deposit known as "Crisco" from Spider Cave, NM. This material resembles a sticky white mud until examined with high powered microscopy. In this image, several sizes of filaments are visible, ovoid bacterial bodies (shrunk by dehydration in the SEM's vacuum), and pits in calcite surfaces created by bacterial action. Much of this material is not as biological in appearance as this sample. Confirmation of biogenicity has to be sought with corroborating information like the use of metabolic dyes, molecular biology techniques, or biochemistry. Image courtesy of M. Spilde.

4. Other sciences

Other sciences like cave microclimatology, some features of stratigraphy, geomorphology, geology, and others may be robotically investigated using newly refined and miniaturized analytical devices becoming available even today. By the time of any missions that are targeted towards Mars caves, these instruments will have become more reliable, ever smaller, and ultimately lower cost. For example, recent innovations have produced a fiber optic "nose" that responds to the volatile odor particles in air (*NASA Tech. Briefs*, June, 2001).

C. Human-conducted science

The eventual arrival of human investigators on the Martian scene, will facilitate further cave exploration. We anticipate that some initial survey and study of at least lavatube caves is likely prior to the arrival of human explorers. This may help to guide their further activities. Indeed, the arrival of humans on the scene will not preclude the continued use of robotics to access small, especially dangerous, or especially sensitive cave sites (Figure 13).

Figure 13: This small opening blooms immediately into a 300 foot pit. Flying, slithering, and gripping microrobots may be much more suited to some cave entries than large human bodies, especially those clad in even advanced skin-like space suits of the future. Image courtesy of V. Hildreth-Werker.

As with the robotic case, the human led science will include mineralogy, geology, solid and gas phase chemistry, stratigraphy, geomorphology, speleogenesis, paleontology, and biology. The latter area of investigation is the one of most concern. Inherent threats to indigenous Mars organisms and possible threats to the human investigators and even our home planet, Earth, must be carefully handled.

The weird life detection dilemma that we are currently facing is a rather schizophrenic dissociation between our policy on one hand to avoid the introduction of Earth organisms as contaminants at all costs and the inevitability of at least some human-associated organisms contaminating at least some parts of Mars when eventual human exploration, research, and colonization will take place. This dilemma has not been resolved, but plans are afoot to try to address these issues in a NASA workshop to be held in late June of this year (2001).

D. Techniques

1. Drilling

Today, direct sampling of Earth's deep subsurface environment for scientific purposes is difficult. Most sampling efforts to date have relied on drilling and coring, (Balkwill and Ghiorse, 1985, Beloin et al. 1988, Bone and Balkwill 1988; Amy and Haldeman, 1997). Such methods have yielded many valuable insights, but they also possess significant drawbacks including possible biological contamination of samples by drilling muds, and exposure of collected material to rapid changes in temperature, pressure, oxygen concentration, light, and moisture. These problems will be further aggravated on planets like Mars where there is little or no atmospheric pressure above to help contain the resulting gushers. Using caves as deeper access points is a very attractive prospect both for science and other purposes. For cave resource extraction, shallower drilling may be all that is needed. Nevertheless, the challenges of planetary protection make *any* drilling technology problematical. We wish to avoid contamination of the subsurface regions of other planets both for scientific, conservation, and functional reasons. Bacterial contamination of fluids is a major contribution to corrosive processes in industry, mining, and other technologies here on Earth.

To be useful to deep subsurface studies, kilometer scale drilling is necessary. However, drilling laterally from deep points on Mars like canyon bottoms and the interiors of caves may greatly reduce the total bore lengths required to reach strata and depths of interest.

Technologies for drilling are under development for a variety of applications that may be relevant to our needs. For example, drilling for application to eventual sample collection from Lake Vostok under the Antarctic ice is being actively pursued. Deep mining drilling technologies are being developed for the deepest mineral extraction activities ever attempted in South Africa (D. Moser, pers. comm.). Indeed, a recent NASA workshop was held to investigate the issues surrounding deep drilling on Mars (Mars Hydrosphere Drilling Workshop http://www.ees4.lanl.gov/mars/index.html).

We have been impressed with the idea presented at the Mars Hydrosphere Drilling Workshop (Briggs, Mancinelli, and Clifford) to melt a hole directly through the rocky overburden into the deep Martian subsurface by means of an ultrahigh temperature device. This device will leave a re-solidified rock borehole in its wake that can provide access for instrumentation, sample collection, and even extractive purposes. This use of rock-melting temperatures will certainly be adequate to incinerate any contaminating organisms of Earth origin. We believe that applications of this type of technology can be modified for use in drilling into subsurface cavities and drilling from accessible caves into even deeper subsurface regions.

In addition to the possibility of lowering instrument packages into the borehole as these investigators have suggested, we are also interested in the extension of our insect robots as sensors and data gatherers that could also be deployed to deep subsurface cavities through such boreholes. If any voids were penetrated during this melt-boring process, various types of microrobots might be deployable to investigate them. The study of both natural caves and direct deep drilling samples are complementary approaches in the search to define subsurface environments.

2. Nanosensors

Miniaturized instrumentation is a strong need for all future missions, both robotic and human. However, our particular demands call for a premium on miniaturization because we plan to mount many of these devices on extremely small robotic carriers. A multiplicity of independently moving microrobots fitted with simple sensors of a variety of functionalities will be a much more robust and fruitful mode of exploration and measurement acquisition than large and highly endowed single or even duplicate larger rovers.

3. Lab-in-a-box fantasy

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. The use of minimal impact, non-invasive analytical capabilities is critical for successful robotic missions into caves. We envision the development of a biological minilab that is easily taken into caves and useful for a variety of chemical and geological tasks. Our future Phase II proposal includes a relatively modest first attempt at such a miniaturized and robotically or human-transported minilab.

E. Human mobility

The mobility of humans in caves is key to both safety and effectiveness. Today's Earth caver adjusts clothing to fit the cave conditions (Figure 14), but few like the constraints of such specialized garments as wetsuits for cold river and waterfall caves, sterile tyvek suits for sensitive biological work that can be stifling in tropical cave environments, and photogenic overalls insisted upon by some cave photographers! The experience of rappelling, ascending, climbing, bouldering, chimneying, and crawling in breathing gear and backpacks in caves with poisonous atmospheres is one not easily forgotten.

Figure 14: Descent into vertical caves currently requires humans with advanced rope skills. This image shows caver Dave Hamer ascending from a 100m pit in a deep New Mexico cave. Imagine doing this in current generation space suits. Flying, crawling, and slithering robots like NIAC-supported mesocopters, transformers, and entomopters (see Kroo, Dubowsky, and Colozza NIAC projects) may be able to negotiate such pits.

Current generation space suits and even those envisioned for the near future are entirely too bulky and inflexible for the conditions found in many caves. While they would be marginally adequate for caves with extensive walking passage or large rooms, anything more challenging would render a would-be astronaut caver essentially immobile and helpless. For example, the new International Space Station construction suits weigh 280 lbs on Earth (~105 lbs on Mars). The mass remains the same and added to that of an average person would result in a ridiculously bulky and unwieldy package for use in even a low gravitational environment. Additionally, a spacesuit whose structural integrity is essential for preserving life becomes much more than just a protective garment, but rather one's own individual spacecraft. Alas, the present multi-layer space suit resembles a whole-body space diaper more than a sleek vehicle. Several new NIAC projects are addressing various aspects of the pitiful state of current space suit technology (see Newman and Hodgson Phase I studies).

One of the biggest obstacles to the use of spacesuits in caves or elsewhere on Mars is the stiff, bulky, and inflexible glove design. The glove of our dreams would be as thin and flexible as good leather driving gloves…a surgical glove type would be even better but possibly unobtainable. The hand is critical for a range of essential functions including rappelling, climbing, grasping, twisting, and manipulating delicate devices and samples. Without that dexterity, many of the advantages of human investigators and explorers (Boston, 1999c) are greatly diminished.

The constant pressure suit design makes joint mobility very difficult. This is another problem that must be solved before humans will be caveworthy on Mars. A material that could be described as a vacuum-rated "turtleskin" (like the product of the same name containing Vectran fiber) could provide the abrasion and puncture resistance of the present material but could maintain the pressure-holding integrity of the suit while remaining as flexible as at least a wetsuit.

Better than *any* garment-like suit, one could imagine the eventual development of some sort of synthetic tissue that could be biologically or semi-biologically produced and form a second "living skin" on our astronauts. Such a living structure might even derive it's energy directly from us in a symbiotic arrangement. Possibly such a second skin could even be directly generated biologically by the modified humans of a future Mars (Figure 15).

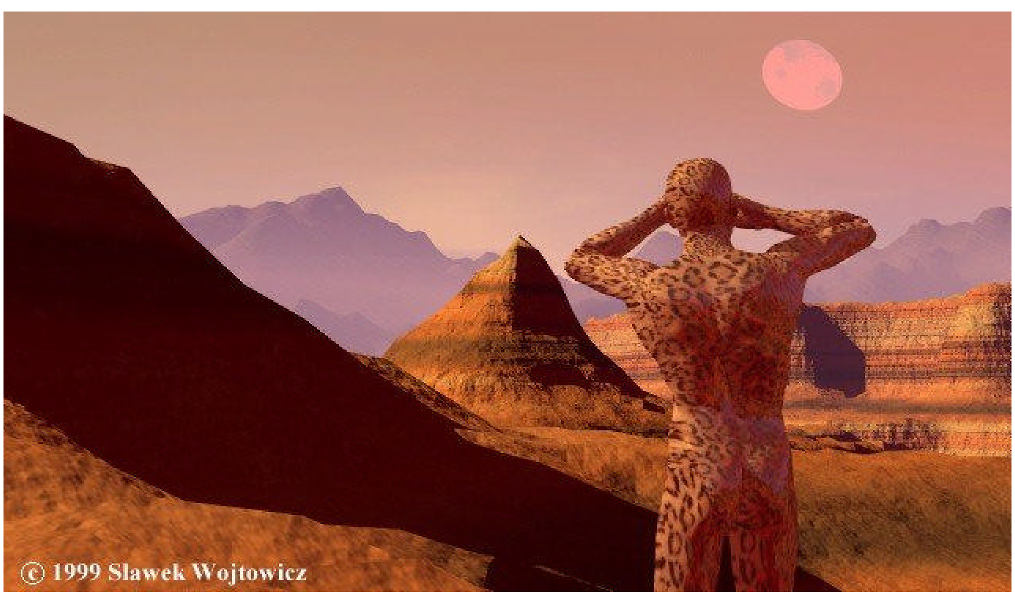

Figure 15: "Living skin" biological spacesuits of the future? This is the ultimate fantasy for the aspiring Martian caver, or indeed, Mars colonist!

III. Habitat

A. Inflatable cave liners

1. Concept overview

Shirtsleeve indoor environments are desirable for all human habitations on other planets. Unique features of the cave environment do exist and should be developed further. These include the advantages 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 (Boston, 2000b). In our initial analyses, 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 inflation of the new unit.

Building on this original vision, there are a number of variations on the above skeleton that are possible. For example, auxiliary rigidifying materials could be employed to provide a more permanent shell that is less dependent upon interior pressure. Such 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 a hazardous situation.

Figure 16: Contrary to the rough and jumbled edges of rock in lava fields and often around the entries to lavatubes, the tubes themselves are often remarkably smooth. This image shows a BBC camera crew in Four Windows Cave, El Malpais National Monument, NM, preparing to shoot cave microbiology work for a television documentary.

Vertigo, Inc. a commercial manufacturer of various inflatable devices, is marketing structures for terrestrial applications fitted with inflatable, higher pressure "airbeams" to provide greater structural integrity to inflatables http://www.vertigo-inc.com/Inflatable_Structures/Inflatable_Structures.html

2. Materials

The present suite of off-the-shelf materials offer 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 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.

Figure 17: Just inside the entrance to Parks Ranch Cave, NM. This smooth-walled gypsum tube located in a giant evaporite basin of Permian age was formed by seasonal flooding events. It averages 3.5 to 4 m in height for large passage down to a meter or less in crawling passage. It has over 5 miles of mapped passage. Although on Earth, gypsum tubes like this one present a drowning hazard during periodic floods, on the now dry Mars similar caves could provide an excellent, low-abrasion site for liner deployment.

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.

Figure 18: Cave scientists Diana Northup and Mike Spilde inspect the smooth wall and floor surfaces of Four Windows Cave, NM for the presence of actinomycetous bacteria. Martian caves of this size and smooth surface texture would make excellent choices for habitat. Additionally, permanent ice stalagmites, stalactites, and draperies adorn some passages further to the interior.

Other potentially suitable materials like high stress polyethylene films are manufactured by companies like Raven Industries for application to inflatables and high altitude research balloons manufactured by Aerostar Int'l, Inc. ILC Dover, manufacturer of all sorts of inflatable devices for aerospace applications and others, has many off-the-shelf materials that they are testing besides their work with Vectran and other well-known materials.

More exotic future developments, many funded by the National Textile Center in Delaware, include the use of "smart textiles" based on environmentally responsive fabrics that can sense physical and chemical parameters and adjust themselves accordingly (e.g. recent work by Foulson et al. and Luzinov et al., at Clemson University).

Especially significant to a potential habitat material is the development of vapor-sensing "electronic noses" based on optical fiber technology. These can be embedded in textile fiber or non-woven continuous sheet and could be used to provide completely unobtrusive air quality control in a habitat inflatable.

Another promising development is the construction of highly application-specific non-linear elastic blended fibers that can do things like conform to non-regular shapes (work by Dunn et al., at Philadelphia University).

A hybrid material composed of micro-fabricated bio-environments and biologically activated fibers is under study by Fowler and colleagues (University of Massachusetts, Dartmouth). These fabrics will ultimately have genetically engineered bacteria and possibly other cell types incorporated into them enabling them to generate and replenish chemical coatings and chemically active components.

Photoadaptive fibers that undergo reversible changes in their optical, heat reflectivity and electrical properties are being developed by Mills and colleagues at Auburn University. Potential applications for these fibers include selective reflection of high intensity infrared radiation, shielding of electromagnetic radiation, and against high intensity visible sunlight wavelengths. Nanometer-sized metal particles of silver and gold in high concentrations reflect infrared radiation and are employed in the photoadaptive fibers as active reflectors. The particles are formed only under high fluxes of photons, that is, under conditions where heat reflection is required.

Walsh et al., Auburn University, are developing fibers from stimuli-sensitive polymers (SSP's) that respond to environmental changes such as pH, temperature, salt, light, electrical field, stress and particular electrolyte. These SSP fibers change character and can regulate the actual performance of fibers in a desirable manner when the surrounding environment change. They possess environmentally "triggerable" microdomains that are capable of interacting with external agents (Logan et al., 1997). Obviously the possible applications are legion. Amongst those suggested by the investigators are controlled-delivery for functional substances (drugs, nutrients, herbicides, etc.) temperature and moisture regulation, separation science, communication, robotic muscles, sensors, and quality control.

Conductive polymers constitute another major area of materials development that could have application to a number of the concepts in this study (e.g.flexible sensors, bendable microrobotic conducting components, electrochromic windows for high radiation environments, biosensors and chemical sensors, and non-linear optics). For a more complete description, consult Appendix B.

3. Airlocks

Airlocks are a critical component of any pressurized structures on Mars or the moon. 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 via aerosol cans of "Airlock-in-a-Drum"?
- Rigid, standardized airlock door and frame assembly (one size can be made to fit all!)

We envision standardized, rigid airlock door and mount assemblies that can be custom-fitted to individual cave openings by means of a moldable, shape-conforming technique. We prefer the relative simplicity of a method that relies on hardening foam to fill in space around the rigid doorframe. The doorframe will have a series of telescoping metal members whose length can be easily adjusted to meet the rock wall. These can 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.

As an alternative, we have considered using flexible, blanket-like material to provide the 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.

Figure 19: *The Perfect Airlock…Transparent, Leakproof, and Fast!*

What materials are currently available that might be useful for this novel technique? The nature of the foam is of primary concern. It must possess flexibility, high insulative value, possible transparency or translucency, and ease of application by hand methods in the cold Martian near-vacuum environment. We believe that recent advances in creating *flexible* aerogel materials for both high temperature (500^{o}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 Appendix B.

Research action items for proposed Phase II project:

1. Test presently available materials for suitability for this application.

2. Currently foreseeable near-term future materials should be considered in greater detail and assigned TRL values.

3. Desirable properties not yet possessed by materials available or foreseeable in the near future should be identified and communicated to materials scientists and engineers.

C. Created metabolically inert and other buffer gas atmospheres

Problem: Need to facilitate human operations in Mars caves without resort to pressure suits

Constraints: Must cause minimum interference to 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 hPa, 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 hPa 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 include:

1) the requirements and methods necessary to adequately seal the cave section of interest

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 humans exposed to external argon gas or exposed to inhaled argon gas

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 CO_2 –derived propellant.

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 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) but have failed so far to obtain an actual copy of the paper. (We note that the astronauts don't *necessarily* have to breathe an argon mix if oxygen breathing gear is used.) If argon is to be breathed, some points to consider include:

- Inert gas narcosis. 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. The effects on astronauts themselves will almost undoubtedly be negligible.
- 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.

The research questions suitable for Phase II study include:

1) Does argon have any microbiological impact at partial pressures of 150 hPa to 1000 hPa?

2) Is it possible to design a functional ambient pressure exploration suit that is warm enough for use in Mars caves?

3) Will argon be obtainable in sufficient quantities from the physical-chemical ISRU (in situ resource utilization) schemes that have been proposed in the literature?

Further information about argon's biological properties and bibliographic and website sources are found in Appendix C

***Figure 20*: The ultimate in "Shirt-sleeve" cave environments. Such an environment is more plausible in habitat and resource providing caves. In research caves, it is unclear whether inert gases raising the total pressure could be deleterious in some fashion to potential indigenous microbiota. Much further thought and research should be done to answer these questions thoroughly before the idea finds its way to a larger audience.**

D. Power and photon solutions

Power requirements are the bane of life support and extraterrestrial operations (not to mention California). Solving the general power problem is beyond the scope of our effort. However, power minimization strategies are always highly desirable. We have several suggestions to offer. Most are useful for any variety of habitat, not just caves. However, they have particular applicability to the subsurface environment and can be employed in novel ways in the cave environment.

1. Areothermal power?

Of course, all of the usual suggested power alternatives have been considered by numerous people trying to plan for eventual human presence on Mars and other bodies. Small nuclear reactors, solar collecting fields, light piping, and others have been suggested. We think that caves might be able to add an additional possibility…that of accessibility to geothermal energy…or "areothermal" power in the case of Mars. Areas of heat flow may persist in some places on Mars. It is possible that residual geothermal or fumarolic activity may persist in volcanic areas even though the primary vulcanism may be long past. If so, then tapping into this energy, particularly from a subsurface source may present itself as a valuable opportunity.

2. Wind power

We may only speculate about the possibility of geothermal energies on Mars but at least we do know that strong winds do riffle the thin Martian atmosphere on an on-going basis (Greeley and Iverson, 1985). This has prompted at least one previous investigator to propose windpower for use on Mars (Haslach, 1989).

Wind power scales as the wind velocity cubed times the ambient density. Density is proportional to pressure and inversely proportional to absolute temperature. Thus, we see that the tenuousness of the Martian atmosphere is a big drawback to wind power. Nevertheless, as Haslach points out in the paper cited above, the Mars wind can average 30 to 60 meters per second depending upon season and latitude. A more conservative model shows average values in the low 20's of meters per second. While this source might not be competitive on Earth, the author points out that there are various applications on Mars requiring sporadic power rather than a consistent source. He suggests that wind power may be appropriate to run some ISRU processing of Mars materials like atmospheric gas separation and conversion to other compounds. These materials are stockpilable and can be replenished on an intermittent basis as long as the stockpiles are large enough to suffice for the usage of the base or colony. Although it is unlikely that we will see the Martian landscape studded with wind turbines in the future, the relatively low mass and easy to maintain construction of windpower generators may make them competitive with higher capability but larger mass systems.

3. Solar technologies

The availability of natural sunlight on Mars has led to suggestions of transparent surface greenhouse inflatables where the photons are "free" (e.g. Boston, 1981). However, the price to be paid for this "free" energy is high: high ultraviolet radiation, high ionizing radiation, high susceptibility to mechanical breakage from impacting objects, high degree of heat loss during non-solar hours, and high demands on materials technology to provide stuff that can stand all that abuse. Alas, no materials currently exist that can hope to approach the needs of a *surface* Martian greenhouse (Chuck Sandy, ILC Dover, pers. comm.).

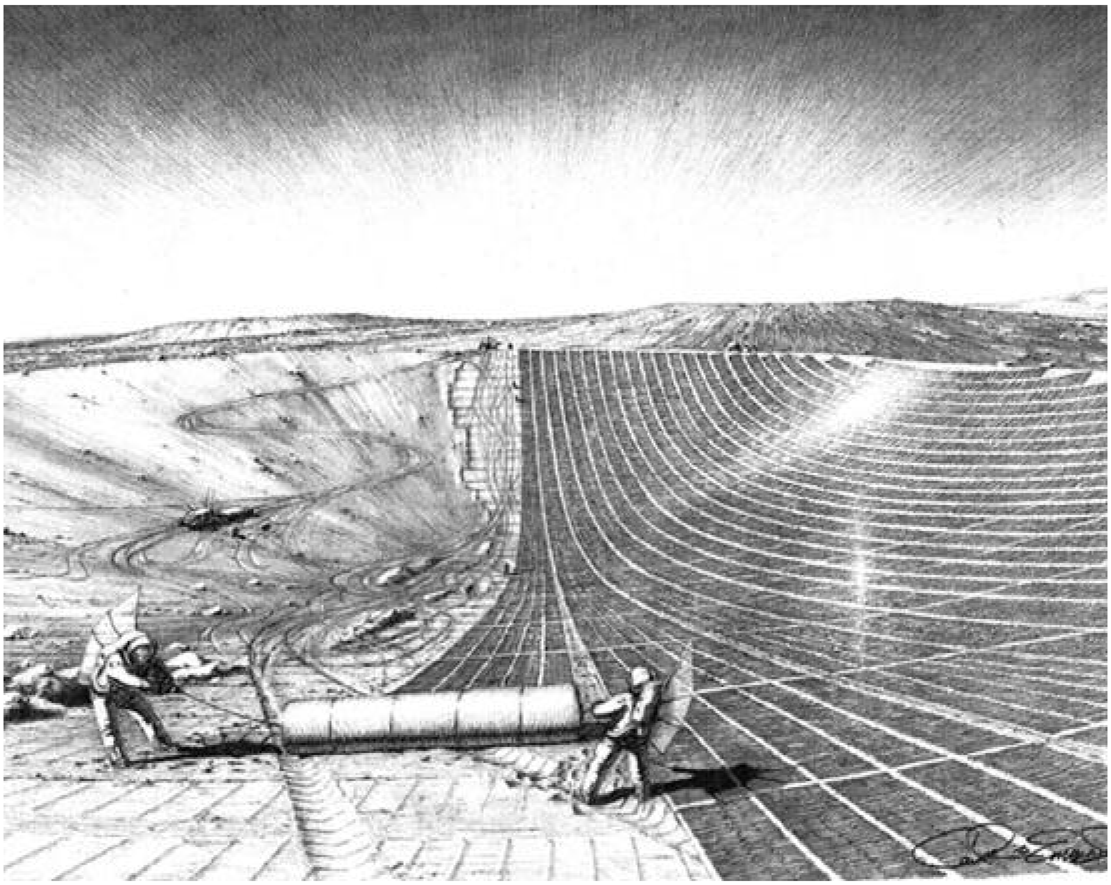

Figure 21: Solar power is a popular option for Mars missions because it avoids technical and sociological issues surrounding nuclear power sources. Additionally, the notion of an entire crater covered with solar collecting surface is appealing. However, a hybrid power system that uses all available sources of energy and accesses them in novel and efficient ways are more likely to succeed in an environment where launch costs, mass, and volume are the economic controllers. Art by C. Emmart.

Solar cells provide a viable option for providing power on the surface of Mars for robotic missions and for a human base. Photovoltaic technologies are gradually improving and proliferating although additional work is needed before the systems are productive enough and low mass enough for the more ambitious Mars applications.

Landis and Appelbaum (1991) did a calculation to show that even with the technology they were assuming (now 10 years old), a photovoltaic powered propellant manufacturing unit on Mars could produce adequate methane from carbon dioxide to match a nuclear powered baseline study's production of the same material (The Mars Direct scenario of Zubrin and colleagues).

Conventional PV cells today convert between 5 and 15% of the energy in sunlight into usable energy. Experimental cells have achieved about double that efficiency, but only under carefully controlled conditions and with expensive materials and high production cost. Efficiency is constantly increasing, however, as new materials and manufacturing processes are developed.

A conventional solar cell consists of a wafer of silicon that is about 1/50th of an inch thick. Typical cells that are four inches in diameter produce about one watt of power, and are grouped into modules of dozens of cells. Modules are further grouped into panels and then arrays, which may produce several kilowatts of power. In contrast, multijunction photovoltaic cells employ multiple layers of semiconducting materials to create two or more junctions. Different layers in the cell absorb different parts of the solar spectrum, so the overall efficiency of the cell can be high.

A number of other metals besides silicon can be transformed into semiconductors and used in photovoltaic cells. Some of them show a great deal of promise and are already in production, while others are in the experimental or design phase. The most hopeful metals include copper indium diselenide, cadmium sulfide, cadmium telluride, gallium arsenide, and indium phosphide. While some of these demonstrate high efficiencies, other factors such as durability, cost, and availability of raw materials can limit performance. Further research may solve these problems making at least some of these alternatives viable options.

Spheral cells are a relatively new solar technology being developed by Southern California Edison, an electric utility, and the Texas Instruments Corporation. A spheral cell is operationally the same as a conventional solar cell, but differs in its geometry. It consists of many tiny spheres of silicon coated with aluminum foil to provide electrical contacts. The advantages of spheral cells are that the manufacturing process is simple, and that low cost, low purity silicon feedstock material can be used.

Because photovoltaic cells are still expensive, it is often more economical to increase the amount of sunlight reaching each cell rather than increase the number of cells. Relatively simple tracking devices are being used to allow an array to follow the path of the sun across the sky to maximize insolation, and concentrators focus sunlight from a large area onto a small cell specially designed for high concentrations of solar radiation. Scientists at the University of Chicago have developed a system to deliver solar radiation concentrations of over 60,000 times the intensity of the sun. The system employs a mirror to focus sunlight on a lens that then concentrates the light even further. Potential special applications include powering lasers for space communications, destroying toxic chemicals, and manufacturing metals, ceramics, and alloys that are superior to existing materials. We believe that sunlight concentration would be ideal for cave habitat systems.

In a conventional dish system for solar thermal electric power plants, the receiver on each dish heats fluid that is circulated to a central generator. In a Dish-Stirling system, electricity is generated at each dish independently. Instead of tubes of fluid at the focal point of the dish, there is a Stirling engine. The Stirling engines convert heat into mechanical motion that powers a small generator. Dish Stirling systems can attain high solar-to-electric efficiencies, up to 32% in recent demonstrations.

In summary, the technology of voltaics is marching along to continuing commercial success and may very well be ultimately the most cost effective means to provide space mission power in the future.

4. Light-piping and light-mining

In contrast to photovoltaics, many of the lighting and heating needs for a cave-based habitat can 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.

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.

Additionally, 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.

Natural or created skylights can also provide access to the surface where individual plant growth modules can be deployed, solar panels may be arrayed, and other surface functions like extraction of Mars atmosphere to make breathable air and mine for water can be conveniently located. These features can be in proximity to the habitats without taking up valuable habitat real estate. The close proximity facilitates routine maintenance, plant-tending activities, and especially response times in emergency situations.

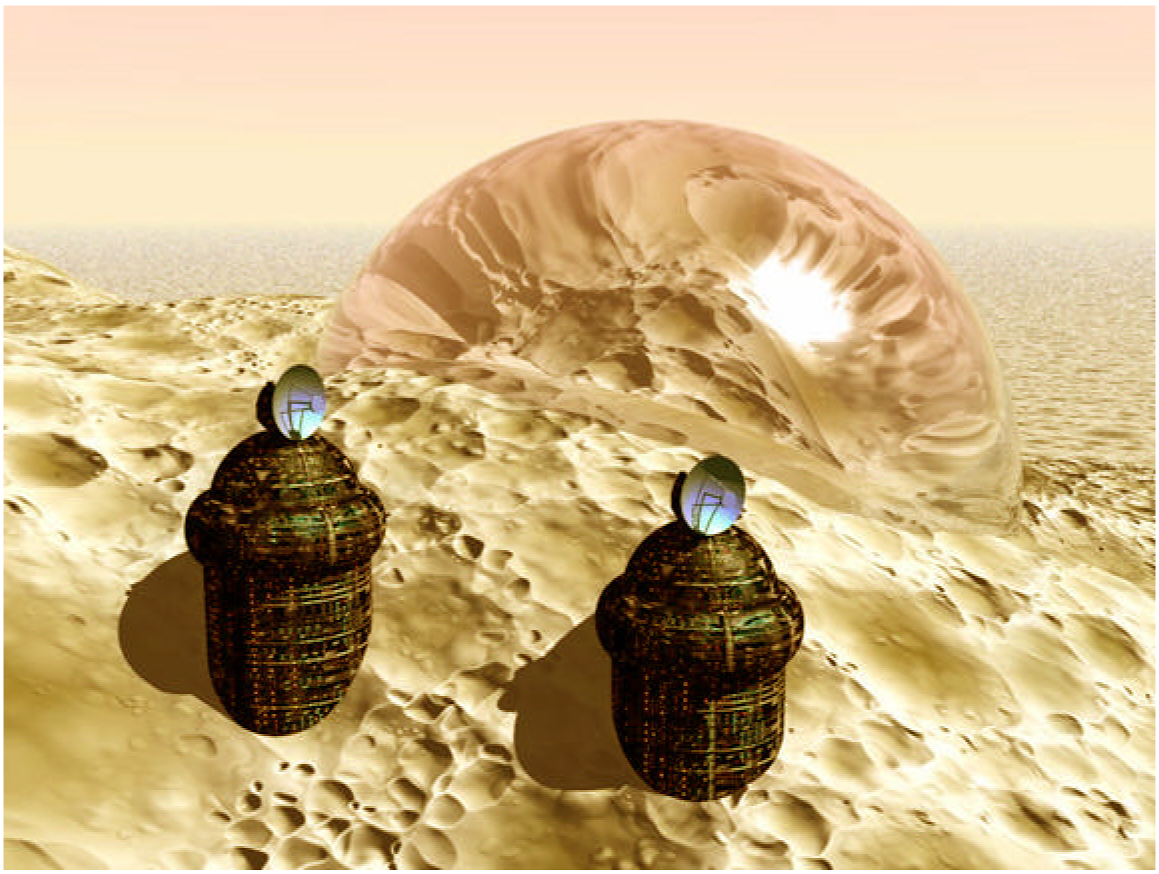

Figure 22: Transparent bubble over the cave habitat below provides light. The ISRU units are busily supplying necessary volatiles to the habitat. Such direct input of photons into a habitat or plant growth facility will depend upon the successful development of radiation shielding transparent materials. Image by R.D. Frederick.

A particularly interesting development for photon management is the ability of some optical fibers to split wavelengths. This enables selective, “designer wavelengths” to be shunted to particular applications. For example, PAR (photosynthetically active radiation) can be directed to plant growth areas.

A final photon management tool in the early to mid development phase is the use of light-emitting polymers. These are being studied by Ballato and coworkers at Clemson University. The fibers are made of a fluoropolymer. Electroluminescent films are being incorporated into the fibers to act as detectors. The application that the investigators have in mind is data sensing, transmission, and sending. However, sensing habitat conditions and responding by light emission could be a very useful property in our cave habitats, food growing areas, and extractive activities.

Not just visible photons flow from the sun, of course. Direct utilization of heat is also possible. The U.S. Department of Energy is looking at new materials for receiving and storing solar heat more efficiently. Researchers at Sandia National Laboratories, for example, are using molten salts as a simple, efficient way to absorb and hold the heat of the sun for later use.

E. Plant Technology

The matter of plants for use in cave habitats is really an issue upon which we have not dwelt, preferring to leave consideration of it to our botanist NIAC friends and others (see Brown and Lomax Phase I studies). However, there are certain properties of plants that will be highly desirable for use in a cave-based growth system accompanying a cave habitat. We detail these in brief below. We do include one particularly novel idea that we are developing for discussion in the general context of genetic alterations of organisms to suit them for extraterrestrial environments whose parameters depart radically from those of the planet of origin.

Curiously, organisms tend to be able to deal with an entire suite of environmental stresses not just one. Stress diffusion genes seem to exist that can handle a spectrum of extreme conditions. This may be due, in part, to the fact that there is a significant functional, biochemical overlap in responses that organisms mount to cope with environmental insults. Indeed, what we consider difficult conditions are normal, even obligatory, for some species. This is a fortuitous situation. It means that there are whole groups of species well-adapted in many of the ways that we would like to endow our food plants with if we can develop the technology to exploit them.

1. Low light plants

There is a vast abundance of plant species well-adapted to very low levels of light. Tapping into this natural genetic pool and attempting to export it to food plant species may hold some promise. Ultimate limits in the actual amount of energy available have not been approached by plants. Greater photosynthetic efficiency and greater productivity while retaining desirable properties like fruit set or seed production may be difficult to co-engineer but certainly worth spending research effort upon. Standard calculations looking at how much lighting a conventional crop containing greenhouse system for Mars will take are ludicrously high. Instead of pursuing the tired path of trying to somehow provide enough energy to drench highly inefficient photon-hogs in light, alteration in the plant material itself is now or soon to be within our grasp.

New genes probably don't even have to be invented. Within plant species, the variables already exist. Some plants employ large light-gathering surfaces. Some photosynthetic microorganisms possess different photopigmentation systems that could potentially be used. Marine endosymbionts often exist in the dim lower photic zone of ocean regions on a mere 20 to 130 μmol photons m^{-2} s^{-1}). Microbial photosynthesis by deep sea hydrothermal ventlight has even been observed.

The genes are out there. Let's go get 'em!

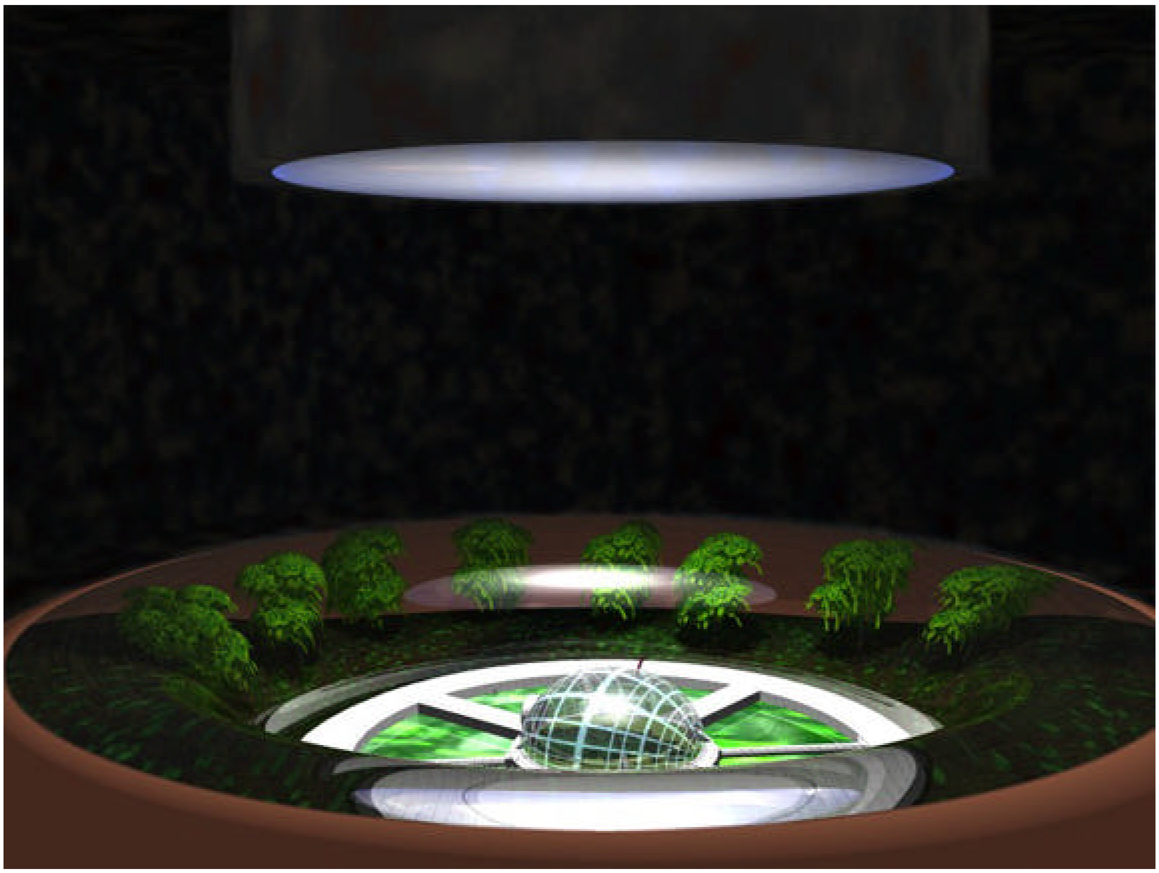

Figure 23: A large greenhouse complex in a mature Mars settlement. Some immense underground cavern houses the facility and the mother of all light pipes provides illumination from above. Art by R.D. Frederick.

2. Cold tolerant plants

Coping strategies employed by cold tolerant plants include a low growth habit, hirsute or leathery leaves and stems, rapid response reproductive triggering, distinctive protein accumulations, osmotic antifreezes of various types, depolymerization of actin that appears to have an adaptive function, and significantly a water stress induced greater cold tolerance. Clearly, dry cold conditions often occur together in alpine, boreal, and polar winters. Plants that can prosper in a cold environment will be well-suited to Martian greenhouses.

They would not have to be heated to the same degree as the habitat and could possibly have more than enough heat gain through lighting. Minimally heated environments could either be located within caves or on the surface attached to cave habitats. Often, in the intensely lit high productivity agriculture model of a greenhouse, heat removal is more of a problem than retention. We hope that a more sustainable and lower power requiring model will be adopted.

3. Low pressure plants

Very little work has been done with plants at low pressures. An early paper describes the growth of radishes under pressure regimes down to around 0.1 Bar (Boston, 1981). Some deleterious effects were noted but the plants survived and actually produced bulbous root tissue like their control counterparts in normal Earth air pressure. K. Corey, A. Schuerger, and others have done some work at KSC at low pressures. It is a prime target area for future research.

Development of plants that could prosper and be productive at lower than sea-level pressures could greatly alleviate the drain on the cave habitat system to provide gases to replace leakage.

4. Ultraviolet photosynthesis

To date, no Earth organism that can photosynthesize using the higher energy ultraviolet photons has been found. Why not? No one knows exactly but the ultraviolet part of Earth's spectrum is a less significant component of the full solar spectrum than it is on Mars. Do existing plants possess component functions that could be artificially combined to produce UV photosynthesis? We don't know but we suggest that the bacterial photoreactivation mechanism for ultraviolet damage repair coupled with presently non-photosynthetically coupled ultraviolet protective pigments found in many microorganisms might be the place to start. Applications of such a talent would be many. Surface greenhouses much less expensive to build could be one reward. Another possible application could be as screening organisms for those who are mjore sensitive to the ultraviolet wavelengths. For example, UV photosynthetic epiphytes could hang above other plants, grow on ultraviolet radiation themselves, while screening plants in the canopy below from its deleterious effects.

5. A better Rubisco

In all the specially adapted plant groupings discussed above they share one thing in common…the key enzyme that drives photosynthesis, rubisco, is a lousy enzyme. It is amazing that this protein, thought by some to be the most abundant protein on Earth, is so very bad at what it does. Rubisco is notorious for being an extremely low efficiency catalyst. It saturates with carbon dioxide, its target substrate, at very low levels. We suggest that a tremendous payoff in many fields including space life support would flow from genetic improvement in the efficiency of this oddly ineffective, yet vital enzyme.

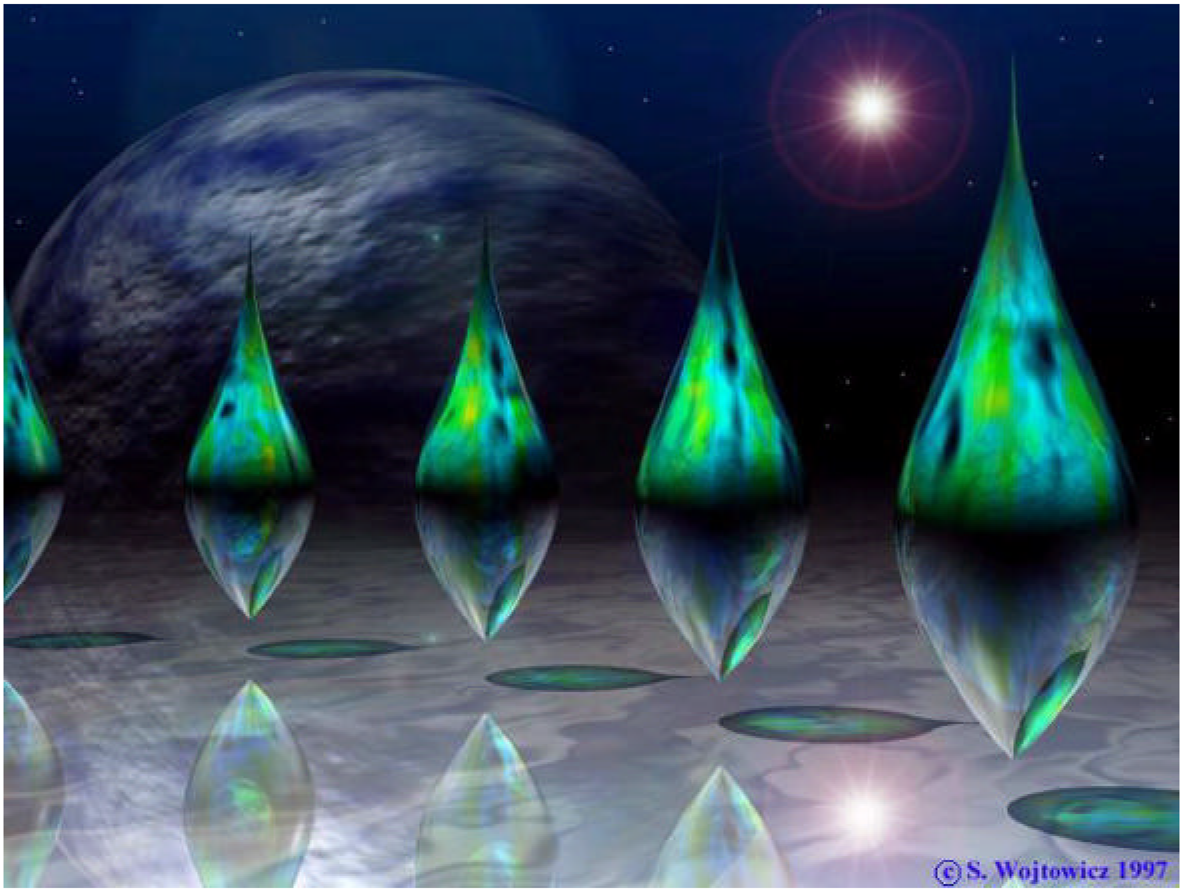

Figure 24: The Perfect Martian Plants. No roots, sealed in a tough transparent coat to conserve water, able to use highly energetic, short wavelength ultraviolet radiation to drive their photosynthetic processes, and able to float to new territories when things become unfavorable. Far fetched? The genetic capabilities of organisms melded with engineering and cybernetics may hold many surprises for us through the coming century…a century that is shaping up to be the Century of Bioengineering.

F. Microbial technology

The general topic of microbial technology is a large one. Below we detail a few of the more promising areas of development that have specific application to our cave habitats followed by discussion of one novel coupled system that could potentially provide both light and oxygen for the habitats.

1. Biosensing, bioproductive, and microbially-inhibiting materials

Materials that combine living microorganisms or some of their chemistries and surfaces are being actively pursued. Applications of this include self-healing of damage to materials, chemical production on environmental demand just as organisms' own chemistries respond to the environment, detecting and responding to changes in the environment, and various methods of inhibition of microorganisms by materials are all subjects of active research. Whether the field yet has a clear moniker or not, this research field could be termed "intelligent interactive smart materials".

Biocidal properties as an inherent feature of materials is something being actively pursued by researchers at Clemson and Auburn Universities. Both groups (see the National Textile Center website, http://www.ntcresearch.org).

2. Bioluminescent light and oxygen generation

We have conceived of a unique combined microbial system that allows photosynthetic organisms in surface mounted batch chambers to produce and sequester biomass, liberate oxygen and send that oxygen through a tubing system for reaction with naturally bioluminescent microorganisms or with a hybrid materials-mounted luciferin/luciferase system. The low bioluminescent light levels 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 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 are preparing a more detailed design for such a system and accompanying experiments that will constitute a portion of our future Phase II proposal.

Figure 25: Is this our distant Martian descendant? Endowed with capabilities and adaptations that we can only guess at, humans will adapt to new environments in the Solar System as they have on Earth.

G. Homosymbionts

The ultimate bioengineering project for future human inhabitants of other worlds may lie in melding them with permanent symbiotic microorganisms that are capable of performing an array of adaptive functions for these new extraterrestrial humans. Protection from radiation, water conservation, and other functions beyond our present imaginations could result from a unique blending of biological forms.

IV. Resources

A. Volatiles

1. Ice lenses

Permanent ice exists even in some mid latitude caves on Earth. The possibility exists for trapping of ancient frozen ices (water and CO_2) in lavatubes that underwent collapse during the era on Mars when the atmospheric density exceeded the triple point of water (Figure 4). On Earth, many other cave types harbor permanent ices in mid latitude to polar regions. Caves on Mars that are open to the atmosphere will presumably have long ago lost their ices to sublimation. However, prospecting for near surface cavities without natural openings may also yield trapped volatiles if the parent rock is sufficiently impermeable to have prevented percolation of sublimated ices.

2. Other volatiles

Caves frequently have sources of various gases that alter the cave air with respect to the bulk atmosphere. Apart from the obvious case of water vapor (with which they are endowed to saturation), H_2S, CO, CO_2, NH_3, COS, SO_2 and other gases flow into caves (e.g. Hose et al., 2000). This material usually accompanies water emitting springs in caves on this planet, but there are also instances of direct gas seepage. Whether such phenomena may occur on Mars is unanswerable at this time, but we should be prepared to exploit such resources should they present themselves.

B. Solid materials

On Earth, many mines are begun within naturally existing caves. This is an obvious result of the visibility of economic minerals, ores, and bulk resources that attract the attention of prospectors. Even in antiquity, archaeological evidence from caves shows that crystals, turquoises and other semi-precious amorphous gems, pigment minerals, saltpeter, elemental sulfur and other useful commodities were gathered at often great risk to the participants using primitive lighting methods like bundled twig or yucca stem torches.

Figure 26: The Watering Hole. The best-case scenario for a cave habitat is illustrated in this depiction of a large lava tube. The permanent ice lake shown could provide an extremely valuable deposit for scientific study as well as providing a large initial amount of water to provision the cave habitat. If located within the same cavity that was suitable for habitat, close proximity would remove the need for cross-surface transport.

On Mars, it is unclear how much secondary mineral deposition, hydrothermal minerals, or ore material might be created. It is a very different planet and mechanisms may be very different. Although Earth is a water-laden planet and aqueous processes dominate much of the geology and mineralogy, in caves we see numerous examples of vapor phase deposition of minerals that have accumulated in the air-filled cavities rather than in veins and fissures in the parent rock. This process may be relatively more important on Mars especially during its long later period when the planet seems to have "dried out".

C. Micromining

Today's mining techniques are still very crude, labor intensive, environmentally intrusive and unsatisfactory for use in sensitive environments. In addition, because it relies on physical and mechanical processes, the extractive phase is unselective. Selection of desired materials is performed on bulk materials in subsequent beneficiation and other chemical techniques. Below we are proposing a more selective, less destructive methodology that could be employed on a small scale and aimed primarily at the recovery of highly specific compounds or elements.

Figure 27: The Martian Miner. The Martian geologist, with rockhammer poised to deliver a blow, reminds us that we will be meeting the planet on its own terms. Valuable commodities on Earth may be scarce on Mars, especially water and other hydrogen sources, but other valuable material forms not present here may prove to have uses as yet unimagined by us. Art by C. Emmart.

1. Biomining

Organisms already perform many mining operations. Plant roots mine soils for water and minerals, often to the depths of many tens of meters. Microorganisms in caves mine the parent rock for traces of organic carbon, phosphorous, and metals while dissolving the limestone in a version of microbeneficiation. Fungal mycelia mine soils for water and extract minerals from deep into the subsoil strata. Planktonic bacteria mine the ocean waters for various elements and compounds that are present in only minute concentrations. Lichens mine igneous and sedimentary rocks via organic acids that slowly breakdown their lithic integrity. These natural talents fit biological organisms to be developed further as purposive tools of micromining for our use if there are no indigenous microorganisms present or in situations where any indigenous lifeforms do not occur.

2. Bioinjection

We suggest that a fluid transport medium, doped with selected and re-engineered microorganisms, could be injected into existing fissures, drilled boreholes and wells, and other access points. The fluid could be a highly specific material that would provide all of the energy sources and other resources that the microorganisms need in order to perform the specific extractive process that we might be interested in. This is analogous to the fluid that accompanies, nourishes, and protects sperm while they are attempting to perform their fertilization activity.

Figure 28: Subterranean cavities depicted within a classic Japanese volcanic cone grace this silk scroll. Bioinjection and nanoinjection mining techniques could take advantage of such natural passages or be implemented in human created boreholes.

Microbial action that requires ready access to oxygen could be supplied by the inclusion of O_2 slow-releasing microbeads that would not interfere with the fluid properties of the transport medium. After the appropriate incubation period has occurred for the microorganisms to perform their tasks, the fluid could be pumped out and the compound or element of interest separated from the fluid and organisms. The microbes can be recovered, the fluid refreshed or replaced, and the cycle could start over again.

Suitable organisms already exist in nature for many tasks that could be envisioned. Microbial degraders that transform nitrogen compounds to others, sulfur compounds to others, iron and manganese compounds to others, and transform one organic compound to another are abundant in many environments. Microbial acquisition and internal sequestration of many materials is common. Organisms concentrate rare earth elements (REEs), mercury, selenium, iron, manganese, and many others. The fluidization of certain materials from the solid form to liquids or gases for easier extraction are another possibility. Further refinement via conventional selection ("breeding") and active genetic modifications could produce highly efficient strains of organisms tailored for many specific purposes.

3. Nanoinjection

Analogous to the bioinjection described above, we also mention the possibility of injection of similarly microbe-sized (~1µm) nanomachines to perform a wide variety of jobs. Should nanotechnology develop as well as some envision, even more capabilities beyond the scope of microorganism abilities could be imparted to the transport fluid. Additionally, if Mars possesses a widely distributed subsurface microflora all its own, then bioinjection of Earth-derived organisms may be unacceptable, and nanoinjection could be a superior choice.

V. Earth Analogs

We have identified two distinct scenarios for future operational simulations of Mars caves in Earth caves. The first simulation scenario will test out various features of our cave habitat. The second simulation will test out our ability to conduct science in a biologically sensitive, unexplored, pristine cave.

A. Habitat cave simulations

1. 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. The atmosphere has been measured to have around 7% CO_2 and requires full breathing gear. The partial pressure of 7% carbon dioxide at that altitude is approximately 60 millibars. The partial pressure of CO_2 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 n Mars.

Figure 29: Sampling the colorful walls of HM Cave, AZ. Large (30 lbs) rebreather backpack is necessitated by the 7% CO_2 atmosphere. Image by V. Hildreth-Werker.

2. Lavatube, New Mexico or Oregon

Lavatube caves located at El Malpais National Monument, NM and near Silverton, OR are possible habitat simulation sites. 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.

B. Science cave simulations

1. La Cueva de las Barrancas, NM

This deep cave (300 ft. entrance rappel) in the Guadalupe Mts. of southeastern New Mexico is the clear choice for a Mars cave science simulation. 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 H_2S 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!

We are developing low impact and no impact analytical techniques to avoid compromising the microbiological value of this site. Using an “experiment as you explore” philosophy, we go further only as we are ready to sample and analyze the microflora and other biology. This extreme precaution is warranted to avoid contamination of the site by human-associated microorganisms and organic debris (skin cells, hair, etc).

One of the primary foci of future Phase II work will revolve 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 envision that our early efforts will address the communication issues first. Integration of these devices onto microrobotic platforms is a more advanced refinement that awaits the development of suitable devices. Initially, we will hand deploy 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 (NIAC team member Jim Werker), and the science investigation team (NIAC team member, Penny 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.

We believe that the cave is speleogenetically similar to nearby caves (Carlsbad Cavern, Lechuguilla Cave, and many others) in a hydrogen sulfide/sulfuric acid origin. It probably falls within the age spectrum of these caves, 6 – 12 million years old as lower bounds based on dating of secondary alunite deposits (Polyak et al., 1998). The actual ages of the caves are probably much older and dating at least 20 million years to a major uplift era. Indeed, it has been suggested that these are continuations of caves formed much earlier than that through three phases of uplift separated by many millions of years (Hill, 1987).

Figure 30: J. Werker on rope in Barrancas Cave. This entry pit leads to the lower main floor of the cave over 300 feet below the surface. Entry is through a gated airlock at the bottom of a small canyon in the Guadalupe Mountains, NM. Image by V. Hildreth-Werker.

2. Planetary protection protocol implementations

We envision that a Mars simulation will involve some version of a protective suit and breathing gear worn by investigators, sterile procedure when onsite, and other suitable precautions. We are presenting this scenario at the NASA-sponsored Workshop on Planetary Protection Protocols to be held in Pingree Park, CO the last week in June 2001.

Figure 31: Shy cave inhabitant peeks out from the shelter of a flowstone-covered overhang in tiny Dimple Puddle (8" diameter) in La Cueva de Las Barrancas, NM. This completely cave-adapted springtail (~1cm long) is one of only three invertebrates seen in the cave so far.

C. Proof-of-concept trials

1. Inflatable and airlock demonstration

We are conducting discussions with several manufacturers of inflatable devices to develop a teaming arrangement for production of an inflatable unit for testing in-cave. Airlock construction will be modeled after the new airlock assembly designed by J. Werker originally for Lechuguilla Cave. These tests will be detailed in our Phase II proposal.

2. Seed-to-seed in cave

Growth of a plant in a closed chamber within a cave may be a useful demonstration of several techniques. To accomplish this, light can be supplied from outside via optical fibers.

An alternative potential plant growth strategy for Mars is the use of individual plant growth modules in residence on the surface. If these modules are sufficiently small, they can be brought in to the cave habitat for tending, thus alleviating the need for greenhouse structures that can accommodate humans.

Research questions include:

- identification of possible light collecting schemes for use of natural Martian sunlight and ways to simulate this in an Earth cave
- determination of the actual PAR (photosynthetically active radiation) that such systems can deliver starting with the Martian sunlight that varies from 36% to 52% of Earth's value depending upon the orbital position,
- foreseeable difficulties in handling surface modules by bringing them inside for tending,
- assessment of potential integration of oxygen production and carbon dioxide uptake from net plant productivity in surface modules and in-habitat plants,
- trade-offs in the tremendous power burden that interior plant growth chambers require if artificial lighting is required.

3. Bioluminescent/oxygen generation microbial demonstration

As part of our Phase II proposal, we will be presenting the idea of testing a benchtop model of the biolum/O_2 system. If this demonstration proves successful, we will prototype a system version for use in a cave simulation in conjunction with the demonstration of inflatable unit and airlock.

4. Inert breathing mixture trials

We are interested in conducting experiments to determine whether argon and argon/nitrogen breathing mixtures have any deleterious effects on mammalian respiration. A simple demonstration of feasibility in laboratory mice is planned. This coordinates with work on a space educational program currently under development by R.D.Frederick, CEMMS (Controlled Environment Mouse Mission Simulation). The first prototype unit is undergoing testing and modification and will be ready for testing with live mice within the next few months. We plan incave testing with mouse inhabitants for this fall.

If the results of mouse argon breathing experiments are satisfactory, we will pursue the avenue of testing argon breathing trials with humans.

5. Human residence trial

We envision the development of the above systems and components as culminating in a complete human residence trial in an inflatable structure deployed within one of our habitat cave simulation sites described above. Simulation duration of from 2 to 5 days are under consideration. Speleonauts will live within the inflatable structure, don suits and breathing gear before exiting into the cave environment, perform scientific and exploration work, test the various systems within and outside of the habitat, and monitor their own health by tracking significant parameters like heart rate, temperature, mental acuity via simple cognition tests, and reflexes. We plan to light the facility with light piping devices and provide power from outside of the cave at levels that would be reasonable for an actual cave habitat that must provide all its own power.

Figure 32: The cave houses of Santorini Island, Italy. One of many examples of uses of caves as habitat by humans today, in antiquity, and in prehistory.

VI. Conclusions

We believe that the use of caves on extraterrestrial bodies for science, human habitat, and resource base is a very exciting prospect. Although caves on other planets have occasionally been the subject of science fiction (e.g. Nordley, 1994; Robinson, 1994), we are grateful for the opportunity to study the issues in reality. Although we realize that there are many challenges inherent in this enterprise, as with any other planetary exploration and utilization scenarios, we believe that they are not insurmountable. Caves are ultimately a very practical approach to the spectrum of future human and robotic activities on Mars and other planets.

We anticipate the presence of numerous types of caves on Mars and other bodies for sound scientific reasons, not just wishful thinking. We expect to find cave formation processes and resulting cave types not found on Earth. These protected underground environments may be the only place in which relict biotas still persist on planets with inhospitable surfaces but with more clement past histories that may have enabled the origin and early evolution of life.

The major themes of inquiry – science, habitat, and resources – remain largely as we envisioned them in the proposal phase. We have identified major secondary areas of development within these broad categories and attempted to make reasonable estimates of Technology Readiness Levels (TRLs) as feasible. We have also identified specific areas for immediate further research that could prove fruitful in the shorter term. We have identified key components of the experimental and developmental scenario that we will be developing as part of our Phase II proposal.

The Phase I NIAC award has allowed us to strengthen our case in some areas, discard ideas that proved implausible, and identify major technological and information hurdles yet to be worked through. We have made steps towards answering the question “Will humans go on to use caves in our future Solar System–wide civilization as so many of our ancestors have done in the past?”

References Cited

Aldrete, J.A. and Virtue, R.W. 1967. Prolonged inhalation of inert gases by rats. *Anesth Anal*g 1967; 46: 562-565.

Amy, P.S. and Haldeman, D.L. (1997) Microbiology of the Terrestrial. Subsurface. CRC Lewis Publishers, Boca Raton, FL. 356 pp.

Arnold, D.E. 1971. Ethnomineralogy of the Ticul, Yucatan potters: Etics and emics. *Amer. Antiquities* 36:20-40.

Arnold, D.E. and Bohor, B.F. 1975. Attapulgite and maya blue: An ancient mine comes to light. *Archaeology* 28:23-29.

Balkwill, D.L. and Ghiorse, W. 1985. Characterization of subsurface bacteria associated with two shallow aquifers in Oklahoma. *Appl. Environ. Microbiol*. 50:580-588.

Beloin, R. M., J. L. Sinclair, and W. C. Ghiorse. 1988. Distribution and activity of microorganisms in subsurface sediments of a pristine study site in Oklahoma. *Microb. Ecol.* 16:85-97.

Bone, T. L., and D. L. Balkwill. 1988. Morphological and cultural comparison of microorganisms in surface soil and subsurface sediments at a pristine study site in Oklahoma. *Microb. Ecol.* 16:49-64.

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 Teachnology Series. pp. 253-265. Amer. Astronaut. Soc., Washington, D.C.

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. 1999a. The Search for Extremophiles on Earth and Beyond: What is extreme here may be just business-as-usual elsewhere. *Ad Astra Magazine* Vol. 11, No.1, January/February 1999.

Boston, P.J. 1999b. A bit of peace and quiet: The microbes of Lechuguilla. *NSS News* 57(8):237.

Boston, P.J. 1999c. 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. Life Below and Life 'Out There'. *Geotimes* 45(8):14-17.

Boston, P.J. 2000b. 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. 2002. The caves of Mars: Possible mechanisms, chemistries, and physical characteristics. In preparation.

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., 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. 2001. Cave biosignature suites: Microbes, minerals and Mars. *Astrobiology Journal* 1(1):25-55.

Brooks, R.A., Evolutionary robotics; where from and where to. *Evolutionary Robotics: From Intelligent Robots to Artificial Life* ER'97, AAI Books, Ontario, Canada, 1997, pp. 1--19.

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.

Brown, C.S. CP 99-03 Phase I – Programmable Plants: Development of an *in planta* System for the Remote Monitoring and Control of Plant Function for Life Support.

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.

Carr, M.H. and Wanke, H. 1992. Earth and Mars: Water inventories as clues to accretional histories. *Icarus* 98(1):61-71.

Colozza, A. CP 00-01 Phase II – Planetary Exploration Using Biomimetics.

Dubowsky, S. CP 99-01 Phase II - Self-Transforming Robotic Planetary Explorers.

Frederick, R.D. 1999. Martian lava tube caves as habitats. Second Annual Mars Society Convention, Boulder, CO, Aug. 12-15, 1999.

Greeley, R. and Iverson, J.D. 1985. *Wind as a Geological Process on Earth, Mars, Venus and Titan.* Cambridge University Press, Cambridge, UK

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.

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.

Haslach, H.W. 1989. Wind energy: A resource for a human mission to Mars. *JBIS*, 42:171-178.

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.

Hill, C.A. 1987. Geology of Carlsbad Cavern and Other Caves in the Guadalupe Mountains, New Mexico and Texas. Bulletin 117, NM Bureau of Mines and Mineral Resources, NM Inst. Mining & Tech., Soccoro, NM. 152 pp. plus maps.

Hill, C.A. and Forti, P., editors, (1997) Cave Minerals of the World, 2nd Ed. Nat. Speleol. Soc., Huntsville, AL. 463 pp.

Hodgson, E. CP 00-02 Phase I – A Chameleon Suit to Liberate Human Exploration of Space Environments.

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. 1999. Microbiology and geochemistry in a hydrogen sulphide-rich karst environment. *Chemical Geology* 169, 399-423.

Jelinek, J. 1975. *Pictorial Encyclopedia of the Evolution of Man*. Prague, Hamlyn.

Johanson, D. and Edey, M. 1974. *Lucy: The Beginnings of Humankind.* New York, Simon and Schuster.

Kokh, P. 1996. Searching Mars for lavatubes. *Moon Miners' Manifesto*, #93. Section 6.9.3.2.093, Artemis Data Book.

Kroo, I. CP 99-01 Phase II - Mesicopter: A Meso-Scale Flight Vehicle.

Landis, G.A. and Appelbaum, J. 1991. Photovoltaic power options for Mars. Space Power, 10(2):225-237.

Leakey, R. E. and R. Lewin (1977). *Origins*. New York, E. P. Dutton.

Leakey, R.E. 1992. *Origins Reconsidered: In Search of What Makes Us Human*. New York, Doubleday.

Logan, M., Cannon, G. and McCormick, C. 1997. pH responsive microdomain formation in a de novo polypeptide. *Biopoly*, 41, 521-532.

Lomax, T. CP 00-02 Phase I - A Flexible Architecture for Plant Functional Genomics in Space Environments

Lourandos, H. 1987. Pleistocene Australia. In, O. Soffer, ed., *The Pleistocene Old World*. Plenum Press, NYNY. 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.

McKay, C.P. 2000. Flowers for Mars. *The Planetary Report*, vol. 20, Sep/Oct.

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. and Nedell, S.S. 1988. Are there carbonate deposits in the Valles Marineris, Mars? *Icarus* 73(1):142-148.

Melim, L.A., Shinglman, K.M., Boston, P.J., Northup, D.E., Spilde, M.N., and Queen, J. M. 2001. Evidence for microbial involvement in pool finger precipitation, Hidden Cave, New Mexico. *Geomicrobiology Journal.* In press.

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. Chapter in *Encyclopedia of Environmental Microbiology.* Wiley and Sons, Publ. In press.

Newman, D. CP 00-02 Phase I - Astronaut Bio-Suit System for Exploration Class Missions.

Nordley, G.D. 1994. Into the Miranda Rift. In, Gardner Dozoi, ed. *Year's Best Science Fiction*, 11th Annual Collection, St. Martin's Press, NYNY.

Northup, D.E. and Lavoie, K.H. (2001) Microbially influenced dissolution and precipitation in caves: A review. Geomicrobio. J. In press.

Polyak, V., McIntosh, W.C., Guven, N. and Provencio, P. 1998. Age and origin of Carlsbad Cavern and related caves from 40Ar/39Ar of Alunite. Science, 279, 1919-1922.

Robinson, K.S. 1994. *Green Mars*. Bantam Books, NYNY. 535 pp.

Rummel, J.D. (2001) Planetary exploration in the time of astrobiology: Protecting against biological contamination. Proc. Nat. Acad. Sci., 98(5), 2128-2131.

Sieveking, A. 1979. *The Cave Artists*. Thames and Hudson, Ltd., London, UK. 221 pp.

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.

Swift, P.D. and Smith, G.B. 1995. Cylindrical mirror light pipes, *J Solar Energy Materials and Solar Cells* 36:159-168.

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.

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. Coodinated 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 Biomorphic 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, Volume15, 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.

Watkins, J.S., Gadsen, R.H. and Watson, K., Seismic detection of near-surface cavities, USGS Prof. Paper 599-A, 1967.

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. Tennesee Press, Knoxville, TN. Wright, R.V. 1971. *The Archaeology of the Gallus Site, Koonalda Cave.* Inst. Aboriginal Stud., Canberra, Australia. 133 pp.

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.

Wymer, J. J. 1982. *The Paleolithic Age.* London, Croom Helm.

Appendix A – Summary of NIAC Phase I Activities

A. May 2000:

Activities:

1. *Presentation of initial proposal ideas to team members.* Initial proposal ideas were distributed to prospective team members to refresh their memories about what we initially intended. Feedback was called for and received from those still interested in participating.

2. *Initial conference call meeting, team orientation to the project.* In the third week of May, the initial conference call between team members occurred. General aspirations, time targets and outstanding immediate needs for information and background work were discussed. An action item list was generated (of course!).

3. *Construction of access ladder for La Cueva de las Barrancas*. One of the biggest technical difficulties that we identified with access to our prospective future cave study site, Barrancas, is the extremely difficult lip between the narrow entry crawl and the acute angle that it makes with the 300+foot entry drop. We arranged for a stainless steel ladder to be made to make the maneuvers involved in getting on rope at the top of the drop safer. This will facilitate survey and planning for future incave activities.

Concept Development:

1. Cave types possible on Mars, the Moon, and other planets
2. Comparison of cave properties in view of Martian and lunar conditions vs. Earth
3. Applicability assessment of Earth test-bed to Martian conditions
4. Delineation of characteristics of science target caves vs. habitation caves

B. June 2000:

Activities:

1. *Presentation of initial ideas at NIAC Fellows meeting* – P. Boston presented the major themes and ideas from the original proposal at the NIAC Fellows meeting at Goddard Space Flight Center on the 6th and 7th of June.

2. *Conference call team meeting* – Starley Thompson, Steven Welch, and Penny Boston had an action item status meeting on the 11th of June to discuss progress and potential problems.
3. *Assignment of concept areas to different personnel* - General areas of further work were assigned to the participants on the basis of expertise and time available.
4. *Presentation of ideas at National Speleological Society meeting* – The idea of caves as scientific target and ultimately human resource on other planets was presented at the Geomicrobiology Symposium held during the Nat. Speleol. Soc. Annual convention in Elkins, West Virginia. Particular emphasis was placed on the scientific aspects of the project.
5. *Installation of access ladder for Barrancas*. – Jim Werker, Val Hildreth-Werker, Mike Spilde, and others installed the access ladder at the top of the Barrancas drop. The entry crawl was widened at several sticking points to allow insertion and emplacement of the ladder.

Concept Development:

1. *Revisiting major concepts in proposal*
2. *Selection of most plausible ideas for further development*
3. *Materials bibliography compilation*

C. July 2000:

Activities:

1. Conference call meeting – 3 July
2. Paper published. Boston, P.J. 2000. *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.* NASA Tech. Mem. 2000-208577. Kennedy Space Center, FL. pp. 9-17. Appended to this report.

Concept Development:

1. Alternative breathing mixtures – S. Thompson
2. Communication infrastructure ideas – S. Welch
3. Inflatables – P. Boston, J. Werker
4. Seed to seed proof of concept in-cave – P. Boston

D. August 2000:

Activities:

1. Site visit to pristine cave, Cueva de Las Barrancas, 10-13 August. P. Boston, J. Werker, M. Spilde, V. Hildreth-Werker, P. Hamer, D. Hamer, and J. Ganter. We spent two days incave, making initial measurements of basic scientific parameters for our ongoing study of this cave. While there, we observed the cave with the goals of our NIAC project in mind. We had extensive discussions of several of the most relevant issues to caves like Barrancas, namely working in a biologically very sensitive site, navigating and exploring in cumbersome space suits, and logistical implications of difficult, deep, multi-level angle-changing descents for bringing in equipment. Discussing these issues while actually in the cave environment brings a greater degree of realistic thinking to bear on the issues than discussing them while ensconced in a comfy meeting room with hot coffee at one's elbow
2. Meeting – Albuquerque, NM, 16 August. P. Boston, V. Hildreth-Werker, J. Werker, and M. Spilde met for a debriefing on the site visit and discussions of means of implementing various possible demonstrations projects of extraterrestrial cave science simulations.
3. Conference call meeting – 24 August. S. Welch, P. Boston, and S. Thompson discussed field operation considerations resulting from the site visit.

Concept Development

1. Suitability of existing materials for in-cave inflatable uses, materials development needs
2. Light mining from the surface
3. Low light plants
4. Bioluminescence and UV
5. Cold tolerant plants
6. Ultraviolet photosynthesis

E. September 2000:

Activities:

1. Labor Day meeting in Palo Alto, CA – S. Welch and S. Thompson
2. Team Meeting – 14-16 September, Boulder, CO
3. Meeting with Director of National Cave and Karst Research Institute (Zelda Chapman Bailey), 15 September 2000, Denver, CO
4. Meeting with Ronal Kerbo, National Cave Management Coordinator, National Park Service, 15 September 2000, Denver, CO
5. Presentation of ideas at NASA workshop – Ecosynthesis on Earth and Mars, Santa Fe, NM, 28-30 Sept.

Concept Development:

1. Air locks and entry technologies
2. Human mobility in-cave
3. Minilab -
4. Bioinjection and Nanoinjection

F. October 2000:

Activities:

1. Team Meeting
2. Presentation of ideas at conference on terraforming science, 10-11 October, NASA-Ames Research Center
3. Presentation of ideas at MIT Mars Week, 20-22 October
4. Meeting with Mark Tilden's microrobotics lab, Los Alamos National Lab, 25-26 October

Concept Development:

1. Molecular triggering
2. Microbial inhibitory surfaces.
3. Prospecting for Caves

Appendix B – Significant Materials and Their Properties

(Listed alphabetically)

A. AEROGELS

Compiled from:

A Brief History of Silica Aerogels, by Arlon Hunt and Michael Ayers, http://eande.lbl.gov/ECS/aerogels/sahist.htm

Silica Aerogels: Technology-Transfer Opportunities/Commercial Availability

http://eande.lbl.gov/ECS/aerogels/sattrans.htm

In the early 1980s particle physics researchers realized that silica aerogels would be an ideal medium for the production and detection of Cherenkov radiation. These experiments required large transparent tiles of silica aerogel. Using the TMOS method, two large detectors were fabricated.

In the late 1980s, researchers at Lawrence Livermore National Laboratory (LLNL) lead by Larry Hrubesh prepared the worlds lowest density silica aerogel (and the lowest density solid material). This aerogel had a density of 0.003 g/cm3, only three times that of air. Shortly thereafter, Rick Pekala, also of LLNL, extended the techniques used to prepare inorganic aerogels to the preparation of aerogels of organic polymers. These included resorcinol-formaldehyde, melamine-formaldehyde aerogels. Resorcinol-formaldehyde aerogels could be pyrolyzed to give aerogels of pure carbon. This opened a completely new area in aerogel research.

Other potential U.S. sources of aerogels are Nanopore, in Albuquerque, N.M that focuses on lower-cost granular aerogels and Aspen Systems, in Marlboro, MA that produces flexible aerogel-based insulation for cryogenic systems.

A new venture, Ocellus, in the San Fransisco area, is currently selling small quantities of R-F, carbon and silica aerogels. They are available through MarkeTech International.

In Europe, Airglass in Lund, Sweden has made batch quantities of aerogels for many years, focusing on serving the needs of the high energy physics community.

In a partial vacuum, aerogels outperform silica powder and glass beads. Inch-thick aerogels have the same R value (a measure of thermal resistance) as inch-thick foams. But when 90 percent of the air is evacuated from a plastic-sealed aerogel packet, the R-7 value nearly triples to R-20 per inch. To match the R-value of aerogels at this vacuum of one-tenth of an atmosphere, silica powder has to be evacuated to a few thousandths of an atmosphere. Glass beads require one-billionth of an atmosphere.

Achieving a vacuum of one-tenth of an atmosphere and sustaining it for the lifetime of a refrigerator is a piece of cake. Existing plastic vacuum packing techniques can do the job. Maintaining a vacuum of one-thousandth of an atmosphere or better is a major technological challenge.

Hunt tried carbon black. The slipper fit. Doped (mixed) with carbon, aerogels turn black and become better insulators. Inch- thick carbon-doped aerogels have been tested and rated at R-25 per inch.

Other potential U.S. sources of aerogels are Nanopore, in Albuquerque, N.M. which focuses on lower-cost granular aerogels and Aspen Systems, in Marlboro, MA which produces flexible aerogel-based insulation for cryogenic systems.

Aspen Systems manufactures a variety of aerogel products such as aerogel powder, monolithic aerogel, flexible aerogel blankets, and clamshell preformed aerogel insulation. Our flexible insulation (patent applied for) was developed for cryogenic applications for NASA Kennedy Space Center's shuttle program. However, the flexible aerogel blanket can be used in high-temperature applications up to a temperature of 500°C. For cryogenic applications, Aspen Systems' aerogel insulation exhibits R values (per inch) of 250-300 in vacuum and 15-30 (depending on the composition) at 1 atm. For high-temperature applications, Aspen's insulation boasts an R value of 3 at 600°C and 1 atm.

Silica aerogels are ideal materials for active and passive components in optical sensors. Their visible transparency, high surface area, facile transport of gases through the material, thermal and chemical stability, and ability to be filled with additional active phases are the key properties that aerogels bring to sensor applications. The Microstructured Materials Group has recently discovered a new process that induces a permanent, visible photoluminescence in silica aerogels (see the section on aerogel composite materials). Shortly after these materials were prepared, it was observed that the intensity of the photoluminescence was indirectly proportional to the amount of gaseous oxygen within the aerogel. The quenching of photoluminescence by oxygen is a phenomenon that is frequently observed in many luminescent materials.

In simple terms, photoluminescence occurs when a material absorbs a photon of sufficient energy. The entity that absorbs the photon may be a discrete molecule, or a defect center in a solid-state material, and if often referred to a "carrier". When the photon has been absorbed, the carrier is moved into a high energy, "excited" state. The carrier will then relax back to its ground state after certain length of time. This "lifetime" of the excited state is usually on the order of nanoseconds to microseconds. The mechanism by which the carrier relaxes determines whether the photoluminescence is termed "fluorescence" or "photoluminescence". If an oxygen molecule collides with a carrier while it is in its excited state, the oxygen molecule will absorb the excess energy of the carrier and quench the photoluminescence. The oxygen molecule absorbs the energy and undergoes a triplet-to-singlet transition, while the carrier undergoes a non-radiative relaxation. The efficiency of the photoluminescence quenching is , therefore, determined by the number of collisions between the material containing the carrier, and oxygen molecules. Since the collision frequency of gases is determined by the number of molecules present, the pressure (P), and temperature (T), at a given P and T, the quenching efficiency, and, consequently, the photoluminescence intensity will be determined by the concentration of oxygen in the atmosphere surrounding the material.

Oxygen sensors based on this principle have been extensively studied. The most common sensor elements studied are those based on an organic or inorganic compound suspended in a thin silicone membrane. Advantages of using an aerogel-based sensor element over these systems include a more rapid response time (due to rapid diffusion of gases through the aerogel pore network), and improved resistance to photo-bleaching (as the photoluminescence is caused by stable defect centers in SiO_2). The Microstructured Materials Group has built a prototype oxygen sensor based on this technology. The sensor is intended to perform as low cost, moderate sensitivity device operating most effectively in the concentration range of 0-30% oxygen. The sensor operates independently of the nature of the other gases present in the feed gas and of the feed gas flow rate. The prototype sensor has been sensor has been successfully operated over a temperature range of -25 to +85 degrees C (this range is based on other experimental limitations of the system, the actual usable range is larger). The highest sensitivity is observed at lower temperatures.

The prototype sensor uses a Hg-arc lamp for excitation (330 nm), and a Si photodiode for detection of the emission (500nm). There is a photograph of this device in the Aerogel Photo Gallery. The prototype design can be easily miniaturized, and a device can be designed with built-in pressure and temperature compensation.

Pieces of silica aerogel have been coated with silicon nanoparticles using chemical vapor methods. The composites emit red light when excited with ultraviolet light. The photoluminescence results from a special process developed at Berkeley Lab that introduces a large number of photoactive defects in the aerogel. This material is the basis for the aerogel Optical Oxygen Sensor.

B. ARGON AS A BREATHING MIXTURE COMPONENT

Points abstracted from:

Argon Affects On Living Things – Humans

Fowler et al 1985

CO_2 has no significant effect on nitrogen narcosis (Hesser, Adolfson, and Fagraeus 1971).

At a constant nitrogen partial pressure, increases in the oxygen partial pressure increase the signs and symptoms of narcosis (Hesser 1963; Frankenhaeuser et al. 1960).

In general, 'the weight of evidence favors the conclusion that ethanol (alcohol) exacerbates narcosis and amphetamine ameliorates it. This is consistent with the view that narcosis depresses the CNS (central nervous system)' (Fowler et al. 1985). (Readers are referred to Bennett (1982) and Fowler et al. (1985) for more complete discussions of inert gas narcosis.)

For example, a person should not breathe air containing more than 0.10 percent CO2 by volume. A level of 20 parts per million of CO should not be exceeded in pressurized breathing systems.

Argon, neon, and hydrogen have been used experimentally as diluents for oxygen in breathing gas mixtures, although these gases are not used routinely in diving operations. However, the results of recent research suggest that hydrogen-oxygen and helium- hydrogen-oxygen breathing mixtures may be used within the next decade in deep diving operations (Peter Edel, personal communication).

Selected papers:

Mixed Gases in Diving by B.R. Wienke, Los Alamos National Lab
http://www.abysmal.com/pages/articles/mixedgases_and_diving.html

Argon Usage in Decompression and Diving
http://www.abysmal.com/pages/articles/argon_useage.html

Bennett , Peter B. and David H. Elliott (Eds.), The Physiology and Medicine of Diving, 1993: 4th edition, 613pp., W B Saunders Co; ISBN: 070201589X

Lots of Diving articles at a Norwegian site:

http://tekniskdykking.org/tekniskdykking/artikler/artikler.htm

Extending the Envelope: Primer on Breathing Mixutures for Diving

http://tekniskdykking.org/tekniskdykking/artikler/aqua/MIX_Diving.htm

Argon Material Safety Data Sheet Info

EMERGENCY OVERVIEW: This product is an odorless, colorless gas that mainly presents pressure hazards. Though the mixture is not flammable, if the product's cylinders are exposed to high temperatures, they may rupture violently and cause a high-pressure release of gas.

SYMPTOMS OF OVER-EXPOSURE BY ROUTE OF EXPOSURE: The most significant route of exposure for this product is inhalation.

INHALATION: Argon is a simple asphyxiant which exerts no other physiological effect beyond oxygen deprivation. Symptoms of over-exposure include dizziness, headache, loss of consciousness, and death.

CONTACT WITH SKIN or EYES: Contact with rapidly expanding gases may cause burns or frostbite. No other health effects are known from contact with argon.

HEALTH EFFECTS OR RISKS FROM EXPOSURE: An Explanation in Lay Terms. This product poses low, acute health risks.

ACUTE: This gas presents a slight risk of causing acute health effects other than asphyxiation. The most severe acute effects would be harm to the skin or eyes when in contact with rapidly expanding gases.

CHRONIC: Argon is not known to cause any chronic illnesses or diseases.

Mutagenicity: Argon is not known to cause mutagenic effects.

Teratogenicity: Argon is not known to cause teratogenic effects.

Reproductive Toxicity: Argon is not known to cause reproductive toxicity effects.

C. CONDUCTIVE PLASTICS

The primary features of conductive polymers compared to conventional conductors are their low mass, robustness, and possibly easy processing methods. Relatively low-cost semiconductor devices undamaged by mechanical deformation is a potential boon to engineers. The current perceived commercial market focuses on production of flat, flexible plastic screens for TVs and computers.

The framework of conductive plastics is a polymer backbone with alternating single and double bonds that provide a pathway for free-electron-charge carriers. These polymers are doped with atoms that donate negative or positive charges (oxidizing or reducing agents) to each unit, enabling current to travel down the chain. The most extensively studied conductive-polymer systems are based on polyaniline, polythiophene, polypyrrole, and polyacetylene.

Another extremely interesting application for electrically conductive polymer materials is the production of biosensors and chemical sensors, which can convert chemical information into a measurable electrical response. Abtech Scientific Inc. (Yardley, Pa.), is making chemical transducers from mostly polyaniline as well as polythiophene and polypropylene for analytical applications. The operational principle is that a very small change in the redox composition brought about by small quantities of a variety of compounds induces rapid and significant electrical conductivity changes. Current development foci include the need to enable highly specific detection. One approach is the creation of biopolymer/conductive-polymer complexes. Using this technique, Abtech has developed a range of enzyme biosensors. For example, immobilized glucose oxidase can be incorporated into a polymer transducer system, a glucose-sensitive biosensor, as the enzyme-catalyzed oxidation of the glucose produces an oxidant by-product that is measured indirectly. Levels of therapeutic drugs in patients can also be monitored in a similar way.

Conductive polymer smart membrane development is being pursued by a team at Los Alamos National Laboratory in Los Alamos, N.M. Benjamin Mattes, technical project leader in the lab's Chemical Sciences and Technical Development Division, and his colleagues have developed engineered porous-fiber materials with electrically controlled porosity using polyaniline. They envision uses in gas separation, pharmaceutical separation, environmental cleanup, batteries, or capacitors. A spin-off company has been established to develop the technology.

Application potential of conductive polymers remains a long one, and includes antiradiation coatings, batteries, catalysts, deicer panels, electrochromic windows, electromechanical actuators, embedded-array antennas, fuel cells, lithographic resists, nonlinear optics, radar dishes, and wave guides.

D. ELECTRO RESISTIVE COATINGS

ThermoCeramiX has pioneered the field of permanent electro resistive coatings that generate heat when a voltage is applied. The heaters are thermally sprayed as composites and laminates onto many different substrates, including plastics, metals and ceramics. The resistance of these coatings can be adjusted to meet any requirement by changing the formulation. Worldwide patents are pending.

ThermoCeramix is able to apply ThermaCoat™ Heaters over complex 3D geometries that cannot be heated by conventional means. ThermoCeramix has successfully applied heaters in many applications where no other type of heater would be possible, such as pump housings and an asphalt spray system. To find out more about this exciting technology, visit the Heaters section. Worldwide patents are pending.

Description of ThermaCoat™ (TCX) Products and Applications To understand the potential of ThermoCeramiX (TCX), it is helpful to understand what TCX is and how it can be used through a series of examples. TCX powders can be sprayed onto virtually any solid surface to form an electrically heatable coating that looks like a layer of incredibly hard paint. These heatable coatings can be sprayed onto or into virtually any shape.

For instance, it is impractical or impossible using existing heating technologies to resistively heat the blades of a fan. With TCX, a layer of resistive glaze is sprayed onto the fan blades and coated with an AlO2 white insulating layer. The fan can now generate heat directly off its blades. A ceiling fan can now heat a house. A hair dryer can now fit in a change pocket. An impeller can now heat and mix a liquid simultaneously.

An industrial application might be a chemical reaction chamber. An existing electrically heated chemical reaction chamber is a round bottom, cylindrical, stainless steel tank. The tank may be wrapped in a copper jacket to increase heat transfer and uniformity. Large insulated, heavy duty, heating coils are wrapped around the tank and packed as densely as possible. Inevitably there will be cold spots along the bottom of the tank, where the coils simply do not fit. The maximum temperature generated will be fairly low due to the limitations of metallic resistive elements. In addition, many such reactors require heat exchangers (or purposely poor insulation) to remove heat that is wasted. These reactors can be extremely expensive to manufacture and costly to run. In contrast, a TCX chemical reactor would look different. It would look like a white tank. Instead of copper jackets, heating coils and heat exchangers, the tank would simply be spray coated over its entire surface with a TCX heater pattern and insulative coatings on either side. The entire coating would be no thicker than a layer of paint, but would heat the reactor with dramatically greater efficiency and uniformity.

An example of a consumer appliance that would benefit from TCX technology clothes iron. If you take your clothes iron apart, you will find a cast metal base and a large resistive coiled element twisted into molded patterns in the heavy metal base. There are electrical contacts, insulation to protect the rest of the device, spacers, etc. The entire mass of the metal base must be heated. This takes time and uses a fair bit of energy. With TCX technology, the outside of the metal base could be simply coated with TCX. A tiny TCX flashed tube would generate steam on demand. Electrical contacts would be simpler. There would be fewer parts. The new iron could be at the desired temperature in less than a second. Retrofitting existing manufacturing systems would not be difficult. The cost of manufacturing the iron would go down.

Allows engineers to design entirely new products that can not be done using existing heater technology. An infinite range of resistivities can be achieved through variations in formulation of the coating.

Properties:

Non-oxidizable (metallic heaters break down easily in many extreme or aqueous environments). Many TCX heaters utilize conductive oxides.

Extremely high bond strength with most substrates.

Extremely thin or thick coatings.

Rapid thermal cycling of thin coatings. Thin layers heat rapidly and can be cooled rapidly as there is little thermal mass (e.g. a clothes iron made with TCX would be at the desired temperature in approximately one second and cool within few seconds).

Rugged, durable, highly resistant to mechanical wear.

Long life. Low cost of ownership.

Can be spray formed as coatings onto 2D surfaces, 3D surfaces or manufactured into 3D heatable parts.

Colors available.

Low cost prototyping and sampling.

Immediate manufacturing capability at ThermoCeramiX.

Extremely high thermal transfer efficiency. Close proximity of heater and substrate.

Increasing or decreasing regions of resistivity via formulation, thickness or geometry changes.

Many TCX materials can be safely heated by magnetic induction (e.g. in a microwave oven).

Environmentally safe. Food safe.

AC/DC/Induction.

NTC or PTC.

Dozens of ceramic combinations to choose from depending on heater requirements.

Low coefficient of thermal expansion.

Extremely high or low temperature range (0°C to greater than 1,600°C, the theoretical limit approaches 3,000°C!).

Surfaces are hard, refractory and machinable.

Heaters with laminated structures are easily made.

No additional parts are required (e.g. contact points, thermocouples, insulating layers, catalytes, etc. can be incorporated as a part of the heatable coating manufacturing process).

Significantly low manufacturing and materials costs. TCX heaters can be manufactured less expensively than most heater applications.

Easily scalable from low to high volume production.

Thousands of applications.

Inert surfaces. Highly resistant to chemical attack.

Catalytic surfaces often can be made.

Clean, safe manufacturing. No harmful chemicals required.

Fully enabling new technology.

CNC programmable manufacturing systems available.

High value added proposition (low cost/ high profit).

Low cost of operation.

Built in circuit failure detection available.

No agency approvals necessary.

Heaters can be spray formed into a shape or pattern using inexpensive template masks.

Manual, semi automated or fully automated manufacturing systems are available.

E. FLEXIBLE SEMI-CONDUCTORS, USE OF CONDUCTIVE PLASTICS

Conductive polymers are long, carbon-based chains composed of simple repeating units called monomers. When the Japanese student made his fortuitous error, he converted the standard single-bond carbon chains to polymer backbones with alternating single and double bonds, a change that provided a pathway for free-electron-charge carriers. To make the altered polymer materials conductive, they are doped with atoms that donate negative or positive charges (oxidizing or reducing agents) to each unit, enabling current to travel down the chain. Depending on the dopant, conductive polymers exhibit either p-type or n-type conductivity.The most extensively studied conductive-polymer systems are based on polyaniline, polythiophene, polypyrrole, and polyacetylene. The principal attractions of these polymers over conventional conducting materials are their potential ease of processing, relative robustness, and light-weight. Successful commercial applications require a fine balance of conductivity, processability, and stability, but until recently, materials researchers could not obtain all three properties simultaneously. The opportunity to produce relatively low-cost semiconductor devices that are insensitive to mechanical deformation is an attractive one. Probably the most exciting development in this area is the intensifying effort to use conductive polymers to produce flat, flexible plastic screens for TVs and computers. This screen technology emerged from the discovery that certain conductive polymers, such as polyÐp-phenylenevinylene, emit light when sandwiched between oppositely charged electrodes, a configuration that fits in well with current flat-panel display designs."

Yet another emerging application for electrically conductive polymer materials is **biosensors and chemical sensors, which can convert chemical information into a measurable electrical response.** Abtech Scientific Inc. in Yardley, Pa., is making chemical transducers from mostly polyaniline as well as polythiophene and polypropylene for analytical applications "in which one measures conductivity and as a result infers what the chemical composition is," said Anthony Guiseppi-Elie, the company's president and scientific director. In other words, a very small change in the redox composition brought about by small quantities of a range of chemicals can induce a large, rapid change in electrical conductivity.

"The challenge," he said, "is how to confer specificity to these materials." One way is to build biopolymer/conductive-polymer complexes. Using this technique, Abtech has developed a range of enzyme biosensors. For example, immobilized glucose oxidase can be incorporated into this polymer transducer system, which acts like a glucose-sensitive biosensor, as the enzyme-catalyzed oxidation of the glucose produces an oxidant by-product that is measured indirectly. Levels of therapeutic drugs in patients can also be monitored in a similar way.

An area with some further-off potential—smart membranes of conductive polymers—is being pursued by a team at Los Alamos National Laboratory in Los Alamos, N.M. Benjamin Mattes, technical project leader in the lab's Chemical Sciences and Technical Development Division, and his colleagues have developed engineered porous-fiber materials with electrically controlled porosity using polyaniline. The technology, he said, could find use in gas separation, pharmaceutical separation, environmental cleanup, batteries, or capacitors. A spin-off company to develop the technology already has been established.

The list of potential applications for conductive polymers remains a long one, and includes antiradiation coatings, batteries, catalysts, deicer panels, electrochromic windows, electromechanical actuators, embedded-array antennas, fuel cells, lithographic resists, nonlinear optics, radar dishes, and wave guides. Just how big an impact the materials will make in these markets remains unclear, however. Most observers are putting their money on antistatic coatings and flat-panel displays.

F. HIGH-PRESSURE INFLATABLE STRUCTURES

VERTIGO, Inc.

MAILING: P.O. Box 117 •

LAKE ELSINORE, CA 92531-0117

Recent advances in **high-pressure inflatable structures** use a braiding process to fabricate seamless tubes capable of containing high pressure and resisting bending. A related development allows curved airbeams to be braided on straight mandrels. Examples of this type of construction have been shown to be structurally efficient, robust and relatively economical. A shelter based on airbeams has several advantages over conventional rigid structures. Shelter skins can be preassembled on the beams so that the entire shelter can be erected with only a few personnel and a compressor working from ground level. The rapid inflation times reduce exposure to possible high winds and when deflated, the lightweight structure can be packed and transported with far less logistical support.

The Aviation Inflatable Maintenance Shelter is a large structure that uses airbeams for support. The preliminary design of the AIMS meets or exceeds Army requirements.

The optimum shelter airbeam was larger than any existing braiding facility could produce. A new braiding machine capable of fabricating airbeams and other high-pressure structures up to 36 inches diameter and 110 feet length was developed specifically for AIMS production.

The airbeams used to support the AIMS structure are 30" in diameter and made of Vectran fibers. The beams will have a span of 82' and a height at the apex of 32'. The beams have a working pressure of 50 to 80 psi.

Approximate designed dimensions for the AIMS:

Width: 66'

Length 135'

Interior height: 28'

There are numerous other applications for shelters of this type. Many are in military and civilian aviation. Large, lightweight, deployable structures also have applications in precision airdrop, space, watercraft, bridges, impact attenuation, and aircraft evacuation.

The Aviation Inflatable Maintenance Shelter is capable of handling snow loads of up to 20 lbs./ sq. ft.and winds of 110 mph with the structural air beams inflated to 80 psi.

Braided inflatable structures are manufactured in cooperation with Fiber Innovations Inc. of Walpole, MA

G. VECTRAN

A unique combination of properties differentiates Vectran fiber from other high-performance fibers and makes it the material of choice in demanding applications where other fibers fail to meet performance requirements.

Vectran is a high-performance thermoplastic multifilament yarn spun from Vectra ® liquid crystal polymer (LCP). Vectran is the only commercially available melt spun LCP fiber in the world. Vectran fiber exhibits exceptional strength and rigidity. Pound for pound Vectran fiber is five times stronger than steel and ten times stronger than aluminum.

These unique properties characterize Vectran:

- High strength and modulus
- Excellent creep resistance
- High abrasion resistance
- Excellent flex/fold characteristics
- Minimal moisture absorption
- Excellent chemical resistance
- Low coefficient of thermal expansion (CTE)

- High dielectric strength
- Outstanding cut resistance
- Excellent property retention at high/low temperatures
- Outstanding vibration damping characteristics
- High impact resistance

Applications include:

- Cut Resistant Clothing
- Cut Resistant Gloves
- Pressure Vessels
- High Pressure Inflatables
- Rope
- Concrete Reinforcement
- Ballistic Materials

Appendix C – Cave Prospecting Technologies and Methodologies: A Website and Publication Resource

Online Papers:

http://southport.jpl.nasa.gov/ProgressReports0496/Schaber.Final.html

http://southport.jpl.nasa.gov/ProgressReports0496/Stern.Final.html

+"remote sensing" +caves

http://www.archaeology.org/online/features/belize/remote.html

+"ground penetrating radar" +caves

http://www.agiusa.com/2Dvoids.shtml

http://lancelot.bms.ed.ac.uk/~wis/papers/TheArchaeologists1998.html

http://oregonl5.org/lbrt/l5isru1.html

http://www.dyetracing.com/company/geophy.html

+"subsurface tomography"

http://www.ees.nmt.edu/Hydro/HydroLetter99.html

http://emlib.jpl.nasa.gov/EMLIB/PIERS97/2a4.html

http://glee.emba.uvm.edu/ded-references.html

http://www.llnl.gov/IPC_Update/issue1-2/issue1.2.html

http://www.technos-inc.com/TECHKARS.HTM

http://www.cmp.co.uk/c23acont.html

+"space shuttle" +radar +cavern

http://observe.ivv.nasa.gov/nasa/exhibits/ubar/ubar_0.html

http://www.jurock.com/news/drtomorrow/arabian.html

http://cgi.pbs.org/wgbh/nova/transcripts/2312lost.html

+shuttle +"SIR-C/-SAR "

http://www.op.dlr.de/ne-hf/projects/sircdesc.html

http://www.meto.umd.edu/~owen/CHPI/IMAGES/patag2.html

http://cassini-radar.jpl.nasa.gov/science/SAR_REFS.html

+shuttle +"SIR-C/-SAR " +subsurface

http://rrsg.ee.uct.ac.za/applications/applications.html

http://www.geo.cornell.edu/geology/eos/research/Interf_DEMs.html

Non-Online Papers:

Berlin, G. L., M. A. Tarabzouni, A. H. Al-Naser, K. M. Sheikho, and R. W. Larson, 1986, SIR-B subsurface imaging of a sand-buried landscape, Al Labbah Plateau, Saudi Arabia, IEEE Trans.

Geoscience Remote Sensing, vol. GE-24, no. 4, pp. 595-602.

Blom, R. G., R. J. Crippen and C. Elachi, 1984, Detection of subsurface features in Seasat radar images of Means Valley, Mojave Desert, California, Geology, vol. 12, pp. 346-349.

Elachi, C., L. E. Roth, and G. G. Schaber, 1984, Spaceborne radar subsurface imaging in hyperarid regions, IEEE Trans. Geosci. Remote Sensing, GE-22, no. 4, pp. 383-388.

Guo, H., G. G. Schaber, C. S. Breed, and A. J. Lewis, 1986, Shuttle imaging radar response from sand and subsurface rocks of Alashan Plateau in north-central China, Int. Sympos. Remote Sensing for Resources Development and Environmental Management 7th Proceedings, ISPRS Commission VII, Enschede, Netherlands, August 25-29, 1986, A. A. Balkema, Boston, pp. 137-143.

McCauley, J. F., G. G. Schaber, C. S. Breed, M. J. Grolier, C. V. Haynes, B. Issawi, C. Elachi, R. Blom, 1982, Subsurface valleys and geoarchaeology of the eastern Sahara revealed by Shuttle Radar, Science, vol. 218, pp. 1004-1020.

Schaber, G. G., J. F. McCauley, C. S. Breed, and R. R. Olhoeft, 1986, Physical controls on signal penetration and subsurface scattering in the Eastern Sahara, IEEE Trans. Geosci. Remote Sensing, vol. 24, pp. 603-623.

Shaber, G. G., J. F. McCauley, C. S. Breed, and R. R. Olhoeft, 1986, Physical controls on signal penetration and subsurface scattering in the Eastern Sahara, IEEE Trans. Geosci. Remote Sensing, vol. 24, no. 4, pp. 603-623.

Ice Penetrating Radar:

From (West Antarctic Ice Sheet science plan):

http://igloo.gsfc.nasa.gov/wais/impl_96.html

Radar soundings of ice thickness are logistically difficult to obtain, but are essential in mass balance assessment. The areas most in need of coverage are ice stream E, Pine Island and Thwaites Glaciers, and a repeat set of measurements across the grounding lines of ice streams A-E and the ice plain of B. The Support Office for Aerogeophysical Research (SOAR) instrument suite is well suited to this data collection task by providing both precise surface elevations and ice thicknesses from a Twin Otter positioned accurately by GPS.

The Support Office for Aerogeophysical Research (SOAR) is a research facility that supports OPP-sponsored aerogeophysical work in Antarctica. The facility operates a suite of geophysical systems (gravimeter, magnetometer, laser altimeter, and ice-penetrating radar) aboard a Twin Otter aircraft. Positional information is provided by differential GPS (both pseudo-range and carrier-phase), supplemented by inertial navigation and precision pressure altimeter data.

For Europa Mission:

http://www.xs4all.co.il/~carlkop/iceradar.html

Antarctic mapping:

http://unisci.com/stories/19994/1214993.htm

A Science Strategy for the Exploration of Europa

http://books.nap.edu/html/europa_explor/