"Towards an Earth-Moon Economy - Developing Off-Planet Resources"

# Moon Miners' Manifesto

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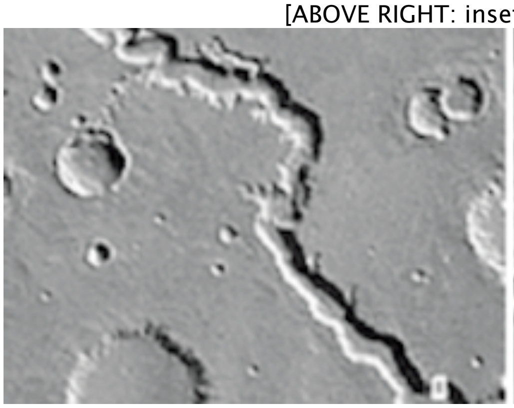
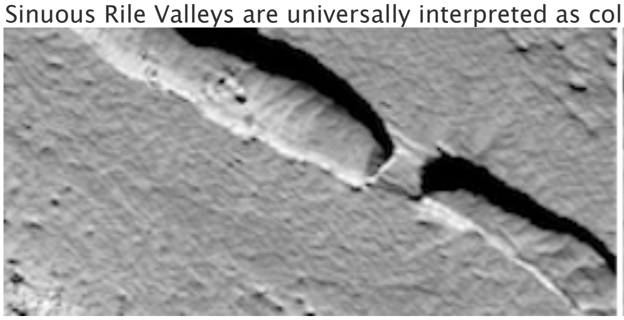
## MMM Classic Themes — Lava Tubes on Moon & Mars

[ABOVE RIGHT: inset image of Subway lava tube in Oregon]



Sinuous Rile Valleys are universally interpreted as collapsed lavatubes. Apollo 15 visited such a site (arrow)



Interruptions (bridges) in rilles are seen as uncollapsed rille sections.  Several "skylights" have been found.

On Earth, some lava tubes have flat sandy floors (Left) due to sand washed in by rain. Lanar lavatubes would retain original floors (Right) with some rocks fallen off walls and ceilings. The scale of lavatubes appears to be in some inverse relationship to the gravity of the host world. Very large tubes on the Moon, intermediate size ones on Mars, the smallest on Earth.

## MMM THEMES: LAVA TUBES ON MO0N AND MARS
## CHRONOLOGICAL INDEX

# MMM THEMES: LAVA TUBES ON MO0N AND MARS
# SUB-THEME THREAD INDEX

## LOCATING & EXPLORING LAVATUBES (on the Moon and Mars)

MMM #25 LAVATUBES
MMM #44 OREGON MOONBASE, Earth-Based Searches for Lavatubes
MMM #58 Microbot Lavatube Explorers
MMM #93 Searching Mars for LAVATUBES, Kokh
MMM #100 Twelve Questions about Lunar Lavatubes
    Remote Mapping of Lavatubes; tele-spelunking on the Moon
    Robotic On-Site Exploration & Surveying
MMM #112 An ISDC '98 Workshop Project to Detect Lunar Lavatubes;
MMM #113 Funds needed for ISDC 98 Lavatube Workshop - Appeal
MMM #124 Searching for Ready-Made Lunar Bases, Allen G. Taylor
    Oregon L5's Lunar Lavatube Locator Project
MMM #130 Lunar Lavatube Locator Project Status Report
    Coasts, Harbors, Lighthouses, Lavatubes
MMM #134 Oregon L5's "Lunar Lavatube Locator" Project, P. Kokh
MMM #198 Lavatubes on Mars.
MMM #**231** Size of Lavatube found by Japan's lunar orbiter Kaguya
MMM #241 Lavatube Skylight Explorer
MMM #267 Exploring Lavatubes on the Moon will not be like exploring tubes on Earth

## DEVELOPING LAVATUBES for Settlement and Industry

MMM #44 ICE CAVES: Could Some Lunar Lavatubes Be Hiding Valuable Resources?
MMM #100 Settling into a Lavatube: Brainstorming an Early Lavatube Town
    (Sub)Terraforming Challenges of Sealing & Pressurization
    "Down Inside" Civilization & Culture: 1 Naming Lavatube Settlements
MMM #101 LAVATUBE CULTURE, P. Kokh; Lunar Lavatube Use, T. Billings
MMM #102 Technical Comments on #101's Lavatube Articles, B. Walden
MMM #132 Collapsed Lavatube Makeovers, P. Kokh
    Skylight Domes for Lavatube Towns..., P. Kokh
MMM #134 Lavatubes: the Developer's Role, P. Kokh
MMM #169 MMM Mail; Sealing Lavatubes, India Planetary Soc.
MMM #172 Lavatubes by Blacklight Fantasy Excursions
MMM #240 From Lavatube Skylights to Settlements P Kokh
MMM #246 Could lava tubes be hiding valuable resources?
MMM #261 Lava) Tubers and (lava) Tubophobes, P Kokh
    (Lavatubes on Mercury) Could we put an Outpost on Mercury? Why would we?
MMM #267 Residents of Lava Tube Settlements May Need Regular Surface Contact.

## MMM #25 - May 1989

# LAVA TUBES

LAVA TUBES By Peter Kokh

In the event that the citizen-funded* Lunar Prospector 1 finds no indications of ice deposits in permanently shaded (permashade) craters near the Moon's north or south poles, there will still be some debatable pluses for siting a base near one of the lunar poles along with a litany of disadvantages. What then?

On many occasions, we have stated that a mare/highland "coastal" site makes the most sense because it allows access to both major soil types on the Moon, important if we want to make intelligent use of lunar resources. Such coastal sites frequently come endowed with topographical features of enormous potential advantage: lava tubes and sinuous rilles. Indeed, the most important site advantage for a base designed with settlement expansion potential uppermost, will be close proximity to accessible lava tubes.

Our evidence for lava tubes on the Moon is threefold, and though indirect, quite strong. The first evidence is the existence in many mare areas of sinuous rilles or valley channels such as Hadley which was investigated by the Apollo 15 mission. These are typically hundreds of meters across and deep and can be a hundred or more kilometers in length. Our best explanation for these features, one now generally accepted, is that they represent collapsed lava tubes. (Rilles bear none of the water-flow signatures so marked in Martian valleys).

The second evidence is the existence of chains (catennae) of rimless craters, often oval in shape, in several mare areas. Our best explanation for them is that they are collapse pits following along the top of a lava tube whose ceiling is within 40 meters of the surface, and with intervening stretches still intact. Finally, we find at least one "interrupted" rille, Hyginus, in which the interruptions appear to be intact lavatube sections, "bridging" the rille here and there.

There are many terrestrial examples of lava tubes, admittedly on a far smaller size scale (the considerably higher gravity on Earth being the determinant here) for example in the lava flow sheets covering much of Oregon and wherever the lava upwelling has had an especially low viscosity such as the Panhoehoe flows that have built up Mauna Loa/Mauna Kea (the Island of Hawaii). Lava tubes on Earth are typically 10-40 meters wide and high and may run several kilometers in length, and as a rule with a very gentle gradient. Their floors are sometimes flat (often with mid-floor channels handy for utility emplacement), sometimes strewn with rubble from ceiling spallation. We are only beginning to realize the extent of the honeycomb network of such tubes on the Big Island.

Our evidence that the lunar maria were formed by very low viscosity lava flows is substantial, and based both on compositional analysis of the mare basalt samples returned and the topography of the very flat flows themselves. Relatively high titanium content may be a factor in this fluidity.

While all those tubes of which we currently have evidence lie near the surface, it is totally groundless to conclude, as most writers seem to have done (we know of no exceptions), that this is the extent of their domain. On the contrary the morphological evidence is quite conclusive that the various mare areas have been built up by a succession of flows, each typically hundreds of meters thick.

Total mare fill thickness can be deduced from the size of subsequent crater impacts that have 'bottomed out.' In the case, for example, of western Mare Crisium (Pierce, Piccard) this thickness must be two km. or more. Another indication is the size and extent of ghost rim craters on the mare (e.g. Yerkes in western Crisium, Prinz on the Mare Imbrium/Oceanus border). Thus Mare Smythii which contains many such features, must be comparatively shallow.

In all probabilityLava tubes radiate out from the source(s) of lava upwellings in one successive sheet above the other. Accordingly, some, subsequently filled or not, must lie quite deep and present a considerable challenge for detection and an invaluable especially pristine resource if found.

Some writers have suggested emplacing lunar bases within lava tubes. While it will be some time before we can afford to seal and pressurize even the smallest of these voluminous features, there are less ambitious ways to make use of them for initial bases or settlements. The Society's Oregon chapter has taken the lead in illustrating the very real advantages of near-surface intact tubes both for original siting and for subsequent base/settlement expansion, going so far as to carry out dry-run exercises with area Young Astronauts in suitable (but much smaller scale) lava tubes in the Bend, Oregon area east of the Cascades.

Lava tubes provide constant temperature volumes (c. -4° F, -20° C) free from the hazards of micrometeorite bombardment, cosmic rays, ultraviolet radiation and solar flares (allowing lightweight inexpensive 'pressure suits') and thus ideal for warehousing and volatile storage (water-ice and gasses), expansive garaging space, and siting automated or teleoperated manufacturing facilities and laboratories that do not need, or even work best without, pressurization. Lightweight inflatable structures, perhaps of Kevlar, that do not need their own shielding overburden can provide whatever pressurized control centers or habitat spaces that are needed.

Access can be by a shaft through the ‘roof’ for freight and personnel elevators, utility conduits, even entry for sunshine concentrated and funneled by heliostats on the surface. It is, moreover, hard to conceive of a safer and more secure environment in which to emplace a nuclear power facility than an isolated section of lava tube.

As these features have already lasted 3.5 to 4 billion years (limestone caves on Earth are likely to last a few million years at best), and will outlast all existent terrestrial features without exception, a lunar lava tube might well be recommended someday as the best site in the entire Solar System to house some future grand archives and museum of all humanity. By the same reasoning, if you will pardon a little fun speculation, there would have been no better site in all the Solar System for ancient visitors from elsewhere who happened to have arrived millions, even hundreds of millions of years prematurely (from our point of view) to have left a calling card of sorts that would survive for as long as need be to be found by some as then barely conceivable native intelligent species (us). As such, lunar lavatubes have been aptly dubbed "attractors of alien artifacts."

Given the way they were formed, lava tubes may provide the best hunting grounds for future lunar gem collectors. At any rate, there is a future for lunar spelunking, although it will be quite a bit different from limestone cave exploration in karst regions on Earth.

The cost of providing access to an intact lava tube pales in comparison with the cost of providing comparable volume by any other method of base construction. So while at least the first residential and agricultural areas will likely be excavated or built in covered trenches, Lunar Industrial Centers built in convenient lava tubes will have an enormous advantage over those that are not.

**Our recommendation:**

The National Space Society should consider raising funds for further studies of the existing photographic records for evidence of near surface lava tubes. Research into the best non-photographic methods of ferreting out such features from orbit also should have very high priority and if task-appropriate instrumentation can be devised, strong advocacy of a so-equipped follow-up probe in the Lunar Prospector series is in order.

* [When Lunar Prospector finally flew, some eight years after this was written, it was NASA who picked up the tap. Lunar Prospector was the 2nd outside mission to be picked up by NASA as part of its Discovery Mission Opportunity program. All attempts at private funding had failed.]

# MMM #44 - April 1991

**Site of the Oregon Moonbase:** Young’s Cave complex near Bend, Oregon, is a cross-linked pair of lava tubes. It has been thoroughly investigated for its potential to support simulated lunar base activities of various kinds, with many potential users. We report on this outstanding NASA-supported project of the Oregon L5 Society NSS chapter, and the prospects for future site development.

## OREGON MOONBASE

OREGON MOONBASE: Report By Peter Kokh

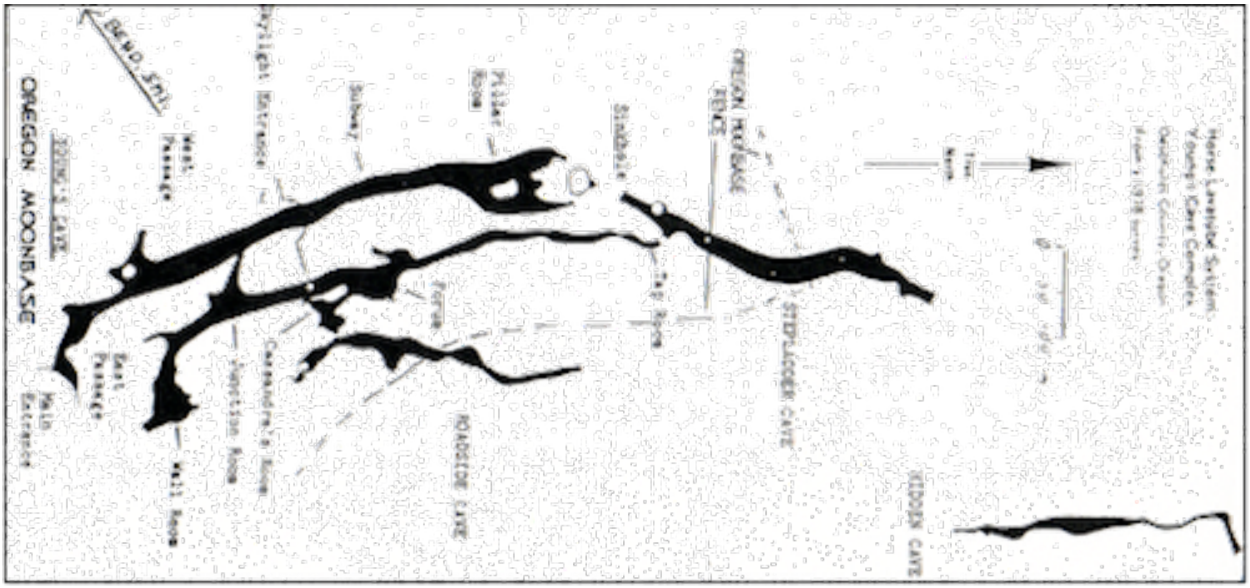
With the help of a NASA Grant, 3 Oregon L5 Society chapter members have investigated the potential of a unique site in their geographic backyard to support lunar base simulation studies of various kinds.

For wildlife, it must have been the depths of hell. Repeatedly, between 17 and 11 million years ago, tensions in the bowels of the Earth split the surface apart between the Cascades and the Idaho Rockies in what is now Oregon and Washington. Runny silicon-poor lava poured out of multiple fissures to form 2000o F floods of red death, as much as a hundred miles wide, advancing at an merciless pace, literally disintegrating animals large and small unfortunate enough to have made a misstep or taken a wrong turn or stumbled in a stampede or simply fallen exhausted from the endless urgent retreat. Such wholesale purges of the area’s flora and fauna happened over and over in episodes typically 10,000 years apart, long enough to allow a teasing Sisyphus -like recovery.

In the process, old valleys and lower hilltops alike were buried under an accumulation of basaltic blankets up to hundreds of feet thick - an estimated total of 77,000 cubic miles (in comparison, Mt. St. Helens released 1/2 cubic mile of material). It is in this context that a number of lavatubes formed in the Bend, Oregon area, when rivers of hot lava within a cooling sheet drained out into lower-lying basins, leaving relic cavities behind. Similar features honeycomb the slow gentle slopes of Hawaii’s great shield volcanoes, features also formed by runny pahoehoe lava (thicker more viscous lava builds up tall cones).

Some four years ago, just a month before the March 1987 L5/NSI merger in Pittsburgh, Oregon L5 chapter leader Bryce Walden, who had read F. Horz’s article “Lava Tubes: Potential Shelters for Habitats” in the 1985 “Lunar Bases and Space Activities of the 21st Century” edited by Wendell Mendell, was present during a Young Astronaut tour of the Portland Air National Guard Base. He suggested a YA field trip to a lava tube near Bend, a proposal which was greeted with enthusiasm. After a chapter team visited many potential sites that spring, a simulation exercise was actually held at Skeleton Cave. The mission tested organization, design, logistics, construction, human factors, and educational opportunities. Included were a surface camp and a ‘lunar base’ 470 meters inside the cave. This consisted of a sleep/work platform, a communications desk, a galley, and a sanitation facility. Mission science included cave mapping, astronomy, geochemistry, and environmental monitoring. The city of Bend, properly impressed, then offered the use of Young’s Cave, a site less visited and less disturbed by visitors and tourists. A third simulation was run there.

[The 12 acre Young's Cave site is owned by the U.S. Bureau of Land Management, but the City of Bend Dept. of Public Works holds the land patent as part of its wastewater treatment plant site, a half mile to the north. Bend has given Oregon Moonbase a 5-year renewable lease to the site for research & education purposes.]




The following year, the Oregon L5 team, after networking with the AAAS, Lockheed Engineering and Sciences, and the Oregon Grotto of the National Speleological Society, began in depth research of the concept of an outfitted lavatube as a site for ongoing professional lunar base simulation activities of various kinds. After exploring many scenarios for use of lunar lavatubes, the team prepared nine proposals for NASA's Office of Exploration Innovation Outreach Program. The day after the 20th anniversary of the Apollo 11 Moon landing, NASA announced the acceptance of one of these: "Site Characterization of the Oregon Moonbase."

After months of contract negotiations, funding was received in March 1990. Meanwhile the team was busy publishing and networking, and circulating Users Surveys to 300 potential interested parties. [MMM/LRS received one of these and was intensely interested, but chose not to reply because there appeared to be no realistic scenario by which we could find the funds to use the site in any of the ways which occurred to us. (Some of our suggestions, which apparently have not occurred to other potential users, are indicated near the end of this article.]

Terrestrial lavatubes are typically 10-30 meters wide and a few kilometers long at best. All indications are that their more ancient lunar cousins are more than an order of magnitude larger, 300-500 meters in width and height with 'roofs' 40 meter or more thick, and many kilometers long. There is every reason to believe the slopes of the great Martian shield volcanoes are laced with similar features on an intermediate scale. In any case we are presented with voluminous shelter from the cosmic elements (cosmic rays, solar flares, solar ultraviolet, most meteorites, and wild surface temperature swings).

These handy features have endured unused and intact for a billion years in the case of Mars, and for 3 plus billion years in the case of the Moon. In contrast, our typical limestone cave lasts only a few hundred thousand years in the context of Earth's active geology. Such places can offer primary shelter for lunar bases of considerable size, or ready room to grow, especially for the area-intensive needs of industry, agriculture, and storage. Too large to seal and pressurize, they offer safe haven for cheaper pressurized structures such as inflatables, and will allow those working within to wear lighter weight pressure suits instead of bulky hard suits, leading to a quantum leap in EVA safety for construction workers. The advantages are so clear, that it would be blind dead-end folly to deploy a major surface base without a suitable lavatube close at hand for earliest expansion. With such an option, the actual surface installation might even be kept minimal.

Lavatubes occur in the relatively flat mare (lunar "sea") areas, typically near to highland "coasts" thus providing a site where industry has access to both suites of materials. Possibly the only refuge from troublesome lunar dust (spallation debris on the tube bottoms will not have been micro-pulverized like the surface regolith blanket - Martian tubes may include wind and flood-borne sands, even ice), lavatubes also commonly offer other handy features: roofs strong enough to support suspended structures like habitats and transport systems above uneven floors, handy sidewall benches, areas of level floor created by cooling pools, frequent mid-floor channels in which to lay utility service runs, etc.

For the purposes of executing the grant project, the Oregon Moonbase Team has been headed by Cheryl York (fka Singer) as principal investigator and includes Walden and Tom Billings as researchers. It next set about doing a thorough site characterization, essential before planning development of a facility that would support the sort of uses envisioned. Young's Cave was thoroughly mapped, the structural strength of its walls and roof assessed by an engineering firm. The surface area was also mapped and characterized. Geological, environmental, and archeological assessments were likewise contracted out to qualified parties.

Once popularly known as Kegger Cave, Young's Cave consists of two main East and West passages roughly 900 and 1100 feet long respectively, gently sloping only a few meters along this length. These main passages are connected by a low intermediate passage that is nearly blocked. Nearby Stepladder Cave, Hidden Cave, and Roadside Cave were evidently once part of the same complex but connectors have been blocked by lava plugs or sinkholes. These caves are part of a long system of lavatubes in the Bend area running in a general line from SSW to NNE. The cross-sections are generally semicircular, the lower portion having been filled by a late flow (there were apparently multiple episodes) that did not fully drain.

The width varies, alternately pinching and swelling. There are areas of breakdown, some early, some recent, with scattered debris piles. There is a layer of sand fill deposited and rearranged by wind currents and water (both of which are absent on the Moon, but at work on Mars). The Geological survey was done by Stephen L. Gillett, a consulting geologist now in Carson City, Nevada. Steve is a member of Seattle L5 and longtime reader and sometime contributor to MMM.

Century West Engineering of Bend did the engineering analysis. A series of borings shows the roof to be generally from 10 to 20 feet thick with 7-19 ft of hard basalt overlain by 0-3 ft of loose soil. Except for a few transverse cooling cracks, the ceiling is relatively intact and rock quality analysis shows the roof should support from 2-60 tons suspended weight per linear foot, depending on the varying roof thickness and the presence or absence of fractures. For this purpose, a system of rock bolts will do. In some weak areas, roof-shoring supports are advised. There is an estimated 6000-7500 cubic yards of sand fill on the floor ranging from 0-6 ft thick as measured by a series of hand-auger holes. This could be removed, if desired, by vacuuming. Rock debris could be removed, if and where desired, by backhoe or by hoists through openings made in the roof, thereafter available for installation of equipment. The shape of surface terrain was also surveyed. Development of the future Oregon Moonbase facility may include some removal of sand and debris, stabilization of some weak roof areas, and some excavations into the basalt walls, floor, and roof.

The USER SURVEY was returned by 33 interested parties (out of 300 addressees). Proposed uses include simulations of automated and crewed Moon and Mars missions, expedition design, testing and demonstration of base systems and subsystems (shelter and habitat, life support, power and control systems, surface systems), resource development, geological and planetological studies, and education. Potential users include NASA, aerospace industry professionals, educators and consultants. Most users indicated the similarity to expected lunar & Martian conditions (verisimilitude) outweighed the remoteness of the proposed facility.

An analysis of user needs indicates "the proposed facility should focus on two main areas: surface/subsurface/subsurface-equipment interaction (construction and excavation techniques, transportation, access) and integration." Shortcomings include the lack of vacuum and lunar 1/6th gravity, about which nothing can be done, and the lack of a lunar dayspan/nightspan cycle, which can be easily simulated underground as needed. As many groups wish to work with full-scale habitation and life-support systems, the facility must provide adequate support systems (power, water) upfront. Eventually, permanent habitation modules will be desirable for on-site housing of the user personnel. As the facility develops, the educational potential will grow with it, from YA mission simulations to public tours and professional seminars.

One whole suite of potential use seems absent from the gamut of suggestions contained in the returned user surveys: materials processing based on basalt. Even though the common basalt in this area is a less faithful analog of what we have found on the Moon than the Mid-Continent Rift basalts used as the basis of the standard Minnesota Lunar Simulant, useful work in crude processing methods could be done at this site. Working with low-tech (thus lunar-appropriate) Cast Basalt to fabricate a wide range of products (from tableware to performance-light structural elements) suggests itself. Based on materials research done on site and elsewhere, a visitors' center could be partially built (or expanded) and furnished with sample items to illustrate the possibilities for lunar base self-reliance to the public. A portion of the cave complex artificially illuminated according to a lunar dayspan/nightspan cycle could house a number of agricultural modules and bioregenerative life-support research and demo units.

The current ambition of the Oregon Moonbase Team is to develop and operate a facility in the wide niche between highest realism/highest cost (i.e. the Antarctic Dry Valleys) and low realism/low cost (i.e. the lab). Some of the work proposed for the site would actually not demand that faithful an analog to lunar lavatubes. Light cycle dependent work, for example, could be done in any appropriately sized limestone cave or even in a large hanger. Even so, the interaction between users at the Oregon Moonbase will confer a matchless advantage to doing work there.

Such an expenditure would be cheap insurance that whatever NASA, other agencies or even private enterprise eventually might deploy on the Moon or elsewhere will work as advertised.

A proposal has been submitted for Phase One Development, the minimum necessary to serve the least demanding potential users, and Phases Two to Four are in process of definition. Phase One will include a Facility Operations Center, a dedicated Teleoperations Center, a powerhouse, lighting systems, water heating and storage, food preparation and storage, general and hazardous waste handling, security and safety systems, plus access and communications systems.

All this will cost money, an estimated $6.2 millions over four years. But such an expenditure would be cheap insurance that whatever NASA, other agencies or even private enterprise eventually might deploy on the Moon or elsewhere will work as advertised.

We can only hope that "the powers that be" realize that this facility is not another luxury but an investment that fills an essential need on the critical path towards the realization of a spacefaring civilization, in accordance with the Space Settlement Act of 1988. It would be a good omen for all of us if the funds needed to begin Phase One development are forthcoming in a timely fashion.

Our hats off to the Oregon Moonbase Team. If all NSS chapters had people as dedicated and determined as this one, who could doubt that the realization of a spacefaring civilization would be guaranteed? While the natural endowment of their chapter hinterland provided them with this splendid resource and opportunity, this writer has no doubts that if they had not been so blessed, they would have found some other way to play a major role. Their work should inspire us all and demonstrates that there IS a place for chapter activity beyond the traditional roles of grass roots activism. **MMM**

# ICE CAVES

## Possible Unsuspected Cometary ICE Cold Crypts Below the Lunar Surface

By David A. Dunlop and Peter Kokh

For centuries we've realized that the Moon's surface was desert-dry. The first good telescopes had shown the great dark areas hopefully called "Seas" to be really dry low-lying plains (filled with a dry quick-sand of dust, many wrongfully supposed). We took it for granted that the Moon had formed wet, as had Earth, and that it its low gravity was insufficient to hold on to its aboriginal atmosphere so that its waters had been lost to evaporation and ultraviolet disassociation.

The findings of the Apollo missions and follow-up studies of their precious hoard of Lunar Samples told another story. The maria seas were really great sheets of frozen lava with the upper few meters pulverized and gardened into a dust blanket (the regolith, a feature shared with highland areas). Moreover, nowhere was there to be found any relics or clues of a past wetter epoch. There is no rusted iron. In fact, even with a gross composition of 42-45% oxygen, the Moon seems under-oxidized. For what iron there is, is either FeO, ferrous oxide (a less oxidized state than our commonplace Fe2O3), or pure iron fines. Nor are there any hydrated minerals or clays, so common on Earth. The Moon had apparently formed hot and dry, quite unlike the Earth, perhaps from vaporized material cast off (but retained in orbit) following a major collision between the forming proto-Earth and a smaller but rival body forming at roughly the same distance from the Sun. Someday we may know the 'rest of the story' but this is our current best solution to the puzzle.

What we have found instead, quite by surprise, is a non-negligible endowment of hydrogen atoms (1 ton in a football field sized area 1 yard deep - far less than in Earth's driest desert sands) adsorbed to the fine particles of the regolith 'top soil', apparently a gift of the Solar Wind which has been softly buffeting the Moon's surface for billions of years.

Some have suggested that volatile elements, otherwise so absent, could have been brought to the Moon by comet impacts, and that some small fraction of the vaporized ices could have migrated to permanently shadowed polar crater and fissure bottoms where they might have frozen out and been preserved cold-trapped ever since. We haveO always been highly skeptical about the chances for any portion of such ices to have come down to our day intact. Any early endowment from the age of heavy bombardment in the Moon's first half billion years, should have been mostly, if not wholly eroded by cosmic rays and Moon-flanking wisps of Solar Wind, even if permanently shaded from direct sunlight.

And the fact that there is now an appreciable aggregate total area of "permashade" (estimates as high as 250,000 sq mi), thanks to the Moon's minimal axial tilt of 1.5°, does not guarantee that this has always been the case. In fact there is some evidence that when the surface-shaping early bombardment finally tapered off, the Moon was left with a tilt of perhaps 12o or more, tidal forces working inexorably to upright it since. However the never-say-die hopes of some have been pinned on the recent Nemesis Theory, according to which the Sun has an undetected distant "brown dwarf" substellar companion in an eccentric orbit which has mischievously disturbed the Oort Cloud, sending waves of comets plummeting into the inner solar system every 26 million years or so. This theory is now in disfavor, mainly because a brown dwarf in such a remote orbit could not be a stable companion of the Sun over geologic time. And we personally have lambasted as incredulous the prevailing belief that episodic comet showers originate in our own Oort Cloud in the first place! [MMM #39 OCT 90 p6 "OORT FOAM"].

Yet we ardently support Lunar Prospector, an SSI lunar polar probe designed to settle the issue by scanning polar permashade areas with a gamma ray spectrometer for three reasons. First we can't afford to be wrong, for such ices, if economically recoverable, would be an invaluable resource that could well accelerate Lunar development by decades. Second, a number of lunar development advocates are stuck on the advantages of a polar site for our first, if not our only base. Even if there are significant icefields at the poles, a polar site would at best play an auxiliary role in lunar development, since the poles offer access to highland type minerals only, whereas all the "coastal" sites offering access to both highland and mare type soils are at some distance from the poles. The alleged around-the-sunth availability of sunlight at the poles is exaggerated. A negative finding by Lunar Prospector would discourage such cull de sac planning. Third, most lunar development planners have been slow to take seriously the need to design dry "Xero-" methods of processing and manufacturing, and the negative results we expect from Lunar Prospector may provide the rude awakening needed to spur work on a more realistic track. But don't get us wrong. We'd be delighted to have our expectations shattered by a positive find.

Yet it has occurred to the writers that there is some possibility, indeed an appreciable chance, that vaporized cometary materials have been cold-trapped in places not exposed to the loss mechanisms of cosmic radiation and solar wind gusts. The greatest wave of comet bombardment of the Moon may have been in the formative era. But even in the past 3 plus billion years since the great impact basins were filled with runny lava, an appreciable number of comets (in episodic waves or not) may have impacted the Moon.

The maria are not totally flat, but have a slow gradient, stepped by lava flow fronts, with highest elevations near the source(s) of the magma upwellings. It is in these relatively higher regions of the mare seas that we expect to find lava tubes. Very near-surface lava tubes would have collapsed, and it is probably their relics we see in the many sinuous rilles (like Hadley, visited by Apollo 15). And we see winding 'rows' of rimless sinkholes which would seem to indicate partially intact tubes a bit deeper below the surface. Here and there, a stray comet might have hit the jackpot, crashing through the roof of a lava tube and vaporizing. While perhaps most of the vaporized material would have escaped out of the impact crater, it is possible some fraction fleetingly pressurized the adjacent segments of the lava tube (too much pressure would only blow out the roof) long enough to freeze out as frost on its floor, ceiling, and walls, at a distance where they wouldn't have been heated by the thermal shock of the impact. Down here, there is no exposure to cosmic rays or errant wisps of solar wind.

**We may have won the Solar 'Lottery'! But we'll have to wait to check it out.**

If this seems far fetched, it is quantifiably less so than sustained lunar polar permashade cold-trapping. While more total volatiles may have frozen out over the poles, they are likely to have formed only temporary deposits. Frosts in some few 'lucky' lava tubes would remain at least until the end of the Sun's stable main sequence lifetime, several more billion years.

How could we detect such deposits? In the pre-Apollo orbital surveys of the Moon, a radar reflection that seemed to detect a buried layer of water or water-ice was detected over western Mare Crisium (Sea of Crises, the conspicuous isolated round 'eye' of the waxing crescent moon). In the wake of the confirmation of the Moon's generally dehydrated state, this anomalous reading has been explained away as a probable reflection off the ancient basin bottom below the lava sheet, in an area where it should be shallow. Yet similar shallow bottom echoes have not been noticed in other mare areas, even those known to be shallow throughout! At any rate, without 'ground truth' confirmation, such a reading is but a romantic teaser, given our present state of superficial exploration.

The technical feasibility of deep-looking radar is, however, quite real. Improvements on the radar that have revealed ancient river bottoms beneath dry Sahara sands, may someday reveal the existence and whereabouts of many near surface lava tubes in the lunar basalt seas. In our earlier article "Lava Tubes" in MMM # 25 APR 88 p4 [SASE plus 15¢ to our PO Box], we stated our belief that deeper lava tubes may lie in subsequently buried early lava sheets. Many of these may have been later filled and plugged, but some few could remain void. But whatever the case, only near surface tubes could have been entrusted with this gift of the comets. Will such improved deep-looking radar find a few unmistakably ice-walled lava tubes as well as the more common bone-dry ones?

If so, will the frost layers be so diffused and thinned out on the inner surfaces of these voluminous hollow sanctuaries that, scientific treasure trove or not, they won't be economically recoverable? That's a possibility. The history of space development scenarios and speculations has been heavy on overly romantic expectations. Despite the dashing of many naive hopes, from hydrated minerals on the Moon, to lichen covered fields on Mars, the promise of a human-settled inner solar system rooted in the use of extraterrestrial materials, spring-boarding from Earth's ever growing energy thirst, is still concrete enough to keep us planning and scheming ways to work with the grain of nature off planet. Ice encrusted cavernous tubes on the Moon may or may not be found. But if we don't find any, it will be a matter of bad breaks only. Until we've checked our ticket stub, we can't dismiss the not-so-unfavorable odds that we've won this Solar Lottery! **MMM**

## EARTH-BASED SEARCHES FOR LUNAR LAVATUBES

Writing in **Starseed**, the newsletter of Oregon L5 Society, Oregon Moonbase researcher Thomas L. Billings discusses ways to search out lunar lavatubes. Tube openings are hard to spot by camera unless you are right on top of them. While intelligent lunar base siting will require better orbital mapping than provided for the Apollo landings, the best method may be to look through the rock. The severe dryness of the lunar surface should make this possible for orbiting radar. (Airborne radar has been used successfully to find lava tubes on the big island of Hawaii.)

To provide deep radar imaging, the antenna diameter must be four times the radar wavelength being used. To penetrate deeply enough we'd a wavelength of 5-20 meters, meaning an antenna 20-80 meters across! That's a lot of mass to put into orbit along with the ancillary equipment.

Billings suggests a way out. Readings from a number of smaller antennas in an interferometer array can substitute, synthesizing an image. It will be tricky to do this in orbit, and an intercontinental interferometer is an option Using a 7 meter wavelength, you'd have a 250 meter resolution and a penetration of 70 meters, good enough to detect a convincing sample, given that many tubes are likely to be larger than this.

However, a considerable amount of power will be needed if the signal returning to Earth is to be detectable. Computer algorithms needed to sift signal from noise are getting better. Nor need the search extend beyond a few months, so maybe the expense wouldn't be out of line with the rewards.

[Ed.: 1) Would it be practical to intercept that signal in lunar orbit where it'd be stronger? 2) Would Earth-based searches be limited to central nearside?] ∞ ∞ ∞

# MMM #58 - September 1992

### Andy Reynolds On Mars Microbot  Lavatube Explorers:

Preliminary idea for the "microbot" you were talking about. There has been a lot of research into superfine optic fibers in the past few years. These fibers are very light weight, fairly strong and most importantly, can carry very "broad-band" type signals like TV images/ Using your idea of a "mother" lander that would carry the rovers to the general area of the lavatube opening, the idea would work something like this. Each rover would carry a spool of, say, a couple miles worth of optic fiber on it. This would weigh a couple of pounds, and shouldn't burden the robot too much. The end of the fiber run would connect to the lander. The lander in turn would relay the data and images collected up to an orbiting craft or directly back to Earth.

As each rover is released, it would simply spool out fiber optic cable behind it, sending back information as it goes. If the data link is made two way, it might be possible for the lander to relay commands back to the rover to stop and look at something it had seen that the lander's computer deemed more "interesting". This set-up would allow a single lander with say half a dozen rovers to explore and map a fairly large area.

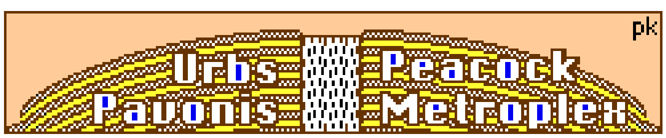
One fault in this scheme might be that the lavatube might not be branched, i.e. it could form a single, linear feature. In this case, it might be advisable to have an alternative approach, say where a rover would first explore the entrance of the tube, determine its initial structure (linear, branching, both), then have the lander select how it could best use the rovers.

In this situation, the rover cable connector might be disconnectable, allowing for one rover to follow a tube to the end of its tether, then have the lander command a second rover to follow it, but with the optic cable disconnected. In this mode, the rover would simply contain the memory of how its sibling had navigated to get to where it was, find the first rover, then plug in its cable to a receptacle on the first one. This would allow it to continue down a long tube, exploring and mapping it in a "relay team" approach. Neither the hardware nor the software for such an approach should be very difficult.

Alternate approaches, such as using radio or lasers to relay data and images, run into inherent problems with unexpected changes in transmission qualities (due to changes in the wall make-up, sudden bends in the tube or other obstructions) that would mean adding increased processing and navigational capabilities to the rover (i.e. remembering when and where the last reliable communications with the lander was and figuring out how to get there). Not pretty, but a start. Well I see I've run on for a bit so will cut short for now. Will think on things some more and see what all else I can come up with. Good reading, like "Moon Miners'", helps the process!

Andy Reynolds, Rochelle, Illinois

## MMM #73 – March 1994




### Urbs Pavonis: The Peacock Metroplex
## The Site for Mars' Main Settlement

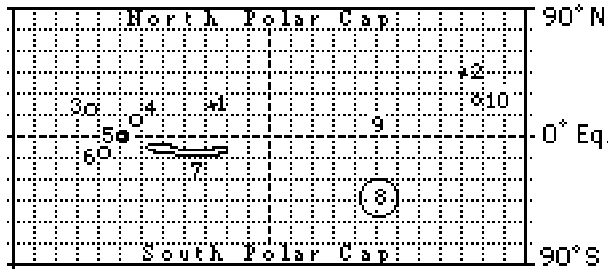
By Peter Kokh with Bryce Walden

**Pavonis Mons' Economic Importance as a Launch Site**

In MMM #18 SEP '88 pp. 6-7 "PAVONIS MONS: Very possibly the most strategic mountain in the Solar System" [republished in MMM Classic #2.] We (Kokh) made the point that the combination of Pavonis' great height and its position astride Mars' equator destined it to play a major continuing role in the development of any Human Martian frontier.

First its west slope could host a launch track, one far better advantaged than any up remotely similar candidate mountains on Earth: Mt. Cayambe in Ecuador, Mt. Cameroon and Mt. Kenya in Africa, Mt. Kinabalu in NE Borneo. The gentle slope of Pavonis reaches at least three times higher than any of these. Nor are there the torrential west slope rains that plague all the Earth sites mentioned.

Add in the lower gravity that must be overcome, with an escape velocity 38% that of Earth's, and the West Pavonis Launch Track (WPLT) promises to be the export workhorse of the Martian economy. Since once such a launch track is installed, it will make no sense to export from Mars from any other site, Pavonis is likely to be central to a major part of the Martian pioneer settlement population.




**Mercator Projection of MARS** with grid lines 15° apart. KEY: 1-2 the two Viking landing sites; 3 Olympus Mons; 4-5-6 the 3 great Tharsis Ridge shield volcanoes: 4 Ascraeus, **5 Pavonis,** 6 Arsia; 7 the Valles Marineris; 8 Hellas basin; 8 Syrtis Major plain; 10 Elysium Mons

While thanks to its tenuous atmosphere which permits aerobraking, it actually requires less fuel to soft land the same payload on Mars as it does on the Moon, Mars is behind the economic eight ball when it comes to exports with which to pay for imports. Volatiles (methane and ammonia, containing precious hydrogen, carbon, and nitrogen; other HCN feed-stocks) shipped to the Moon, LEO, and Space Settlements from its moonlets Phobos and Deimos are Mars' one real salable asset. Any manufactures made in the Martian Settlements themselves and intended for export, will either have to be something of very unique value made nowhere else, or find a way to compete on price via dirt cheap launch, i.e. up the "Pavotrak".

(Someday, if Deimos can be "nudged" just 1900 miles closer to Mars into a synchronous orbit above Pavonis, and if Phobos' orbit can be moved out just 271 miles to cycle three times a Mars day exactly, and given just a little inclination with non-precessing nodes (much the bigger trick), then a Pavonis-Deimos Elevator could be built spanning a distance only 4/9ths as great, against a gravity load only 3/8ths as great as a similar elevator on Earth, thus requiring much less exotic materials.)

**Pavonis Mons as a Major Settlement Site**

What we say here holds true of the other great shield volcanoes on Mars: Olympus, Ascraeus, Arsia, Elysium, etc. But Pavonis' equatorial advantage gives it an enormous edge.

In the previous MMM article sited above, we had also pointed out that the basaltic Pavonian slopes would allow us to build shelter with materials and methods with which we would already be familiar from our lunar experience. It is right here, on the topic of settlement construction, that we want to look at Pavonis again, and speculate about the "annexation" of this site into the Human-Gaian Diasporal reach.

Enter into play another trump card. Shield volcanoes, like Earth's largest, the Hawaii Big Island Mauna Loa - Mauna Kea complex, are built up of layer upon layer of relatively "runny" (melted tar-like) broad sheets of extremely fluid lava of low silica and gas content and very high temperature (1100°C = 2000°F). This is what gives shield volcanoes their gentle slopes in the 3-5° range (as opposed to the more photogenic classical cone shaped volcanoes like Fuji). Part of the process by which these layers are laid down results in the formation of numerous lavatube conduits. The Big Island is "laced" with them, with 482 now listed and more being formed in each eruption. In the continental U.S. the Medicine Lake Volcano in northern California is another well-studied example.

Ronald Greeley, in his paper "Lava Tubes in the Solar System" (in G. Thomas Rea, Ed., 6th International Symposium on Vulcanospeleology, National Speleological Society, 1992) proposes **lavatubes** on Mars. In high-resolution images from the Viking Orbiter spacecraft, open channels and roofed channel segments are clearly visible as radial patterns around the summit caldera of Hecates Tholus, a shield volcano more than 200 km across, for example.

"Many of the lava flows that built both the shield volcanoes and the plains [of the Tharsis Ridge] were emplaced through lavatubes and channels. Some volcanoes such as Alba

Patera, are enormous structures covering thousands of square kilometers and are composed of individual lava flows fed through extensive tube and channel systems" (p. 226). Greeley does not single out Pavonis Mons. He also says While lunar basalt is enriched in titanium, some Mars basalts may be komititic flows, "magnesium-rich."

To judge by the cross-section of lunar sinuous rilles which are collapsed lava tubes, lunar tubes are very much larger than those we have found on Earth, perhaps 50-100 times as high and wide and long. This may be due in part to chemical differences in the lava but probably has more to do with both the great volumes and depths of the sheets and with the much lower 1/6th gravity. We might expect Martian lava-tubes (gravity 3/8ths Earth standard) to be of intermediate size. Caverns tens of kilometers long and tens of meters wide would be very handy ready-shielded volumes indeed within which to place residential, commercial, industrial and agricultural areas of a major settlement complex.

Unless and until proven differently by a ground expedition, the expectation should be that Pavonis is honeycombed with many thousands of miles of lavatubes. In addition, we can conjecture about the chemical composition of the host terrain on much more solid grounds than we can about other sites on Mars. Therefore we can also plan now, a suite of building materials industries based on local resources.

[I had put the question to my friends Bryce Walden and Cheryl York of Oregon L5 (members of the National Speleological Society, the other NSS, and the principals behind the Oregon Moonbase effort in a natural lavatube, outside Bend, of which they game me a royal tour in July of ‘92.) “What percentage of the volume of a typical shield volcano is void, i.e. lavatube? That is, how large a ready laid out metroplex area might we find within Pavonis?”

Bryce sent back by email a veritable treatise on the subject, carrying his calculations, based on the Medicine Lake example, through some 58 equation steps! All the other sources cited in this article are contributed directly or indirectly by Bryce.]

**The Argument from Medicine Lake** (Bryce Walden)

Rogers and Rice, in "Geology and Mineralogy of Lava Tube Caves At Medicine Lake Volcano, California, give “over 300 caves” ranging from "short grottos under ten meters long to braided systems nearly ten kilometers long. Passage sizes range from 0.25-meter high crawlways a meter wide to 'dirigible passages' up to 25 meters in diameter." According to the authors, these caves represent 18% of the total lava tube volume originally formed (the others collapsed or were filled; that number is mostly derived from collapse trenches).

Medicine Lake is "a large shield over 33 kilometers in diameter which attains an elevation of 2,417 meters." Interestingly, lavatubes appear to form "in a zone on both the northern and southern flanks at approximately 1,370 meters in elevation ... with 1,250 meters taken to represent the base altitude of the volcano, leaving a net height of the volcano of 1,167 meters.

The average of the cave sizes quoted above is 5 km long with a diameter of 12.75 meter. We (Walden) estimate the actual average cave would be more like 1 km long with a 5 meter diameter. This is the approximate size of each major side of Young's Cave at the Oregon Moonbase, and comparable in size to many caves in Lava Beds National Monument. This yields a volume of a cave cylinder of 19,635 cubic meters per cave or 0.0000196 km3 or a total of 0.00589 km3 of "known" voids for the whole volcano.

Next, we calculate the volume of the volcano to be 332.7 km3, consisting of an upper “shell” volume of about 37.59 km3 including the 150 feet (45.72 m) nearest the surface from which all our evidence is taken, and a 295 km3 “core volume” remnant, to which the argument might be extended.

Of the older caves deeper in the mountain, many will have collapsed or otherwise filled in over time, so this quotient won't hold for the whole volcano. If we estimate the core volcano originally did have a similar void quotient but has been 85% filled in by erosion, collapse, or subsequent flows (Cheryl York thinks this may be pessimistic, perhaps only 50% have been filled, but agrees with using this conservative figure at present), then the void quotient of the core would be 0.00235% and a net void figure for the mountain 0.0128 km3. Please note this is about 13 million cubic meters of void in one small shield volcano. In sum, we might project 0.00386% of the Medicine Lake shield volcano volume is lavatube void with nearly 2 caves per cubic kilometer.

**Extending the Argument to Pavonis on Mars**

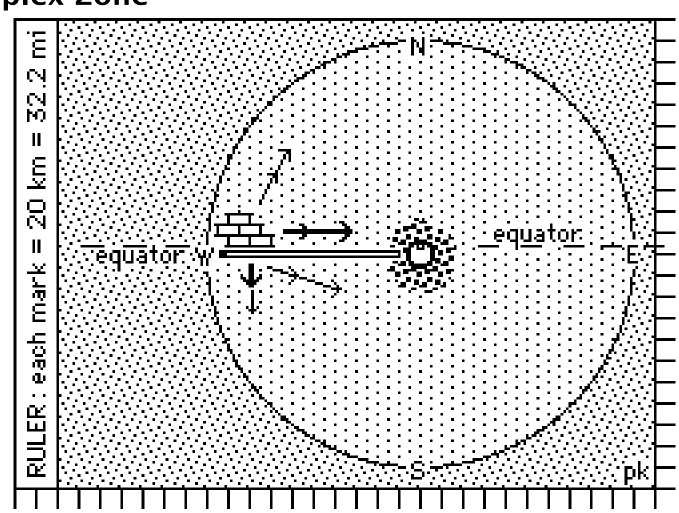
Now Pavonis Mons has a volume 700-1000 times larger than Medicine Lake. (Pavonis is 7 times the diameter of Medicine Lake, covering 50 times the area and is perhaps 15-20 times taller). Taking the smaller figure and extending the same argument, we might expect 10 billion cubic meters invol-ving wider, higher, longer caves spaced further apart. If we postulate an average Martian tube interior ceiling height of 30 meters, that gives us a floor space of about 150 million square meters = 333 square kilometers = 128 square miles, the size of an American central city in the 1,000,000 population range - in a host mountain with a footprint of 40-45,000 square miles, bigger than Iceland and comparable to the size of states like Ohio, Kentucky, Tennessee, Virginia, Mississippi, Louisiana, or New York. (For comparison some other American states in thousands of sq. mi. are: CO 104, OR 96, MN 80, WI 55.)

Pavonis (genitive form of Pavo, Latin for Peacock) covers an area about twice that of the BosWash Megapolis with its 40 million people. Since the lavatubes are not cheek by jowl, the potential population of the Peacock Metroplex will be significantly smaller than that. Add in the fact that it has to include within this shielded area support agricultural areas that will perhaps occupy the major fraction of available space (unless this function is taken care of in surface greenhouses - bear in mind that glass protects against UV damage and only seed corn need be protected from radiation.) We still come up with a ready to build-within protected area that can be home someday to tens, perhaps hundreds of thousands of Terro-Martians. As the economy expands to include similar satellite communities in other “Montes” shield volcanoes like Olympus, Ascraeus, Arsia, Elysium, etc., the valcano-hosted urban population of Mars could soar into the millions.

Because these pre-excavated areas are so spread out along the surface of these enormous volcanoes, they are likely to be incorporated as a number of separate communities representing individual tubes or convenient clusters of tubes, all sharing some Metroplex functions in common. We’ll find names like Pavo Heights West, Pavo Cliffs, Caldera Crest, Rim Town, North Peahen, and many others whose names make no reference to the host site at all.

In addition, of course, there will be a scattering of “conventional” surface-trenched towns plying the mineral and other pluses of various sites. We’ll have a better idea of where such specially advantaged spots might be after future robotic missions complete geochemical and altimetric maps of Mars.

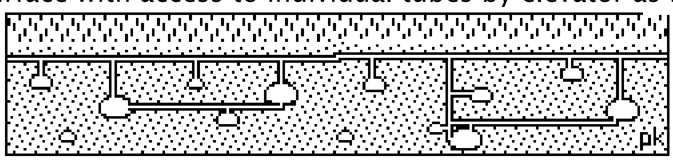
## The Pavonis Metroplex Zone



**Plan of the Pavonis Mons Metroplex Area:** The lavatube-riddled shield volcano slopes cover an area about 250 mi. in diameter. The corridor for the launch track up the west face of this equator-straddling mountain is shown, along with the site for a Pavonis-Deimos Elevator Base in the caldera summit. The suggested site for the first settlement is indicated by the brick-pattern area with arrows showing logical directions of early metroplex expansion. Eventually, the entire base of the mountain could be occupied, attaining a population of up to a million citizens or more.

So how might the Peacock Metroplex take shape? We could expect the initial settlement areas to hug the lower end of the Pavotrak launch track complex site and expand as the economy grows and demand arises along the track and around the mountain. Development might leapfrog areas in which lavatubes are relatively sparse or widely spaced to areas where they may be clustered. Some locations might offer enhanced concentrations of volcanic minerals. Sites near the caldera rim may support tourist activity.

The lavatubes being arranged more or less radially away from the summit, locally they will be arrayed more or less in parallel. Those nearest the surface will be the first to be exploited. This suggests that pressurized cross-connecting roads might best be trenched into the mountain slope surface with access to individual tubes by elevator as illustrated below.

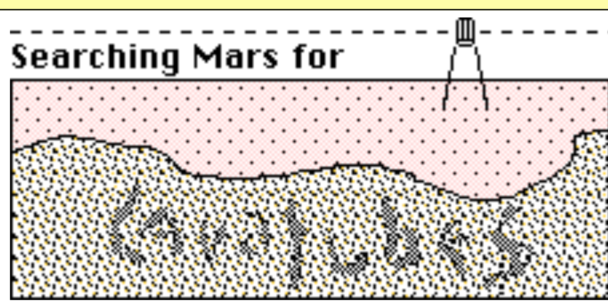



**Schema of lavatube habitat areas** and their pressurized connectors. (Shown: cross-section of mountain slope perpendicular to radius) Dashes at top indicate mountain slope surface and direction of the summit. Principal "cross-connectors" are most logically trenched and covered at the surface, with access to individual lava tubes by elevator banks. Cross-tunneling only makes sense between major close neighbor tubes and tube systems. Some lavatubes will be "off the beaten path" and by-passed in creation of the Metroplex.

Freight and Passenger traffic are likely to be separated especially in elevators. As to solar access, it will be possible, and more efficient in the long run to pipe in sunlight by mirrored shafts or fiber optic bundles than to use surface-avail-able solar power (just 36-52% as intense as at Earth, depending on the time of Martian year) to produce artificial lighting tied to the sunrise-sunset period above. We might see both, with nearer-surface tubes trying direct access, deeper tubes opting to repeat surface lighting electrically. Either way, it will be more cost effective to faithfully follow the seasonally varying length of daylight than to produce a standardized day-night cycle below.

Pressurizing leaky lunar lavatubes won't be smart. On Mars where we want to alter the given atmosphere over time, we might do just that. Pavonis Mons will be one of the most interesting settlement scenes in the entire Solar System. PK

## MMM #93 - March 1996



## Mars' vast shield volcanoes & lava sheets are prime territory for lurking lavatubes & prime real estate for the New Martians

By Peter Kokh

Whatever geological and scenic attractions may beckon siren-like to the first manned Mars expeditions, the "California" of future waves of Martian homesteaders is more likely to be the expectedly lavatube riddled shield volcano flanks of Olympus, Arsia, Pavonis, Ascraeus, and Elysium - and likely similarly endowed vast lava sheets of the attendant Tharsis uplift region.

The pre-excavated radiation shelter and the thermally buffered retreat of the tubes will make any settlement establishment much easier, giving it a considerable head start, as well as an enduring advantage. Mineralogical assets will also count, of course. And happily, the Tharsis region impinges on the head of the great Valles Marineris canyonland complex where many strata of rock will lay revealed for prospecting ease. **Pavonis Mons**, a great shield volcano already cited as possibly the most strategic mountain massif in the entire Solar System, its western flank the ideal site for a launch track complex, neighbors this canyonland head region on its eastern flank. [Cf. MMM # 18 SEP '87, pp. 6-7 - MMM Classics #2]

But all this is little more than reasoned speculation. We do know what kind of terrain sports lavatubes on Earth and we do see analogous terrain on Mars. But that's it. On the Moon we have the added advantage of seeing actual examples of partially and wholly collapsed lavatubes (e.g. Hyginus and Hadley Rilles, respectively). Surveying such features on the ground will take generations. If we can search for them with orbiting instruments, our pre-settlement "treasure" maps of Mars will be enormously more helpful and propitious.

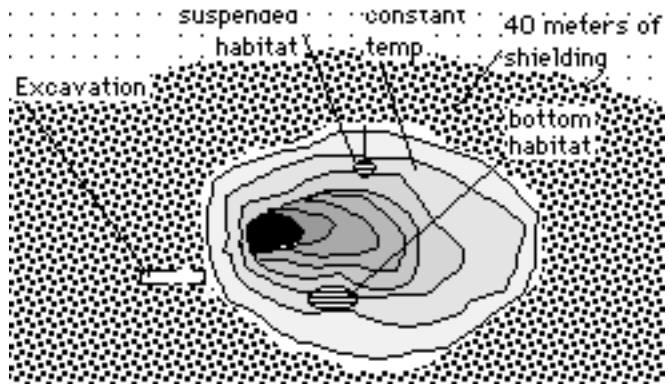
While many, if not most tubes may lie within lava sheet layers that have been subsequently buried by later flows and thus be well below the surface, those in the uppermost flows should lie near enough to the surface to be detectable by appropriately tuned radar.

Cf. MMM # 44 APR '91, p. 6, in which we report on the suggestion of Tom Billings of Oregon Moonbase (and published in Oregon L5's **Starseed**) that since airborne radar had been used successfully to find lavatubes on the Big Island of Hawaii [i.e. the Mauna Loa / Mauna Kea shield volcano complex], given the dryness of the lunar [and Martian?] surface, it should be possible to map near surface tubes with orbiting radar. To penetrate deeply enough we would need a wavelength of 5-20 meters, meaning an antenna 20-80 meters across.

Given our experience with the quixotic results of some of the Viking lander experiments, it only makes sense to fly such instruments first in low Earth orbit. We can then compare the findings with known "ground truth" and check the verisimilitude of the readings and better correct the calibration. Finding unsuspected tubes in various regions on Earth may be reward enough to merit such a precursor mission.

This being done, a second such orbiter mission could do its tricks in orbit above the Moon, adding enormously to the practical knowledge necessary for intelligent planning of lunar development scenarios. The third tubefinder mission would head for Mars polar orbit. Lessons learned at Earth and at the Moon would allow mission planners to fly the leanest and lightest and least expensive probe to Mars capable of doing the job usefully well.

Would permafrost deposits interfere with the readings and conclusions. Not likely, as the radar wavelengths for the former are LONGER - SHORTER by a factor of X. However the radar instrumentation needed for the two global searches would seem to make made-in-heaven bus mates — a "tundra and tube" mapper. If we did find permafrost and tubes in the same region,. and we may not, that would mark the location as especially attractive for settlement development.




**LAVATUBES AND THEIR USES:** On Earth, these features are typically a few tens of meters wide and high and hundreds to a few thousands of meters long. On the much less gravid Moon, and with the scale of Hadley Rille as evidence, we expect to find lavatubes hundreds of meters wide, and many tens of kilometers long. On Mars, with its in between 3/8ths normal gravity, we might expect such features to be in between in size, say 50-100 meters wide and a few kilometers long. On both the Moon and Mars, “tubing” will be a major outdoor hobby, akin to limestone cave spelunking on Earth.

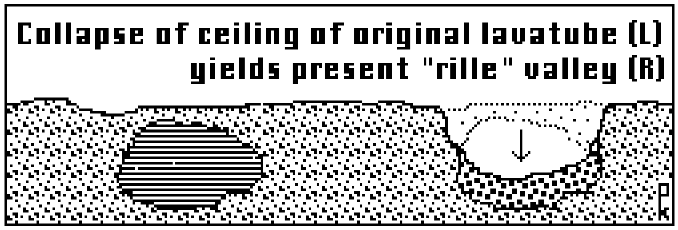
## MMM #100 - November 1996

## The Lure of the Moon’s Hidden Covered Valleys

In this Apollo 10 photo of Hyginus Rille in Sinus Medii (central nearside, 5°E, 8°N) are visible a number of “gaps” in the rille. The arrow points to the most prominent of these, about 10 miles long. The only geologically viable explanation is that this “interruption” is an uncollapsed segment of an original lava tube once well over a hundred miles long. Someday such ready-made sanctuaries from the cosmic elements may house the bulk of the Lunan urban population.  Much more on pages below in this special “Lava Tube” issue of MMM.

## Twelve Questions About Lunar Lavatubes

> **What is a "lavatube"? How are they formed?** A lavatube is a relic of a river of molten lava, self-crusted over on the top as the exposed surface cools, and then at least partially voided out as the lava spreads out eventually on the surface as a sheet.

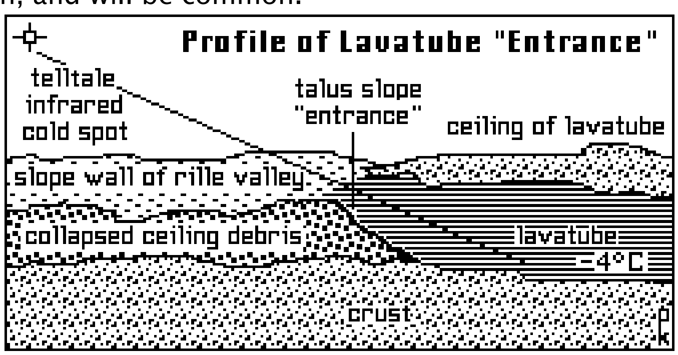



> **Where do we find them on Earth? in what kind of terrain?**

On Earth we find lavatubes in the flanks of shield volcanoes such as Mauna Loa/Kea in Hawaii and Medicine Lake in California. We also find them wherever we have had vast state-sized flood sheets of lava, as in Washington-Oregon, the Deccan flats of southern India, in northeast Siberia, and elsewhere.

> **How sure are we that similar features exist on the Moon?**

The lavatube-rich lava plains found on Earth are geologically analogous to the maria or Seas we find on the Moon. On those grounds alone, we would have a high expectation of finding lunar tubes. But for a second higher order of evidence we also have, in the same type of terrain, long sinuous valleys on the Moon called rilles (the Latin class name is rima]. We have found hundreds of these features in orbital photographs and have visited one (Apollo 15's visit to Hadley Rille). The consensus explanation of such features is that they represent collapsed lavatubes. For a third even more convincing order of evidence, some lavatubes are clearly segmented with interrupting stretches of valley-free surface [see the photo on page 1 of this issue.] These can only be sections of the original lavatube that have not collapsed and remain still intact. Such sections should by themselves be enough to give future lunar developers ecstatic dreams. But if there are partially intact tubes, it is inconceivable that elsewhere, if not nearby, are to be found wholly intact tubes. Lavatubes are a natural concomitant of maria formation on the Moon, and will be common.




> **Are they near surface objects only?**

Those we have direct or indirect evidence of (from rilles) are/ were near surface features. But keep in mind that the maria were filled with a series of lava floodings, and the formation of each successive sheet should have its own lavatubes. On the plus side, lavatubes in deeper layers have been more protected from collapse due to later meteorite bombardment. On the minus side, some, maybe most (a defensible guess for whatever your temperament), were filled up and plugged by later episodes of flooding. Deep tubes are unlikely to be discovered from orbit or from the surface. We could hope to find some of them serendipitously (where tubes in successive levels just happen to cross) by radar soundings taken on the floors of near surface tubes by actual explorers.

> **How might typical lunar lavatubes differ from typical tubes found on Earth?**

(1) The formative episodes of lava sheet flooding on the Moon are all very ancient events on the order of 3.5-3.8 **B**illion years ago. Surviving lavatubes on Earth are all much much younger than that, some only thousands of years old.

(2) In addition to being very ancient, lunar lavatubes differ in scale. Probably because of the lower gravity in which they formed (1/6th Earth's) tube-relic rille valleys already observed, photographed and visited run an order of magnitude (**ten times**) typical terrestrial dimensions in width, ceiling height, and total length. Lunar tubes are BIG.

(3) Lunar lavatubes have never been exposed to air or water (unless a comet happen to pierce the ceiling and vaporize inside with some of the volatiles freezing out on the tube's still intact inner surfaces - a real "lucky strike"!). Like tubes and caves on Earth, the temperature will be steady, but colder (Earth in general is 50°F warmer than the Moon because of the oceanic-atmospheric heat sink.)

> **How intact and stable would lunar lavatubes be? How prone to future collapse, total or partial?**

Any lavatubes that have survived to this day wholly or partially intact are likely to continue to do so for the rest of time. The vast bulk of major asteroidal bombardment which has pocked the Moon took place in the first billion years of the Moon's history. Lunar lavatubes, not subject to any sort of active geological forces or to any kind or weathering are perhaps the safest, most stable, protected volumes to be found anywhere in the solar system. They are veritable vaults, sanctums, sanctuaries we can bank on - no bet-hedging needed.

> **What aspects of lunar lavatube internal environments are most attractive for human purposes and to what uses might we put them?**

1) "Lee" vacuum protected from the micrometeorite rain, from cosmic rays, from solar ultraviolet, and from solar flares, and unlimited volumes of it, is a priceless and odds favoring handicap toward lunar outpost and settlement establishment, expansion, and maintenance. In these conditions, only simple unhardened lighter weight pressure suits need be worn, for much greater safety, comfort, and convenience. Lee vacuum is ideal as well for storage and warehousing and in-vacuum manufacturing.
2) Steady temperatures at all times (-4°F), protected both from dayspan heat (+250°F) and nightspan cold (-200 some °F), the "body-heat" of the subsurface Moon being much higher than the "skin" heat of the exposed surface
3) Lunar lavatubes are dust free. The regolith Moondust blanket is the result of eons of micrometeorite bombardment or gardening of the lunar surface. The unexposed surfaces of lunar lavatubes have been protected from all that and, good housekeeping measures adopted and religiously followed, will remain dust-free sanctuaries. Given the insidious invasiveness and machinery- and lung-fouling character of moondust, this asset is a clincher!

For construction purposes, shielding now provided as a transcendental given and dust-control vastly easier, lavatube sites will be much simpler and easier places in which to build. We have only pressurization to provide and maintain within these natural macro-structures.

As a package, lavatube assets effectively remove (squelch, eradicate, nuke) most of the common objections to the Moon as a development and settlement site, reducing worries to lack of around-the-clock sunshine (an engineering energy-storage and usage/scheduling question) and gravity one-sixth Earth normal (as if life hasn't always been able to adapt to **any**thing!).

> **Are there any more special resources we might find in lunar lavatubes here and there as extras?**

Mineralogically, lavatube surfaces and their host terrain will be boring, fairly homogeneous basalt. Other elements, not present in local basalt, can be mined and processed elsewhere and the products made from them brought to the site. But not to be overlooked is the possibility that we have hit the cosmic jackpot with a volatile-rich comet strike of just the right size to puncture, but not collapse, a lavatube. Frozen volatiles would be the prize. These would not be subject to most of the loss mechanisms that will surely operate in polar permashade ice fields (micrometeorite bombardment, solar flares and solar wind, cosmic rays, splashout from other impacts). To date, the only (and it's inconclusive) teasing evidence we have is an anomalous reading over western Mare Crisium that on first interpretation would seem to indicate subsurface water-ice. This reading has been (but should not be) routinely dismissed as spurious.

> **What lavatube uses are near term, what uses are more challenging and likely to be realized only in the far future?**

Warehousing and storage; industrial parks; settlement as opposed to outpost; archiving. All of these can benefit from the use of lavatubes much as we find them, without wholesale modification. The idea of pressurizing tubes for more "terra-form" settlement presents a number of enormous hurdles (sealing methods, sealant composition, pressurization stress, importation from Earth of astronomical volumes of nitrogen, etc.) and while in toto vastly easier than wholesale terraforming of a whole surface (e.g. Mars) is still something we will not tackle for some generations perhaps.

> **How much total ready to go protected volume are we talking about?**

For political purposes internal to the pro-space movement, let's express our back-of-envelope guesstimate range of the total available volume of intact lunar lavatubes in terms of O'Neill Island III Sunflower space settlement units. That's ready-to-occuppy-and-use-NOW (for those without 1-G and 24-hour sunshine hangups - they can wait the generations it will take to build Sunflower units from scratch !)

The surface area of the host terrain, the lunar maria, comprise some 17% of lunar surface = 2.5 million square miles - compare with 3 million square miles for continental U.S. Now if (we have to start the argument somewhere!) we assume that available floor and wall terrace surface of intact lavatubes compares to 1/1000th the taking 1/1000th of this aggregate lunar maria surface area, we get 2,500 square miles. This is in our estimate, a very conservative fraction. Counting supposed lavatubes in lower level lava sheets, 1/100th is a fraction that could be closer to reality. That would yield 25,000 square miles, an area comparable to West Virginia.

Subtracting for window strips (as we have for lavatube upper walls and ceilings), an O'Neill cylinder, if ever realized in full ambitious scale, might have 100 square miles of habitable inner surface. Argue about the figures, it won't change the overall picture. We are talking about ready to occupy network of lunar lavatubes that compares to 25 to 250 Island III units. If you are going to hold your breath until these free space oases are built, I can only hope your life expectancy is much more Methuselahn than mine {P. Kokh].

> **Can we expect to find other similar hidden covered valleys elsewhere in solar system?**

Yes, as they seem to be a standard concomitant of lava sheet flooding and of shield volcano formation, we might expect to find lavatubes on Mars, Mercury (the temperature swing refuge would make them hot property), Venus (they would be too hot, and share Venus' over-pressurization), Io (protection from Jupiter's radiation belts), and even on little Vesta..

> **By what Latin class name are such features likely to be referred?** (e.g. rima = rille)

Cava, tubus, and **ductus** are available Latin words. The latter better indicates the mode of formation.

# Remote Mapping of Lunar Lavatubes

## Tele-Spelunking on the Moon

[Reprint of MMM #44, April '91, page 6]

### EARTH-BASED SEARCHES FOR LUNAR LAVATUBES

Writing in **Starseed**, the newsletter of Oregon L5 Society, Oregon Moonbase researcher Thomas L. Billings discusses ways to search out lunar lavatubes. Tube openings are hard to spot by camera unless you are right on top of them [but see note below]. While intelligent lunar base siting will require better orbital mapping than provided for the Apollo landings, the best method may be to look "through" the rock. The severe dryness of the lunar surface should make this possible for orbiting radar. (Airborne radar has been used successfully to find lava tubes on the big island of Hawaii.)

To provide deep radar imaging, the antenna diameter must be four times the radar wavelength being used. To penetrate deeply enough we'd need a wavelength of 5-20 meters, meaning an antenna 20-80 meters across! That's a lot of mass to put into orbit along with the ancillary equipment.

Billings suggests a way out. Readings from a number of smaller antennas in an interferometer array can substitute, synthesizing an image. It will be tricky to do this in orbit, and an intercontinental Interferometric is an option Using a 7 meter wavelength, you'd have a 250 meter resolution and a penetration of 70 meters, good enough to detect a convincing sample, given that many tubes are likely to be larger than this.

However, a considerable amount of power will be needed if the signal returning to Earth is to be detectable. Computer algorithms needed to sift signal from noise are getting better. Nor need the search extend beyond a few months, so maybe the expense wouldn't be out of line with the rewards. **TB**

**Editor's Questions. & Suggestions:**

1. Would it be practical to intercept that signal in lunar orbit where it would be stronger?
2. Would Earth-based searches be limited to central nearside?
3. We could use the same instrumentation package to search for tubes on Mars, Mercury, Venus, Io, and Vesta, worlds with shield volcanoes and lava sheets.]

### Using Orbiting Infrared Cameras to Find Collaborating Evidence

According To Bryce Walden and Cheryl Lynn York of Oregon Moonbase, orbiting side-looking infrared detectors may on occasion peer into the entrance of a fortuitously oriented lavatube, detecting its characteristic subsurface temperature, clearly distinct from ambient surface readings, in sunshine or out. Illustration in previous article. MMM

ROBOTIC ON SITE EXPLORATION & SURVEYING

By Peter Kokh

We are back on the Moon, to stay it seems, and we've detected a number of lavatubes from orbit, some handy to our first beachhead outpost. The catch is that there are so many things needing priority attention that we cannot afford the manpower and equipment costs to outfit even a single lavatube exploration expedition. But if we don't "go in" and actually explore and survey, how can we plan intelligently to "move inside" in concrete particulars?

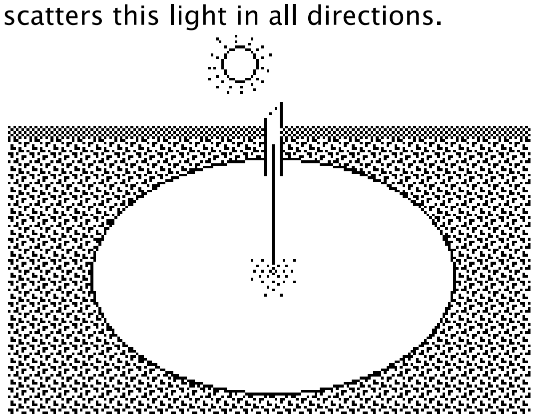
Here is a way we can survey in detail all the lavatubes we have detected remotely from photographic evidence, from orbiting radar and infrared equipment. The costs, in comparison to a single limited human expedition, would be negligible.

**A surface crawling drilling rig**, using high resolution orbital radar lavatube location data, finds its initial drill point over an indicated tube site. This rig can be teleoperated or manned. Given the repetitive nature of the tasks involved, a highly automated remote monitored operation will be ideal.

**(1)** Its first task is to drill and stabilize (with a sleeve? with side-wall fusing or sintering lasers?) a hole through the surface and penetrating the lavatube ceiling some tens of meters down. The hole might be only a few inches in diameter.

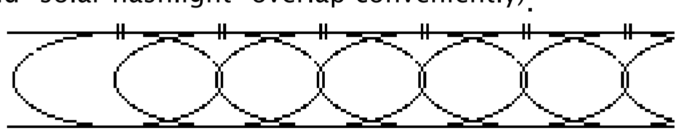
**(2)** Next the rig winches down through the shaft hole a radar-mapping instrument and/or CCD optical camera down to a height midway between lavatube ceiling and floor (determining that position is the first task of the radar device). Then a flare attached to the bottom of the instrument package is released and dropped. The radar mapper and camera pan 360°, and from near vertical up (zenith) to near vertical down (nadir). The instrument package is retrieved. A latitude/longitude/altitude benchmark is then lowered to the tube floor directly below.

**(3)** The rig then winches down to the same point a length of fiber optic cable, securing the top end to the collar of the shaft hole. At the top end is a solar light concentrator which passively gathers available dayspan sunshine and channels it into the optic fiber cable. At the bottom end a light diffuser scatters this light in all directions.



The idea is not to provide future human explorers within the tube with enough light, throughout the surface dayspan period, to find their way around with the naked eye, but only with enough light that they can find their way using off-the-shelf night-vision goggles. Of course they will carry battery-pack spotlights to light up areas needing closer inspection, as well as for emergencies e.g. they are forced to stay inside after local sunset on the surface above.

**(4)** Meanwhile, data from the radar/camera probe is being turned into a contour map of the lavatube's inner surfaces. From this map, it will be clear in which direction the lavatube runs and the location of the next drill hole can be determined, picked so that data from it (and the reach of the left behind "solar flashlight" overlap conveniently).



As the instrument package is removed from each successive shaft hole, another passive solar flash light chandelier is installed. On and on until the entire intact lavatube is surveyed from source to outflow. The rig then moves to one end of the next orbitally detected site to be investigated.

The result will be a set of tube surveys and maps from which preliminary rational use scenarios can be put together  all prior to commitment of man-hours and man-rated equipment packages. Now , with all of these robotic surveys, safely made, when we do go in to explore or set up shop, we can be sure that the tube section picked is right for the purpose intended, including the offer of adequate expansion room for foreseen development options.

This is the basic idea. Possible embellishments are designing the solar flashlight chandeliers to serve as line-of-sight relays for radio communications by exploring crews, and/or as direct radio antennas to the surface.

If the tube surveyed by the surface-crawling robot drilling rig has already been picked for future development, a “sleeve-bag” of sundry provisions and resupplies could be lowered to the tube floor beside the benchmark prior to sealing the shaft with the solar light fixture apparatus. These provisions would lighten the burden in-tube explorers need carry along. Alternately, the solar light fixtures could be removable if the shaft is needed for lowering provisions or other narrow diameter equipment to the area below it.

This exploration plan will only work, of course, for those near surface tubes that have been sniffed out by our orbiting probes. But that will be an important start!


## Brainstorming an Early Lavatube Town

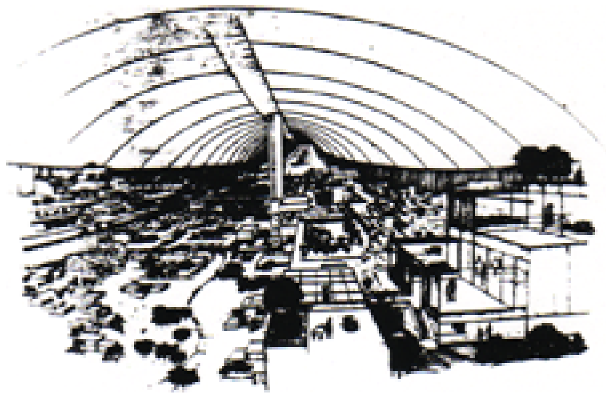
By Peter Kokh

Many of our readers will be familiar with the classical Island II “Stanford Torus” space settlement design [Space Settlements: A Design Study, NASA SP-413, 1977]. Not counting multiple levels, this ring with an overall diameter of 1800 meters and a torus cross section of 130 meters, has a circumference of 5.655 km or 3.5 miles and a usable surface area (lower slopes included) of about 50 acres.

With multiple levels, it was estimated some 10,000 people could occupy 106 acres (Manhattan like sardine packing, i.e. quite dense by modern urban standards of c. 5,000 people per square mile = 640 acres.) That seems overdoing it especially since off Earth settlements wherever they are will first and foremost be farming villages: = lots of plants hosting very few people, not vice versa.

But thanks to the copious artwork that has accompanied the settlement design studies of the seventies, such a torus does give us an assist in conceptualizing a lavatube settlement. Cut it at one point and unroll it, and you have something comparable, if on the small end, to what we might someday see in lavatubes. The average lavatube is likely to be several times wider than the torus of the NASA study.

interior torus view, art by Pat Hill, IBID, p. 90

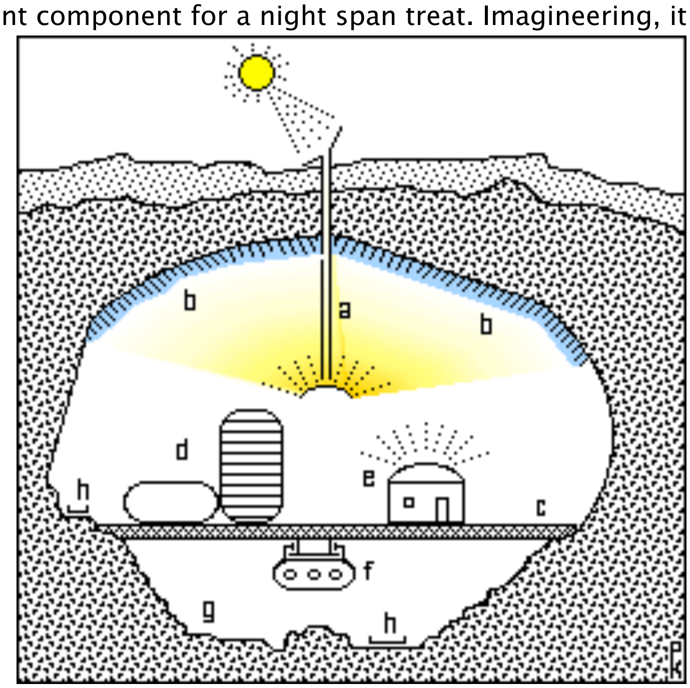


In practical fact, however, this scene gives us more of a goal to hold before us, than a model for feasible near term reality. Sealing a lavatube so as to pressurize it may be easier said than done. If we succeed, filling the immense volume with the usual buffer gas of nitrogen imported from Earth in a 4:1 ratio with lunar oxygen may be budget-busting. But more on this in an article below.

Near-term, pressurized ceiling clearances will have to be kept to a minimum. We will use lavatubes at first not to escape the vacuum, just to escape the deadly cosmic weather that normally comes with vacuum – on the exposed surface.

The tube ceiling vault functions analogously to the Biblical “firmament” protecting Lunans in their hidden valleys (lavatubes) from cosmic radiation etc. and from the otherwise omnipresent dust. Even if the tube is not sealed and pressurized it may be feasible to spray a high albedo coating on the upper walls and ceilings (CaO lime, or Aluminum Oxide or Titanium Dioxide, all producible cheaply and in quantity, are white. The trick is to make an anhydrous “whitewash.” Unfortunately, bluing this inner “sky,” e.g. with locally-producible cobaltous aluminate would be expensive.

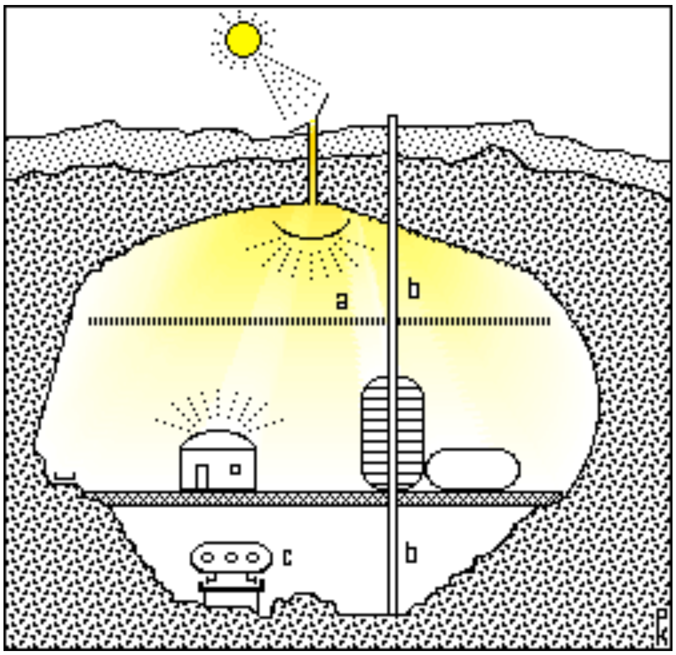
Sunshine could be brought in down simple shafts or through optical cable bundles, to be turned on this sky-firmament, thus providing comfortable daylight type ambient light. During nightspan, nuke or fuel-cell powered lamps on the surface could use the same light transmission pathways. Possibly any whitewash material on the upper vault of the tube could have a phosphorescent component for a night span treat. Imagineering, it is called.



KEY: **(a)** sunshine access and defuser system; **(b)** whitewashed “firmament” for best sunlight reflection; **(c)** “town deck” on tube-spanning beams; **(d)** assorted structures; **(e)** “yurt/hogan” type home with translucent dome to flood interior with firmament-reflected sunshine; **(f)** monorail transit system; **(g)** lavatube floor left natural; (h) nature walks.

Instead of grading or even terracing the lavatube floor, it could be left natural with the town built on a spaceframe deck spanning the lavatube shoulder to shoulder. an overhead crane riding rails along the sides of this deck could be useful in constructing/erecting habitat structures. The use of stilt platforms is a possible alternative to the deck span, shoulder to shoulder beams

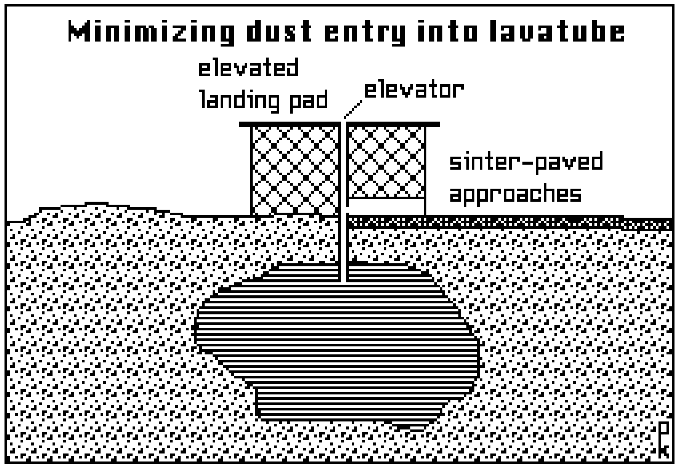
Elevators to the surface can either be incorporated into “skyscrapers” reaching to the tube ceiling, or be built free-standing to provide great views of the town on the descent from or ascent to the surface.




Access to the settlement from the surface is vital. This can either be by freight and passenger elevator shafts or by a ramp road up the talus slope of a nearby natural entrance. We think the first option will bear the brunt of the traffic.

**KEY to illustration above:** **(a)** sunshine access via suspended “daylux” defuser grid instead of coatings; **(b)** elevator shaft through “skyscraper”; **(c)** transit system on stiltway over tube floor.

The tubes are given to us dust-free. Thoughtful engineering of tube access systems will help keep them that way. For example, elevators could have their topside terminals opening not onto the dusty surface directly but onto a suspended platform/launchpad complex.

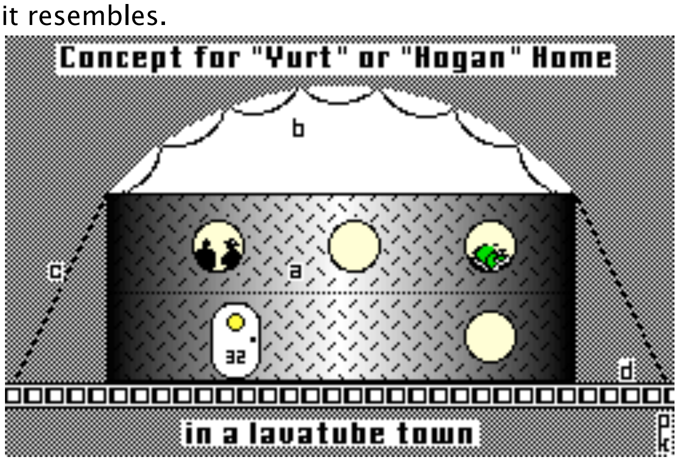



Appearances aside, a vital part of the settlement will be out on the surface and building material and component manufacturing out of “pre-mined” regolith, “the” asset of the surface. Once a processing, manufacturing, or gas scavenging position is past the “dust-using” phase, further processing, manufacturing, assembly, or separation can be more safely and more economically done in the lee vacuum environment within the lavatube. Industrial siting decisions will take into account the degree of involvement of solar power and concentrated solar heating. Operations that are electricity driven and not reliant on moondust, will be the first to move into the tube.

For the lunar architect and contractor, however, freedom from the need to be concerned with shielding is a considerable gain. Tube residences and other structures can have simple windows, and lots of them, through which to behold these nether-world landscapes. The shielded windows of in-surface structures which use mirrors and bent optical paths to thwart radiation, will be a cumbersome relic of pioneer beachhead days, still used where Lunans must live in the regolith blanket surface rather than in provident subsurface voids. Tube structure windows may be characteristically convex, curved in to the pressurized interior, so as to put the panes under compression. Glass and concrete are stronger under compression than under tension. Nor will in tube windows need sacrificial panes.

The subsurface Moonscapes within the lavatubes will be quite different from the surface ones, though sharing one all important, all infecting aspect: their barrenness and sterility. So tubers may share with topside moles the practice of placing plants in front of windows as a psychological filter.

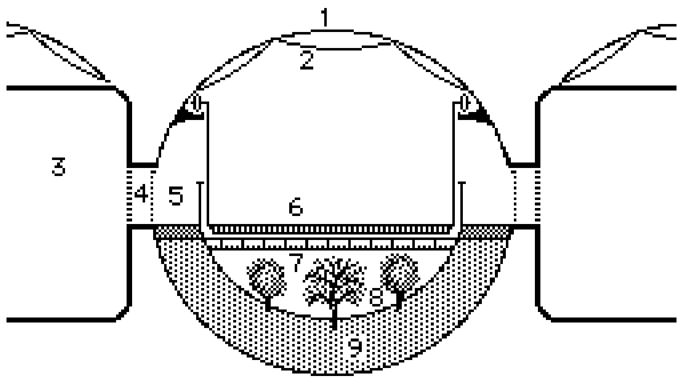
Many architectures are possible. One simple tuber home plan would be a squat 2-story vertical cylinder section topped off by a convex-paned geodesic dome to let in the tube’s ambient light. The design type might be called the Yurt or Hogan after the Mongolian and Navaho home shapes it resembles.



**KEY: (a)** 2-story vertical cylinder section, bedrooms on the lower level; **(b)** lunar translation of the geodesic dome for a high trans-lucent ceiling vault over the family room and other common areas including a central garden atrium; glass panes are neither flat nor concave, but convex; **(c)** cable stays prevent internal pressure from literally "blowing off the roof"; **(d)** the residential deck of the townsite, leaving the tube floor ungraded.

**NOTE:** upscaled, the yurt/hogan design will make a fine church, synagog, or meditation chapel, with the simple use of stained glass convex panes in the roof dome. A shaft of direct sunshine on such a dome would surely help set the mood.

The early lavatube settlement will not be an assembly of individually pressurized buildings, but rather, like the in-surface burrowings, a maze of structures conjoined by pressur-ized walkways, streets, alleys, and parkways. In the nether-spaces, thoroughfare cylinders can be generously paned with convex windows to flood their interiors with ambient reflected and diffused sunshine and views.




**KEY: (1)** cylinder section; **(2)** convex-glass panes to let in ambient reflected sunshine and views; **(3)** Yurt/hogan style homes opening onto street via entrance tubes (**4); (5)** pedestrian "sidewalks"; **(6)** rail-suspended goods delivery platform; **(7)** "crosswalks"; (8) landscaped, concrete free garden strips; **(9)** dust-purged, conditioned regolith geoponic soils.

Along with solar access for reflection off coated upper tube surfaces, there can be some sunshine ports that direct intense pools of light downward, say on the convex-paned lunar geodesic domed park squares. Nothing is so soul-renew-ing as a visit to a pool of strong over-illumination, the feeling of being outdoors in the undiluted brilliance of the unmediated Sun. Directed sunlight, minus the infrared removed by proper glass filters, will also be needed over agricultural areas.

You can see how construction and architecture in lavatube settlements differ from the other types of in-surface settlements we have discussed before. Initially, there will be a strong reliance on inflatable structures and inflatable-rigid hybrids. Here, in lee vacuum, with no need to cover them with shielding, no vulnerability to micrometeorite puncture or ultraviolet and flare and cosmic ray aging, inflatables will have their heyday. All the same, as the costs of new made on lunar building materials and building components come down, and appropriate construction and erection methods are perfected, the bottom line money consideration will move settlement expansion in that direction.

An intermediate phase may involve the use of inflatable structures as slipforms for cold-casting (poured and sprayed lunar concrete) and arch/vault component placement.

As more generous endowments of nitrogen become financially feasible, larger domes over park space commons will make their entrance, affording a more generous "mid-doors" and the more obvious comfort of luxuriant flora and fauna, plants and urban wildlife.

Meanwhile, in the lee vacuum but visible out the abundant windows of lavatube structures will be other extensions of the settlement: sculpture gardens and Japanese style rock landscaping. Electronic displays on the tube walls, even something reminiscent of drive-in theaters, or should we say through-the-windshield theaters? Backlit murals on glass can infuse the citizens with the dream of a Green Luna, not altogether out of reach. And I'm sure sooner or later we'll see some gross examples of tagging by artistically inclined youth without direction or access to approved ways of expression.

Nature walks can educate citizens on the fine points of lunar geology, variations in lavatube textures and formation.

The lavatube settlement will not be a solitary community. To provide around the clock manning of industrial and agricultural facilities owned in common, a string of 3 villages with staggered day/night lighting (the solar access ports can be shuttered after all) will provide a succession of prime work time day shifts. A trio of villages can be separated by some distance along the inside of a lavatube, with intervening light baffle curtains (where convenient bends in the tube route do not offer the same benefit. Mass transit will unit them, and they can share 24 hour around the clock metropolitan facilities and amenities, including schools and parks and other investments that need to earn their peak full-time, or should we say all-time.

Settling the first lavatube should be part of a well-thought out **Outpost Conversion Strategy.** An initial beachhead outpost is succeeded by a surface Construction Camp once a mature set of feasibility experiments leads to the production of on site building materials. Proper site selection will have taken "graduation" to a nearby lavatube into account as an essential ingredient. Finally, after robot exploration and surveying of the proposed first site, will come the erection of lava-tube village one, village two, a metro complex, and village three. Along with warehousing, farms, and industrial park sections - a whole mini urban complex.

## (Sub)Terraforming Challenges

## Challenges of Sealing & Pressurization

By Peter Kokh

While the volumes available in lavatubes are comparable in cross-section to space settlement designs, especially that of "Island Two," they may not be so readily pressurizable. Lavatube walls were not formed as "pressure vessels" and have never been pressurized (except for the possibility of comet puncture and vaporization). Whether they could structurally withstand the expansive stresses of full atmosphere is uncertain. After all, they exist in an ambient vacuum. Deeper lava-tubes will have a better chance of maintaining their integrity, more shallow ones a greater chance of "blowing their lid."

Even though lunar lavatubes have come down to us intact through nearly four billion years of time, that does not mean that there are no fractures in their surfaces that could let an atmosphere eke out slowly but inexorably. And those tubes with entrances provided by past section collapse (illustration on page 4), will have to be closed off somehow. Those without open-vacuum entrances can be many miles long. That means they suck up enormous volumes of lunar oxygen and terrestrial nitrogen.

Of the three principal lunar-scarce volatiles, necessary for life, Hydrogen, Nitrogen, and Carbon, it is nitrogen that is most deficient on the Moon in comparison to the quantities we would like to have. But even if the import cost were no problem, or if we find cheaper extraterrestrial sources (the rocks of Phobos for example) there is the question of the sealants needed themselves.

We could use microwaves of laser sweeps to glassify the lavatube inner surfaces, making them impervious to gas transmission. But introduce water and humidity and we have a problem. Water attacks glass over time. Epoxy resin coatings could not be processed from known lunar materials, and in the quantities needed would pose an astronomical cost.

But if water seems to be the problem, it may also be the solution. For if we saturate the lavatube with water vapor, no matter to what level we manage to raise the inner surface temperatures in the tube, at some point in the peripheral rock, water vapor will form a rock-saturated frozen seal against further loss. Water vapor may be self-sealing.

But this brings up another problem which, all the denial in the world notwithstanding, affects space settlement designs as well – the likely prevalence of permafrost, a serious challenge to our biospheric and agricultural visions.

Suppose we solve most of these “engineering challenges.” For safety sake, both against possible decompression accidents and biological contamination, we may want to develop a system of sphincters that can pinch shut convenient sections of lavatubes if need ever arises.

Yet the dream of recreating some part of the Earthly paradise is a very strong and persistent and infectious one. In a lot less time than it will take to overcome the challenges of terraforming the Martian surface, we will be able to start terra-forming limited lavatube sections. In contrast to the case on Mars, terraforming the Moon’s hidden valleys will work to keep the out-vac surface comparatively pristine. For the Moon’s dusty surface which has never known water of air, that is important. An attempt to terraform the surface (it is estimated that an Earth-dense atmosphere would hang around for a few thousand years – and that is practical for human purposes), any such attempt is likely to backfire and create a dust-bowl condition that will last some centuries.

The more modest goal of terraforming lunar lavatubes will be a lot like terraforming O’Neill’s Space Settlement structures or Dandridge Cole’s hollowed out cigar-shaped asteroids (e.g. Eros).

In H.G. Wells’ “First Men on the Moon,” we discover a native “Selenite” civilization tucked away in caves within the Moon. The idea is not new, and now it is more timely than ever.

**GOALS of an early lavatube terraforming experiment program**

We can safely experiment on a small scale, sealing off and pressurizing small sections of tube for transformation into metropolitan centers and village parks. If these special urban facilities failed, it would not interfere with the operation of the rest of the close-pressurized settlement maze.

The next step, tried before we risk pressurizing a whole settlement, might be a lavatube “Natural Park(way)” – Designed as a safety valve and as a bit of Old Earth for those who cannot afford or physiologically risk a trip down the maw-throat of Earth’s hexapotent gravity well, our parkway would be visited and toured, but not open to settlement. Here Lunans could appreciate what they might have missed on Earth, and find themselves renewed and inspired to carry forward the great Lunan experiment. Trial biospheres rich in flora and fauna could be developed without risking would-be residents. A place for honeymooners and lovers and students and retirees – for everyone, The Mecca for Lunans.

Next, a more confident, lesson-learned suite of bio-spheric experiments behind us, we will have the confidence to tackle bigger and better projects. Biospherics could come to Garden Suburbs, whose condo-owners would pay the cost of experimental installations. And why not a tube amusement park?

There is another question here. Creation of a bio-sphere for our terraformed volume. The go slow experiments above will educate us and give us confidence before we risk citizen lives.

## "Down Inside" Civilization & Culture

By Peter Kokh

**Part I: Naming Lavatube Settlements**

People pick place names for all sorts of reasons: to remember a home town or country, in honor of a fellow pioneer who did not survive the transplantation journey, for a nearby geographic or geologic feature, for a character in a book the leader happened to be reading. The list or rationales is endless. It will be no different on the Moon.

But perhaps there will be a conscious effort among the first pioneers, for whom lavatube life is something new and untried, to make allusion to hidden valley, subterranean, and submarine places and kingdoms of ancient lore. After all, it will be this aspect, something not yet taken for granted, that will be foremost in their consciousness as they embark on this new adventure.

A dictionary or encyclopedia I have of mythological and fictitious places gives lots of leads, but most of them are obscure. Pellucidar (Edgar Rice Burroughs) and all the local place names associated with this fictitious region will be a prime source. Then there are the submarine legends like Atlantis – after all, lavatubes lie beneath the congealed waves of ancient lava seas. And then there are the hidden valley stories like Shangri-la. Shangri-luna, anyone?

Once the novelty wears off, lavatube and lavatube settlement names are more likely to come from nearby surface features (rilles, craters, etc.).

"Co-names" might include Depths, Nethers, Cloisters, Retreat, Lair, Anchorage, Haven, Warren, Trove, Sanctuary, Sanctum, Burrow, Hollow, Grotto, Lower-, Nether-, -neath, and similar descriptive choices. MMM

## MMM #101 - December 1996

# Lavatube: "Down Inside" Civilization & Culture

**Part II. Lavatube Culture**

By Peter Kokh

That we can predict a substantial and marked difference in the maturing cultures of those Lunan settlers who live on the surface, snuggling up under their protective regolith blanket, from that of those who build their townsites within ready-to-occupy lavatubes, should be clear from the length of the list of their respective "transcendental worries".

| "Transcendental" Needs of Lunan Settlers | |
|---|---|
| **surface sites** | **lavatube sites** |
| • Shielding<br>• Pressure Hull<br>• Biosphere | • Pressure Hull<br>• Biosphere |

Coddled by a womb world in which all these basic things are already provided, freeing us to concentrate all our worry-power on lesser if analogous concerns (weather, harvests, economics), it is not hard to see how much more squarely Lunans might feel themselves "behind the 8-ball" than Earth folk. It should also be clear that lavatube dwellers have a substantially reduced worry burden.

Shelter one can count on and take for granted against micrometeorites, against decompression accidents from meteorite debris, against cosmic rays, against the raw naked ultraviolet heat of the Sun, against Solar Flare temper tantrums – this bequest of the lavatube is bound to make its havened citizens a noticeably more carefree lot – even if only in a relative sense. To be sure, the two remaining “transcendental worries” will still provide a strong bond between these two “branches” of Lunan culture.

Hopefully more in friendly jest than in contempt, those of either persuasion may take jabs at those of the other. Surface dwellers may call their cousins “tube toads”, “cozies”, “womb-retentives”. In counterplay, lavatubers may call their surface relatives “mound moles”, “dust eaters”, and the like. One side or the other may retranslate the long litany of ethnic jokes, translated oft before (the very same jokes some tell of Poles, Poles tell of Russians, etc.). We can hope. such jibes will be more a symptom of friendly rivalry than a hint of unjust contempt.

On the other hand, in describing themselves, surface folk might call themselves “blanketeers” or “the star-sighted” or some other name which heralds the compensating glories of a life on or just under the surface. By the same token, tube folk might call themselves “down insiders” or “the sanctuaried” or by some other term that highlights the advantages they enjoy and appreciate.

**Being a “Tuber”**

Settlers who live much of their lives within the lavatube environments may exhibit as a group, relatively speaking, a more “laid back” personality, They must still be much more alert to individual and communal danger and potential catastrophe than most terrestrials. (Granted many of us Earthlubbers relish in the nature-daring risks of living on active faults or on the slopes of active volcanoes or in the path of hurricanes etc.)

In addition to this somewhat more relaxed mien, tubers will employ different set of architectural solutions in building their homes and settlements [see last issue, pages 7-9 “Settling into a Lavatube”]. They will look out their windows on radically different underworld “moonscapes”. They will tend to establish and preferentially use their own distinct “networks” with other outposts, settlements, industrial parks, farms, resorts, etc. “up” or “down” the line in the same tube, or in intersecting neighboring tubes (in comparison to the mainly overland connections between in-surface outposts).

Tubers, doing all the ordinary things to earn their individual and communal living as settlements elsewhere, will be further boosted in their sense of fulfillment by the very unique to their situation communal “vocation” of “archiving” [see below]. And finally they may feel a certain affinity with settlers in the geologically analogous lavatubes we expect to find on Mars, and elsewhere. All of these strongly distingui-shing characteristics should work to give tubers a sense of special identity and fellowship.

Will they in fact identify themselves as “tubers”, refer to their communities as “tube towns”, and to their collective realm as “Tubedom”? Or will they call themselves lunar netherworlders, or underworlders, or selenospeles, or find some other set of words? That’s up to them.

Surely they will publish their own magazines (<Lunar Tubes & Trails , Lunar Tubeways , Hidden Lavascapes>, or whatever.) These publications will share information about new tube-appropriate architectural and construction methods, about new Lavatube developments and recreations, about the developing culture and arts and crafts of nether-worlders, and promote continued lavatube exploration in adjoining areas, lower levels, and new areas.

**Ever “Remapping” the Moon**

It will be the tubers who keep publishing ever new editions of lunar maps. The surface having been well mapped for a long time, new selenographical discoveries will be predominantly those coming from discovery, surveying, and exploration of new lavatubes, of lavatube extensions and connections, of lover level tubes etc.

Nor will this be information relevant only to scholars. The expansion of the <Terra Habitabilis Cognita> (known habitable [= pre-shielded] land) on the Moon, the identification of natural <metropolitan complexes>, the growing square mile count of known usable tubes reserves — this will all have considerable economic significance.

Special legend maps will be color-coded to indicate the relative density or paucity of the subsurface maze. The latest maps, with their “upwards revisions” of the real expanse of “Terra Habitabilis Cognita”, will be on hand in quantity at space frontier development trade shows on

Earth or elsewhere, to acquaint would be developers, investors, and settlers, with the ever expanding opportunities.

**Lure of the Covered and Hidden**

In the last issue [page 11 "Naming Lavatube Settlements"], we mentioned some of the especially romantic names available from Earth's literature and mythology that would seem specially appropriate. While choosing such names might have a welcome initial moral-boosting effect on the settlers (after a time, a name becomes just a name), the naming of a new or proposed settlement or of its host lavatube, will be a very conscious and deliberate part of "packaging" aimed at prospective new settlers, developers, and investors – in a mostly friendly but ever serious rivalry for the most and the best. After all, any community is a virtual "team", and some teams are quite frankly better and more successful economically than others.

Together, rival lavatube settlements can chose language, phrases, conjure up images etc. that will predispose would-be-settlers to choose one of them over a surface settlement. The safety angle of given all-but-invulnerable shielding ("Realm of the [Inner] Firmament [Down Under]") will be played up. Brochures will invite: "Come to the Moon's Inner Sanctum", "Visit the Inner Worlds of Luna", "Experience the Mystique of the Moon's "Hidden Valleys."

To reinforce the general impression, some developers will specialize, not in settlements per se, but in "Utopia for a Moment" resorts: Lunar Hidden Valley recreations of mythological utopias: Camelot, Shangri-La, Walden, Briggadoon, and so on. Tongue-in-cheek, a legend of lavatube formation, not as relic dry subterranean lava wadis or arroyos, but as "lavaworm holes" will catch the attention of the over imaginative fantasy-loving.

And something too for the all important market segment: the risk-it-all for adventure types. Ads will hype the possibility of finding more than just empty wall-fused vacutoria – of finding special treasure troves of inestimable market value. If we find just one lavatube in which a penetrating-but-not-collapsing comet has vaporized to freeze out as a minable coating of ice on the tube's walls, a new "49er" or "Klondike" rush will be on. And there may be insupportable and unconscionable talk of lavatubes full of gems, or of easy-to-imagine alien-left troves of high techno-logy craft and equipment, etc.

**That Extra, Communal Vocation – "Archiving"**

The primary asset offered by the lavatube environment is "protection – protection with a multibillion year warranty". Any intact lavatube on the Moon has already survived nearly four billion years and will loooong outlast any feature, surface or subsurface on the geologically active Earth.

These are sanctuaries from bombardment – the vast bulk of tube-collapsing impacts occurring in the 500 million year epoch early in Solar System history, when there was still a lot of planet-forming debris to sweep up. Team that up with the "ideal" designer combination of radiation-free, ultraviolet-free, solar flare-free, fixed temperature ultra-dry "lee" (shielded) vacuum. What we have, in great abundance, is a place in which to achieve, store, and preserve humanity's treasures , not just for the current age, not just for millennia, not just for millions of years, but for billions of years to come, for as long as humanity will be able to inhabit the Inner Solar System.

And Beyond. Long after we have vanished from the stage, what we have preserved in lunar lavatube archives will remain a well-preserved, degradation free reliquary for the examination of any other intelligent folk who come our way. Eons-stable lavatubes are the very first place, indeed the only place, any visitors would think to look for preserved ancient relics of a native but now-extinct or just-vanished spacefaring species. Such visitors might indeed be <our own distant progeny>, making a pilgrimage to legendary Earth Space in search of their roots.

The establishment of some Grand Archives of All Humanity in a lunar lavatube site is potentially the greatest gift (after an environmentally rescued and preserved home planet, of course) we can bequeath successor human generations to come. So what might we store and preserve therein.

- Artifacts and Art Treasures and Libraries: Just consider how much has already been lost forever: the Library at Alexandria, the Mayan Codex, the art treasures of Florence ruined by flooding of the Arno, architectural treasures devastated or destroyed by wartime bombing, by earthquakes, by acid rain, etc. And books whose doomed high-acid content pages might have been stabilized in cold, dry, radiation-free vacuum. And films!
- Collections of Biological Specimens. Sperm and Seed and Pathogen Banks
- Collections of Antique Furniture Treasures
- Collections of motor and other Equipment that will never rust or be attacked by corrosives
- Genealogical Files
- Cryogenic storage of bodies, for burial, for future medical science, for future revival

Only a small number of lavatube settlers may be involved in this special industry tailor-made for tube towns. Yet that the lunan lavatube community as a whole serves this special unique added function of inestimable economic impact long term and a vocation of unfathomable cultural, psychological, and spiritual impact, is likely to insert itself in the general communal consciousness at large. It will be a point both of pride, and duly prideful self-identity. In archiving, Lunan lavatube dwellers will serve a need no other pocket of humanity, not even (especially not) any of the bulk of humanity still on Earth!

This Service will quickly become a tradition. It may in time even take on trappings that are quite “sacerdotal” (priestly) in nature. Special technologies will be developed precisely to better preserve, index and catalog, access, and display all of these priceless, timeless treasures. There are sure to be college courses and degree programs (in the various Lunan universities at least) in “Lavatube Archival Science.” **<MMM>**

**More on Lavatubes in this issue**

NOTE: See Tom Billings’ Artemis Data Book™ article on lavatube use which follows below

## Technical Comments on the MMM #100-101 Lavatube Articles

By Bryce Walden, **Oregon Moonbase**

Congratulations to **Moon Miners' Manifesto** on its 101st issue! We have enjoyed every issue, chock full of interesting and provocative ideas on the development of the space frontier.

The Oregon Moonbase team especially appreciates the extensive coverage given to the topic of lavatube caves in Issue #100. Peter Kokh did a lot of work developing the arguments and provided some very nice illustrations of various concepts.

In the interest of completeness, I would like to add a few technical comments as they occur in my reading of the articles.

**Lavatube Stability vs. Human Activity**

In "Twelve Questions About Lunar Lavatubes" Kokh correctly states that caverns that have survived for over 3 billion years are probably very stable. Yet I feel obliged to add the caveat that human activities could at times threaten that safety. A lavatube that has survived may still have suffered trauma that makes certain parts of it weaker, such as a meteorite strike over part of the roof. Sections that survived the relatively minor moonquakes over the millenia may fail if we blast during construction. Also, lava that is strengthened by incorporating super-strong anhydrous glass may weaken over time if exposed to water vapor from atmosphere or other gas-releasing activities. Sealing and pressurizing a lavatube will also introduce new stresses, as he himself mentions in a subsequent article. To mitigate these effects, there are engineering precautions that can be taken on a case-by-case basis.

**Lavatube Temperatures**

The "steady temperature" of -4 °F is based on Apollo temperature measurements that reached equilibrium within several centimeters from the surface and stayed fairly constant from there to as far down as the astronauts could measure, roughly 2-3 meters. Deep mines on Earth get quite hot from heat bleeding away from the mantle; this could happen on the Moon, too, but probably to a much reduced extent due to the relative coldness of the small lunar core. As a rule lavatubes don't have much vertical development but run parallel to the surface. There may be older lavatubes in deeper layers of lava, as his article points out. Once again, the real problem is likely to be human activity. Lavatubes are good insulators. On Earth, cold air can fall into a lavatube in winter and remain below freezing through summer heat. Our case will be just the opposite. Human activity generates a great deal of heat, and the lavatube is a relatively closed environment. For awhile this could be an advantage, and raise lavatube temperatures to comfortable levels, but we are likely sooner rather than later to have to engineer some heat-sink solutions. Changing temperature can also be a source of stress to the cave vault.

**Gross Available Lunar Lavatube Volumes**

In terms of ready volume available now, we did a poster session at the 22nd Lunar and Planetary Sciences Conference that partially addressed this question. Cassandra Coombs, for her doctoral dissertation under Dr. B. Ray Hawke, identified a number of probable lavatube sites from high-resolution Apollo photographs and Lunar Orbiter pictures. Only the largest possible candidates were resolved by these sources. Cheryl Lynn York and I selected the largest 20 of these sites. Making a working assumption of circular caves of width and length identified by Coombs, then half-filled with congealed lava or breakdown, we computed over 3 billion cubic meters of volume, nearly 14 million square meters of "floor" area, or about 0.0531 of Peter's "O'Neill Units" of 100 square miles. The average of these twenty large lavatubes was 470m diameter, length 1,370m, roof thickness 66m, floor area 687,685 $m^2$, and volume 157,908,640m $m^3$. Incidentally, these "Top 20" lavatube caves were located in only four rille formations, with rille "collapse trenches" separating the various caves.

**Lavatube Volumes vs. O'Neill Habitats**

I checked Kokh's 100 square mile "O'Neill Unit" with O'Neill's figures in **The High Frontier**. He claims an Island Three habitat, 20 miles long and 4 miles in diameter, would have 500 square miles of land area. Each of the three "valleys" in the interior would be 20 miles long by 2 miles wide, or 40 square miles. Three of these totals 120 square miles. Total cylinder interior surface area (including windows) is 251 square miles, while endcaps area equals a sphere of radius 2 miles, or 50 square miles. The remaining 199 square miles must be made up by numerous small "agricultural modules" outside of the main habitat, in O'Neill's total design. But for convenience in figuring, 100 square miles is very roughly correct for the popular conception of the "valley" areas in an Island Three habitat.

**Lavatube Remote Mapping**

On "Remote Mapping of Lunar Lavatubes," Tom Billings' paper "Radar Remote Sensing of Lunar Lavatubes from Earth" was published in **the Journal of the British Interplanetary Society**, Vol. 44 pp. 255-256, 1991. A more inclusive treatment of "Lavatube Remote Sensing" was given to a seminar sponsored by the Lunar and Planetary Institute in 1992. In regard to side-looking infrared, the detection of a lavatube temperature signature would, we think, be easier during lunar night, when the exposed surface temperature reaches -240 °F. The comparatively "warm" -4 °F lavatube interior would then be virtually the only "warm spots" on the volcanically inactive Moon. During lunar day, it would probably be harder to differentiate cave interior temperatures from normally shadowed areas on the surface. Such an investigation would have the serendipitous (or even primary) effect of finding any volcanic "hot spots" that may be expressed at the surface (there are indications of a few areas of recent lunar volcanism). Such areas would be mineralo-gically (= resources) interesting.

Kokh's articles about lunar lavatube habitats and environmental manipulation were right on the money. Beside our own work on these topics, including a study performed for Lockheed, another researcher who has given some thought to lunar lavatube habitats is Andrew Daga, <Daga1@aol.com>.

In all some very inclusive articles, "in depth" coverage of lavatubes, as it were, most welcome and well done. Thank you, Peter!

**Bryce Walden**, <BWalden@aol.com> Oregon Moonbase, P.O. Box 86, Oregon City, OR 97045-0007

# Lunar Lavatube Use

By Tom Billings <itsd1@teleport.com>

http://www.asi.org/adb/02/01/lavatube-use.html

The Lunar Base Research Team of the Oregon L-5 Society looked into the possibility of coating lavatube caves in some work they did for Lockheed in 1988-89. Remember that lunar lavatubes probably can be far larger than the (approximately) 25 meter diameter limit here on Earth. In addition, any nonmetallic native coating material can be expected to crack as it cools.

Measurements of collapse trenches believed to be associated with lunar lavatubes indicate diameters of several hundreds of meters. Given this situation, the Team evolved several ways to use lunar lavatubes.

First, it would make sense just to use them as shelter from radiation, temperature changes, dust, etc. for rigid or inflatable habitats brought from Earth. This alone could mean large cost reductions by reducing the "emplacement costs" otherwise necessary for such shelter requirements.

Second, it was noted that lunar glass fibers might be combined with native meteoritic iron-nickel particles to produce larger habitats from resources on the Moon. During the 1980s, Dr. Brandt Goldsworthy showed the possibility of making very strong glass fibers on the Moon. Native meteoritic metal could be refined by the "carbonyl" method, and the metal carbonyls used to produce a thin, tough, airtight metal layer on the inside of a habitat woven from lunar glass fibers. These habitats, inside lavatubes, would increase the available sheltered cubic volume greatly, and do it with cheap native materials.

Finally, if it is required to have an entire town inside one of these very large tubes, with the entire tube sealed, then the meteoritic nickel-iron could be used again. First use the carbonyl process to produce the pure metals in powdered form (micron-sized particles), as is done at Sudbury, Canada in producing much of the Earth's nickel supply. Then, chill the powder with Lunar LOX. Now, put it through a modified (bucketless) mass driver some tens of meters long and shoot it at the walls of the lavatube at a 90-degree impact. With a velocity of about 2-3 kilometers/sec., the powder particles will splatter/self-forge to the wall of the tube, building up a layer of metal that seals all but the smallest cracks. To make sure that no leaks remain, we may now introduce gaseous carbonyls into the tube, and use Laser Chemical Vapor Deposition with a solar powered laser's beam to get a final continuous film producing an airtight seal.

The advantage to these methods is in limiting the amount of molten material that is handled in any bulk, especially in the open, especially around any humans. Either molten metal or molten rock/glass/lava are very corrosive. They require large amounts of energy to produce. In the case of molten aluminum, this means large amounts of electrical energy, which is already a major bottleneck in space operations. Carbonyls are non-corrosive liquids at room temperatures and are reduced to metal and CO at about 200°C at low pressures. The iron and nickel carbonyls require only carbon monoxide gas passed over the native material at 160°C to generate the carbonyl. In the vacuum of space they should be much safer and cheaper to handle. This should allow significant cost reductions to lunar base activities fairly soon after the first outpost is in place, or with sufficient telerobotic preparation, at the first outpost itself. ##

MMM #112 - February 1998

# Brainstorming a Project to Detect Lunar Lavatubes

Workshop Directors: Tom Billings, Bryce Walden
Oregon Moonbase

Ten years ago this May, in the hallways of Denver's Stouffer Hotel during ISDC '88, three space activists got together to launch what would become Lunar Prospector. Now that this mission project has at last become reality, fulfilling a dream, it is time to begin another such effort. Tom Billings and his associates in Oregon L5 have begun an effort to detect possible lunar lavatube entrances in the voluminous photographic data from the DoD's Clementine mission of two years ago. Even more interesting is his suggestion that we could then remotely "x-ray" such candidate sites to detect any actual lavatubes in the vicinity. To do so will require a special combination of Earth based radar and a fleet of small two-part surface-impacting "flash" probes.

The goals of the workshop are to do a preliminary design of the impacting "flash" probe, set its size and mass, and define and design a "mother ship" to carryx a fleet of them to the Moon, launching them one at a time to selected targets. The workshop will also set action points for the search for a Principal Investigator, and universities and contractors to collaborate on the project, and a timetable to advance the project to a point where a bid for a future Discovery class mission opportunity can be made.

The evidence that lunar lavatubes exist is extremely strong, but it is indirect. Until direct confirmation of their existence and whereabouts is made, a campaign to familiarize the public with the enormous opportunities offered us by these "Hidden Valleys of the Moon" would be premature. Positive finds of near surface oases sheltered from the cosmic elements, in a "1-2 punch" combination with Lunar Prospector's hoped for confirmation of lunar polar ice fields, will at last excite the public's imagination.

The public, the media, and sadly many space enthusiasts think that what the Apollo missions found is "all there is" to the Moon. In that light it is understandable that their superficial dismissal of the Moon is the order of the day. "Been there, done that."

You might think that activists could not hope to get something real started.

Well, Lunar Prospector is exciting proof to the contrary. Bring your talents and expertise to the workshop, and let's roll up our sleeves. You can be in on the beginning of Project HavenFerret (working name) <ISDC '98>

## MMM #113 - March 1998

# ISDC 98 Workshop for Lunar Lavatube Detection Mission

**Needs Funds to Make Project Real**

Tom Billings, Workshop & Project Director

[FOLLOWUP on last month's announcement of the Project HavenFerret (temporary name) Workshop at ISDC '98 in Milwaukee, WI May 22-25. 1998. Tom Billings, the workshop director, outlines here the seed funds needed to make the project real.

At stake is supplying the 2nd part of a 1-2 "discovery" punch that will change public perception of the Moon as an unpromising place for a beachhead outpost and eventual settlement.

Punch 1 - Confirmation of Water Ice at the Poles

Punch 2 - Finding sheltered "Hidden Valleys" on the Moon - Lunar lavatubes.]

The work relating to Lunar Return scenarios is progressing on several fronts. Lunar Prospector, started at the 1988 ISDC as a private project is now in orbit around the Moon gathering crucial data on water availability. Water resources may make any Moonbase cheaper.

But there are other contributions to cutting the cost that should be made as firm as those from water. Using lunar lavatubes as lunar base sites is one excellent possibility for further cost reductions.

The Lunar Base Research Team (LBRT) of the Oregon L-5 Society is proceeding with work to locate probable lavatube cave sites using surface indicators in the Clementine data now available on CD-ROM.

The workshop, which is to be held at ISDC '98, will start-up a proposal process for a Discovery-class mission to follow up this work with a means to verify lunar lavatube caverns underneath the lunar surface. The concept uses ground-penetrating-radar in an innovative fashion to achieve lower initial and incremental costs.

==> The workshop will concentrate on bringing together a concept for "radar flashbulbs" that will impact the lunar surface and use the NRAO's Very Long Baseline Array, back on Earth, to receive the reflected signal, which penetrates the lunar surface and reflects from voids underneath it. This signal will be processed as a radar interferometer signal would, to allow images of the lunar lavatubes to be generated at resolutions between 5m and 120m, depending on wavelength of the signal. This resolution should be adeuate to confirm the presence of the sort of large caverns expected from previous work.

The precursor work, the Workshop itself, and the follow-up work to bring the project to realization as a Discovery-class mission proposal will require funds beyond what grass roots space supporters can provide. However, there are already incomplete resources for some of these, and good hope for others.

We ask your support in reaching the point where these other resources can be attracted for the full range of activity required.

The following three steps in the project are:

1 C**omplete specific needs of the workshop precursor Clementine Data Search project:**

| | |
|---|---|
| | •Sun SparcStations running Solaris 2.0 donated by Tri-Met and by Mitron Corp. |
| | •JARtool software for searching the Clementine database donated by Jet Propulsion Lab. |
| | •Research computer floor space and security donated by Lewis & Clark College |
| | •2000 man hours for image evaluation work donated by LBRT volunteer members |
| | •6X CD-Rom Drives compatible with Sun |
| $1,300 | •SparcStations running Solaris 2.0 |
| | •88 CD-ROM disks with the Clementine |
| 800 | •Probe's raw data |
| $2,180 | •Subtotal required |

**2 Arrangements for the workshop at the 1998 ISDC, including:**

| | |
|---|---|
| $ 250 | •Graphics, worksheets, etc. for 20 participants - Printing cost |
| 1,200 | •Travel to ISDC for 3 presenters |
| 500 | •Demonstrator models at the workshop itself |
| 400 | •Printing of Workshop's result for publicity |
| 000 | •travel for one presenter courtesy ISDC '98 |
| $2,350 | •Subtotal required forWorkshop |

**3 Activity to get the project ready for acceptance as a Discovery mission:**

| | |
|---|---|
| | •Academic Team Formation-600 manhours donated by Workshop par!ticipants |
| $2,000 | •Education about project and the Society's role in promoting it |
| 500 | •Networks on websites to exploit the results to accomplish lunar bases |
| $2,500 | •Subtotal required for workshop |
| $4,530 | •Combined Subtotal required |
| 2,500 | •education, exploitation of workshop results |
| **$7,080** | **• Grand Total Required** |

We would like to find all of these funds. Any part of them would be very helpful, and very much appreciated. If there are any questions about the proposal, please do not hesitate to e-mail me. If you wish to phone, then evening after 6 pm during Pacific Time Zone hours is best, at (503) 232-1788.

Thank You,

Tom Billings – istd1@teleport.com
"Oregon L-5 Society" (payable to)
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MMM #124 – April 1999

# Searching for Ready-Made Lunar Bases

Allen G. Taylor, Clementine Project Leader
Oregon L5 Society – agt@transport.com

In December of 1972, Gene Cernan lifted one foot, then the other, off the lunar regolith as he ascended the ladder into the Lunar Module. That was the last human contact with the Moon. Now, 26 years later, we are no closer to sending people back there than we were in 1961, when President Kennedy startled the world by setting the goal of sending a man to the Moon and returning him safely to Earth.

Sending humans to the Moon and returning them safely to Earth is still an extraordinarily expensive endeavor. It hardly seems a worthwhile thing to do, if the lunar explorers can only spend a few hours there, before their supplies start to run low, and they must return to Earth. In order for humans to play a useful role on the Moon, they must be able to stay for an extended period of time. To do that, they must have a place where they are protected from extremes of heat and cold, solar storms, micro-meteorites, impact ejecta, and cosmic rays. That kind of protection requires mass and low thermal conductivity.

Transporting an adequate shelter from Earth would add a major fraction to the expense of just getting there. The best place to locate a lunar base is underground. The best way to excavate such a base is not to excavate one at all, but rather to use a cave that is already there.

There **are** caves on the Moon – "lava tubes." Early in its history, the Moon was very active volcanically. Lava flowed freely on the surface, forming tubes that roofed over and have waited several billion years for us to arrive and use them. The roofs of some of those tubes have collapsed, forming the rilles, some of which can be seen through telescopes on Earth.

Sections of tube have remained uncollapsed, inviting us to come and take up residence. The lava tubes that are visible to Earth-based telescopes might be too large to provide good candidates for lunar bases. Such lava tubes of large diameter need a great depth of overlying rock to keep from collapsing. Any intact large tubes would lie inconveniently far underground. Most useful would be lava tubes too small to be discerned from Earth.

The Clementine spacecraft, which mapped the entire surface of the Moon to an unprecedented level of detail in 1994, gives us a view of these smaller lava tubes. Over 1.9 million images in the visible, near infrared, and mid-infrared portions of the spectrum were captured.

The Oregon L5 Society has undertaken the task of finding and cataloging the small lava tubes in the Clementine dataset. Of particular interest are small sinuous rilles that contain interruptions which represent uncollapsed portions of a tube that has partially collapsed. Once cataloged, the candidate base locations can be examined more closely for suitability.

Considerations would be proximity to resources, sites of scientific interest, or favorable locations for siting of a railgun satellite launcher. Clementine captured images of the lunar surface in several spectral bands, spanning the visible, near infrared and long wavelength infrared. Collapsed lava tubes show up well in the visible part of the spectrum, given that the sun angle is suitable. Of the 1.9 million images taken, 620,000 were high resolution images in the visible spectral band. Manual examination of even a significant fraction of those images is far too time-consuming to be feasible. Some form of automated search is the only practical way to thoroughly analyze such a large number of images in a reasonable time.

Lunar rilles are inherently difficult to characterize, making it difficult to teach a computer how to find them. Such geological features do not have a common form, or a characteristic diameter or length. Due to differences in topography, some have numerous sharp bends, while others are quite straight. Some appear in clusters, while others seem to be isolated from other rilles. These considerations make an automated search a difficult technical challenge.

A similar, but smaller scale problem was faced by researchers at the California Institute of Technology and the Jet Propulsion Laboratory in searching the Magellan radar dataset for small volcanoes on the surface of Venus. An adaptive recognition tool named JARTool was developed for the purpose of automated analysis of large datasets, and the Magellan dataset was used to test the effectiveness of the tool at recognizing target features, and rejecting features that might resemble the target features but that are not of the class.

The CIT/JPL team, led by M.C. Burl used JARTool to find volcanoes in 30,000 Magellan radar images that contain some 1 million small volcanoes. His team developed an algorithm that proved to be effective at identifying volcanoes, based on a series of training images containing volcanoes identified by geologists, that were presented to the JARTool before it was tasked with identifying volcanoes in the remaining images.

Our effort has adapted JARTool to identify sinuous rilles in the Clementine images of the lunar surface, particularly those with interruptions or gaps in the rille. We assume that such gaps represent uncollapsed segments of lava tubes. The goal of our project is to produce a catalog of uncollapsed lava tubes on the Moon. Researchers can then search the catalog for a wide variety of research purposes, including finding the best candidates for lunar bases, based on proximity to lunar resources, or areas of scientific interest.

JARTool was written on Sun workstations running the Solaris operating system. Mitron Corp. donated several surplus Sun Classics to our project, and Sun has given much needed technical support. This let us to get the project off the ground.

Now however, progress is seriously hampered by the slow performance of the obsolete Sun Classics. An up-to-date Sun processor would make a major difference in our ability to locate and characterize promising lunar base sites. Recently Sun has reduced the prices of its UltraSPARC 5 and
UltraSPARC 10 processors. A new UltraSPARC 5 will cost $2400. Such a machine would improve our progress by at least an order of magnitude. We are currently seeking ways to fund the acquisition of an UltraSPARC 5 to move our project forward.

If you have any ideas on how we might make such an acquisition please contact me at agt@transport.com. <AGT>

## ORL5's Lunar Lavatube Locator Project

An Appeal from the MMM Editor & LRS

MMM solicited this article because we have supported the Lunar Lavatube Locator project from the start – Taylor's work constitutes Phase I of this project. LRS / ISDC '98 underwrote the presence at last year's ISDC in Milwaukee of Tom Billings who is working on Phase II, designing a "flash-bulb probe" that would be able to illuminate any subsurface voids (i.e. lava tubes) in the area of impact to a wide-based net of radar installations on Earth. Taylor's work, Phase I, described above, is necessary to find appropriate promising targets for Billings' probes.

Pinpointing individual lavatubes on the Moon and mapping their extent, even if only partially, would form the 2nd part of a 1-2 punch ¶with Lunar Prospector's discovery of water ice reserves at the pole. Such a mission would add enormously to the crescendo of reawakened interest in the Moon in the wake of Lunar Prospector.

If we are to return, and pick the most propitious sites (plural – one site does not make a global presence on the Moon real), the Lunar Lavatube Locator Project is a must.

If a permanent human presence on the Moon, with resource using industrial settlements is a high priority for you, please reach into your pockets and cut a check to help the Oregon L5 Society purchase the new UltraSPARC 5. - PK

"Oregon L5 Society"

Clementine Project, P.O. Box 86, Oregon City, OR 97045

## MMM #130 - November 1999

# Of COASTS, HARBORS, & LIGHTHOUSES and, oh yes, LAVATUBES

By Peter Kokh

To build a bridge one must have knowledge,
To know where to build it one must have wisdom. -Charles V. De Vet

The difficult we do immediately.
The impossible takes a little longer. - Army Corps of Engineers

**Lavatubes as "leeward lagoons"**

When early exploring ships reached the coasts of the Americas and of Australia, they didn't put into shore just anywhere. They turned either right or left and sailed along the coast looking for a natural harbor that would shield their anchored ships from the wind and waves.

Before the first Apollo craft landed, our Lunar Orbiters had already found only cosmic storm washed coast-surface. The Lunar surface is alien and hostile and unwelcoming.

Today we know that this picture is not quite accurate. While the lunar surface is all "windward coast," it hides lavatubes that are "leeward" lagoons, "breakwater-protected" volumes of vacuum ready to serve as safe harbors, anchorages offering real refuge from the dangers of the cosmic ocean.

**A natural Harbor along an otherwise unwelcoming coastline offers wind and wave free anchorage.**
**Lunar Lavatubes offer analogous leeward shelter against the ravages of cosmic and solar weather.**

**Breakwater Outposts**

Lavatubes are unlikely to offer dock slips to incoming space craft. Rather they offer volume that is thermally moderate, relatively free of moondust, and unexposed to Solar ultraviolet and Solar flares, "dry" from the constant micrometeorite rain, and free from cosmic rays. This is useful for settlement expansion, including industrial parks, warehousing, and square-footage intensive geoponic agriculture for crops that do not do their best in hydroponics.

In these benign pre-shielded spaces, two things become much easier.

- **With no need for extra shielding**, inflatables, hybrid-rigid inflatables and unhardened rigid modules will all be at home, less expensive option in comparison with what will be needed o\n the exposed surface-coast. The lavatube roof/ceiling becomes a protective ramada or hanger for everything below.
- **SImple pressure suits will do.** Similarly, personnel occupied with tasks outside the habitat/ lab and other structures within the lavatube need only unhardened pressure suits: lighter, easier to carry, and easier to work in.

But these user-friendly weather-free lagoons of the void out top, will not be the exclusive locations for lunar outposts. Some areas of the Moon rich in resources we will want to tap, are not handy to mare lavatubes. In such parts, there will be no ready alternative to digging in and covering up. But even in lavatube-endowed locations, there will be a need for a surface outpost and transfer station for goods and people on the surface near the lavatube entrance.

**Entryside Service Installations: Division of Labor**

Near the entry point to our lavatube main site, we will need a surface "interface" facility. A "construction camp" to prepare the rampway into the lavatube, or install an elevator if what we have is a "skylight" entrance. The surface post would then be the initial construction camp for deployment and construction within the lavatube.

**Surface Facilities**

As and if the demand for construction support winds down, a surface installation will still be needed to process visitors and goods, as a transportation mode transfer point and as a base for surface field work and expeditions. In addition, surface-shielded facilities will be needed at a spaceport location and as inns and service centers along major surface intersettlement transportation routes. While surface installations may outnumber occupied lavatubes, given that construction is simpler and easier within a lavatube environment, it is likely that overtime, perhaps a majority of Lunans will live in adopted lavatubes.

Ink-black Lavatubes can be sunlit via fiber-optic bundles connecting surface solar concentrators with in-tube light diffusion systems. For further reading on the possibilities, see MMM # 100 and 101, NOV & DEC, 1996, both online at www.asi.org/mmm/.

**Lighthouses**

On Earth we put lighthouses in two types of coastal locations: (1) on major headlands and peninsulas; ((2) at the entrances to major harbors. There does not seem to be an analogous situation to the former use, only for the latter. It would be a good idea to have a lunar version of a lighthouse at the entrance of a lavatube in any stage of occupation or adaptation for human purposes.

Even if Oregon L5"s Lunar Lavatube Locator mission succeeds in jumping through all the hoops and over all the hurdles, it will have performed well if it maps even a small fraction of the Moon's population of intact and partially intact lavatubes. We will be discovering new ones, perhaps for generations. We might well put transponders near each identified entrance. But not all tubes will have open entrances. Nor are they navigational hazards, either for surface vehicles or spacecraft. <PK>

**MMM #132 - February 2000**

# Collapsed Lavatube Make-Overs

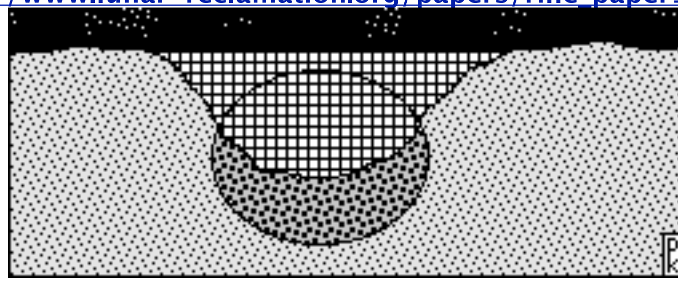
## Recreating Shelter Space inside Rille Valleys

By Peter Kokh

We've talked a lot about the use of lavatubes with their ready made shelter from both the harsh cosmic elements and the harsh surface conditions of extreme temperature swings and insidious moondust. But what about "ex-lavatubes", the collapsed lavatubes whose ceilings were evidently too thin or too weak to stand the test of time? Are these no more than fascinating, scenic, geological ruins? After all, some areas may have rilles but no handy intact Lavatube sections? And even if a site offers both, as is likely, can anything useful be done with rilles?

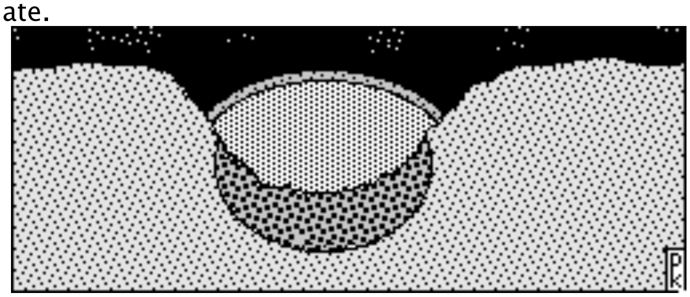
We got our first and only up close look at a sinuous rille valley when the Apollo 15 crew visited Hadley Rille at the foot of the northern Apennine Mts. which form the SE ramparts of Mare Imbrium and separate that great "sea" from Mare Serenitatis. Hadley is about 150 km SE of the rim of the prominent 75 km wide crater Archimedes. The rille itself is about 135 km [c. 85 mi] long and 1-2 km wide from rim to rim [1,000-2,000 meters or yards]. The small section actually visited was 370 m [c. 1200 ft] deep. We can assume this as typical, with rilles that are both narrower and shallower, and wider and deeper. These dimensions give us a fairly accurate way of reconstructing the size of the original tube.

**The whole report referred to at right is online at:**
**http://www.lunar-reclamation.org/papers/rille_paper1.htm**



In the illustration above, the current cross-section profile of the surviving rille is cross-checked. The oval represents the size and location of the original tube. The cross-checked area above the lavatube ceiling has collapsed onto the lavatube floor and is represented by the heavily checked area below the current rille floor.

If the mission plan for the chosen site calls for the establishment of a sizable surface shelter, any rille valleys within the site boundaries should be seen as substantial pre-excavated areas that need only be spanned with regolith covered arched roof spans to provide the same protection from the cosmic elements as did the once intact lavatube. A plate-covered space frame arch, extending from one wall to the other, partly down both slopes, could then easily be blanketed with regolith by dragging material down on top of the arch from the rille shoulders above. The arch could be of any length, with an original section extended in either or both directions at a later date.



In the illustration above, a strong, lightweight arch of space frame construction (lunar glass composites) spans the rille valley from one wall to the other, and has been covered with 4-6 meters of loose regolith using drag lines to pull loose material down from the rille shoulders above. The lightly shaded area below, represents the space, still vacuum, that is now in the lee of the cosmic elements: cosmic rays, solar flares, and the micrometeorite rain that still washes the exposed space above the blanketed arch. The floor of the protected space lays above the rubble of the collapsed ceiling of the old lavatube.

**Previous Treatment of the Concept**

During the winter of 1988-89, in response to NSS' Space Habitat Design Competition, an eight person team used the idea of spanning a rille valley as the keystone of the Lunar Reclamation Society's second place entry in the category: advanced lunar base for 1,000-5,000 people. We were looking far into the future, as the competition guidelines asked, and designed a pressurized two-tiered arched shelter. We published a serialized report under the title "Ventures of the Rille People" in MMM "s 26, 27, 28, 29, 31`, and 32. [Reedited, reillustrated and republished in MMM Classics #s 3 and 4]

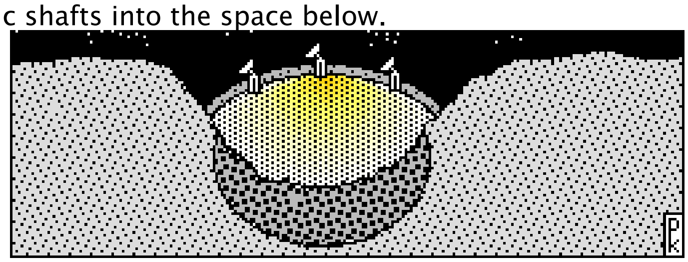
Here we are taking a more modest, near term look at the possible utility of rille valleys and are proposing a simple shielding arch, open at both ends, providing shielding but not pressurization. What we get from this is a spacious calm, lee space anchorage, ideal volume for the erection of a modular base or outpost complex of either hard shell or inflatable shell modules or both, that will not need further protection. Such a protected site, within which construction workers and others need only wear simple unhardened pressure suits, is very attractive.

This idea is similar to the concept of a hanger shed outpost such as we described in MMM # 89 )CT '95, p. 3 "Shelter on the Moon" [text only at: http:// www.asi.org/ adb/ 06/09/03/02/089/shelter.html] In comparison, rille valley structures would be both larger and easier to cover with shielding moondust.

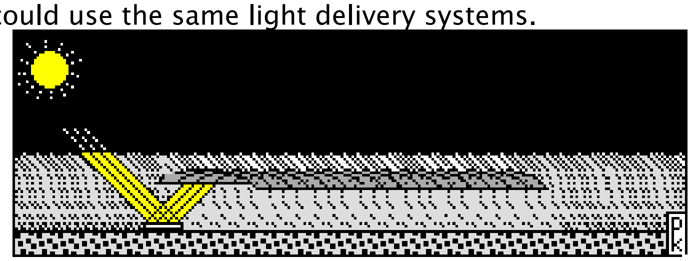
**Improving the Lee Space Underneath**

While the space underneath such shielding arch-hanger would be environmentally benign in comparison to the exposed lunar surface, without further modification, it would be pitch black even during lunar dayspan. There are a number of ways to channel diffused ambient sunlight to the sheltered space below, making it much more attractive.

Banks of sun-following mirrors on top of the vault shield could channel concentrated sunlight via fiber optic shafts into the space below.



Similar banks on the rille valley floor, fore and aft of the hanger area, could bounce channeled sunlight off the underside of the vault for diffuse ambient lighting. During nightspan, large electric lamps could use the same light delivery systems.



The result would be a benign, construction-friendly, softly lit environment with moderate temperatures. The cost of constructing a vault shield can be balanced against the costs of excavation and unit by unit shielding of alternative surface methods.

That undertaking such an effort implies the establishment of a prior glass composites building materials industry can only be seen as a welcome foundation for an eventually much more diverse lunar industrialization. The time to take such a committing plunge is at the outset. Delay in crossing the industrial threshold only extends the period of vulnerability to program cancellation.

**Future Upgrades**

The initial vault shield can be extended up and down the rille as the outpost-settlement complex grows underneath. "IF" care is taken to secure cables crisscrossed over the top of the structure to bedrock deep into the rille walls, the ends could be closed and the volume within pressurized.

Sinuous rilles are to be found in mare areas around the Moon, in the same haunts as suspected lavatubes, their surviving sibling features. Why did some tubes collapse? Thin, relatively weak ceilings could easily have been compromised by modest meteorite bombardment. But the rilles' very large size leads this writer to suspect that they may be the ruins of unusually large lavatubes forming from unusually wide and rapid flows of lava, leading to ceilings too thin in proportion to the width spanned. If so, it suggests that most surviving intact tubes will be somewhat smaller in cross-section. For whatever the reason or reasons, these features are there. We might take advantage of some of them, preserving the rest for scenic and geological enjoyment. <MMM>

# "Skylight Domes" for Lavatube Towns & Vaulted Rilleplexes

Like so many "mushrooms" sprouting from underground fungal mats, floral gardens, arboreta, picnic park areas, and restaurants could grace domes capping elevator shafts from below.

By Peter Kokh, with thanks to Uffe Jon Plug at uffe@ploug.dk for his suggestion

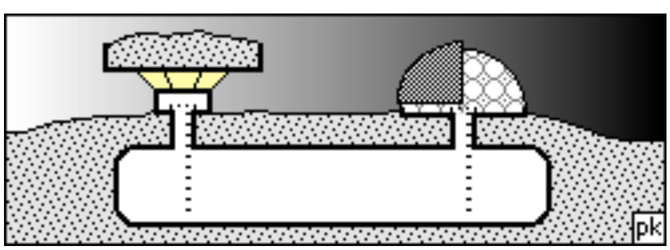
We have talked several times about solar and visual access for Lunan pioneers who must live under a blanket of moondust to enjoy the same protection from the cosmic elements that we Terrans take for granted from our blanket of air. Periscopic windows, fiber optic shafts for sunlight are one thing for habitats immediately (2-4 meters) below the surface. But what about providing solar and visual access for those living much deeper below within lavatubes or under rille-spanning regolith covered vaults?

There will be elevator access for both goods and people as a matter of course. So why not add a few more elevators, at intervals, that open up on the surface within pressurized domes, more generously flooded with sunlight and affording expansive views of the surface. Cosmic ray shielding afforded by such domes would be minimal, so no one could live there, or even habitually frequent such delightful places.

What about operating personnel - gardeners, restaurant waiters, and others? What might work is for each exposed surface facility to be "sistered" with several other places offering similar employment down in the lavatube or under the rille shield. For example a surface restaurant could be part of a chain, the others all being in fully shielded surroundings. Waiters and other personnel would then take turns - for example working one day a week up above, and even that on a volunteer basis. That way, accumulated exposure could be managed. But even then, one would want to limit the years spent in such a pattern.

Even if one visited such surface facilities on the same frequency that city dwellers on Earth may go to the local arboretum or a botanical gardens or to a tower top special occasion restaurant, just having such places to go to would relieve the psychological pressures of living below surface.

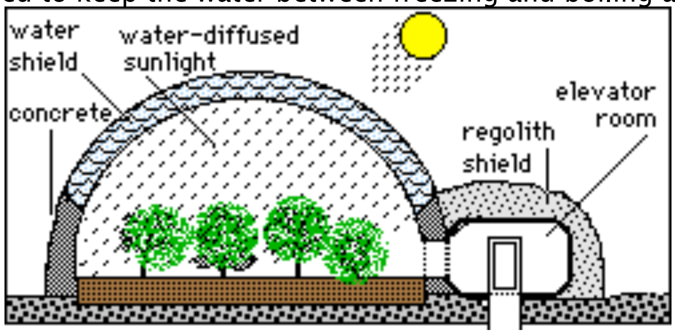
As glass is much stronger under compression than tension, geodesic domes will have convex panes, curved inwards, to help manage the considerable forces of pressurization. If the facility serves mainly as an observation area, it could be built more like an airport control tower than a dome. a row of windows with panes sloping outwards at the top could be covered with a generously shielded roof with wide eaves. This would reduce exposure to cosmic radiation to the few degrees hugging the horizon. A movable shield could protect windows facing the sun when it was near the horizon, as on the day of dawn or the day of sunset or very near to the poles.




On the right, a glass dome, with a rotating half shield facing the Sun. On the left, a top-shielded observation tower, reminiscent of an airport control tower. Exposure to radiation coming from all directions of the sky is minimized by the shielded top cap. The base of the tower could have a pedestrian EVA airlock.

Non-public areas in which personnel spent any appreciable percentage of their time might be fully shielded: the kitchen or the access area to the dumbwaiter if food is prepared and dishes washed below; bathrooms, utility rooms.

The ultimate would be a dome within a dome, with the space between filled with 2 meters of water. The “hydro-dome” would provide soft filtered glare-reduced ambient light and considerable radiation protection. The “devil lies in the details” of all the plumbing and water circulation tricks needed to keep the water between freezing and boiling at all times.




Such “escape valve” facilities must complement, not replace, more conventional ways to channel abundant dayspan sunlight, via mirrored shafts or fiber optic cable bundles, into the general habitat areas, to provide warm ambient light, accent-focus light, or both. Access to sunlight should be provided not just on special occasions, but as a matter of course. Yet lush surface dome gardens, picnic spots, and moonscape observation perches can provide more special treats. Lunans, and Martians as well, will have given up very much to earn a chance to pioneer new worlds. Every effort must be made to keep them as comfortable as possible and their lives as full as possible, and to minimize the sense of loss of Earth’s incomparable outdoors.

<MMM>

## MMM # 134 - April 2000

### Lava Tubes: the “Developers Role”

By Peter Kokh

In MMM #131, DEC, 1999, pp. 10-12, we considered the “Developer’s Role” in “improving” a potential Moonbase-settlement site to make it more attractive and marketable to would-be entrepreneurs. In this issue, we want to take up the topic again with specific application to lava tube sites, something the first article touched on briefly.

> “Another joint venture would be to provide improved access (graded ramps and elevators) to any buildable lavatubes in the area. Shafts drilled through the lavatube ceiling/ roof filled with fiber optic cables, with sun collector on top and light defuser within the lavatube, would be an immensely attractive improvement, as would be a lavatube floor topographic map. No enterprise will buy space within a lavatube, no matter how many theoretical advantages it offers, without solid concrete information, and prepared access and minimal lighting.”

Here we want to expand upon these points. In MMM #100 NOV ‘96, page 6, we wrote about remote mapping methods, with radar “flashbulb” impacting probes to detect subsurface voids and side-looking orbiting infrared detectors to spot exposed lavatube entrances. In the next article, pp. 6-7, we wrote about on site robotic exploration and surveying techniques.

A surface crawling drilling rig, using high resolution orbital radar lavatube location data, finds its initial drill point over an indicated tube site. Given the repetitive nature of the tasks involved, a highly automated remote monitored operation will be ideal. It would:

(1) Drill and stabilize (a sleeve? side-wall fusing lasers?) a hole through the surface, penetrating the lavatube ceiling some tens of meters down. The hole might be only a few inches in diameter.

(2) Winch down through the shaft a radar-mapping instrument and/or CCD optical camera down to a height midway between lavatube ceiling and floor (determining that position is

task one). A flare is released. The radar mapper and camera pan 360°, and from near vertical up (zenith) to near vertical down (nadir). The instrument pod is retrieved. A latitude/longitude/altitude benchmark is then lowered to the tube floor directly below.

(3) Winch down to the same point a length of fiber optic cable, securing the top end to the collar of the shaft hole below a solar concentrator passively gathering available dayspan sunshine, channeling it into the optic fiber cable. At the bottom end a diffuser scatters this light, so future explorers can find their way with night-vision goggles.

The drilling rig would then move on to the next position along the lavatube, guided by the data from the previous drill as to direction and distance to provide a continuous overlapping mapping. Now both the internal topography maps produced and the minimal light shafts produced in this effort can be considered an improvement. This would enable future manned science expeditions but only tease would be users. What can be done to really "improve" the site?

- Enlarge and multiply the number of light shafts to provide significant "naked eye" lighting
- Feasibility and cost analysis of various ways to provide a high albedo "sky" within the lavatube for maximum eye relief and ambient lighting, e.g. with direct coatings or suspended grids.
- Providing a graded vehicle-worthy ramp down an entrance talus slope, if there is one.
- Providing a surface supported elevator shaft through the tube ceiling/roof, the cage lowerable to the floor by cable winches (no guide structure within the tube). The cage should be of freight capacity able to lower vehicles and modules.
- Topographical maps of the floor with suggested grading using minimal (5-10%), moderate (15-30%) and major (above 40%) shifting of existing floor debris, and making use of "benches" and other features that may or may not be present. This would include recommended floor "road" corridors in each case. It would also locate recommended locations in each case for placement of modules and structures of various sizes.
- An engineering test of the ceiling at intervals to find its capacity to support suspended weight
- A minimal line of sight communications relay system, built into the "benchmarks" mentioned above using antenna when the benchmark is in a low spot, or into the light diffuser system.

Some of these "improvements" would entail nontrivial investment in the site, especially the freight elevator. A developer might be able to market the site on the basis of the less expensive of the suggested improvements in the site, along with a contractual commitment to provide the rest upon receipt of good faith money/down payment by the proposed customer. These further improvements might include minimal floor grading to provide a continuous travel corridor through-out the length of the tube, further grading up to the user.

Lavatubes offer immense volumes safe from surface temperature extremes, sheltered from radiation and other hazards of cosmic weather, and relatively dust free. That said, they are raw assets that require basic "improvements" to be useful. ##

## MMM #169 - October 2003

## Mail For MMM

**"Sealing a Lavatube"**

9/17/03, pioneer137@yahoo.com (David Dietzler) writes:

“Whenever I think about lava tubes I imagine space-suited workers on scaffolding slapping plaster or cement on the walls. My own stupidity amazes me at tim-es. After sealing the opening, we should just send a wheeled robot in there that sprays the cement or plaster all over the porous walls, if the walls are very porous to begin with. Then all we have to do is condense the water vapor if it doesn't freeze out in there. A few robots the size of pickup trucks is all we'd need. Then we just pressurize the tube, go inside and start stacking bricks, pouring concrete, wiring, plumbing, etc. and build the Lunar Hilton.

All we have to do is find a nice lava tube.”

Editor’s response:

I understand it, the rock around the lavatube is likely to be fractured. Cement or plaster may help, but would probably freeze before it could bond.

I wonder if spraying with steam or water vapor wouldn't be the only thing we'd need to do. The water vapor would find its way into the cracks and freeze, sealing them in the process. Tube temperature is likely to be no more than 80 Kelvins, pretty cold. To me, sealing and pressurizing a lavatube is an advanced, farther future, endeavor.

Yet spraying the dark tube walls with concrete or a lime whitewash would definitely brighten the tube and make it possible for less lighting to do more. Near term I would:

**Phase I**

1) Grade the entrance for ease of entry and exit
2) Knock down any loose debris, preemptively
3) Grade a roadway through any rubble on the floor
4) Erect space frame platforms above the rough areas
5) Deck same
6) Deploy insulated inflatable structures and pressurized passageways between them. The advantage would protection from both cosmic radiation and micrometeorite impacts without having to cover the structures, directly or indirectly, with enough loose regolith soil to provide such protection. Plus plenty of room to expand.

**Phase II**

7) drill holes through the ceiling to run optic fiber bundles through, and using surface sunlight reflectors, condense sunlight about 36:1 to dump through the fiber optics to a diffuser just below the ceiling. LOTS of these. Someday maybe light blue glass diffuser panels suspended below the ceiling fiber optic inlets to create the illusion of a backlit light blue sky. A hard trick to pull off right away.
8) After testing, attach rows of rock bolts to the ceiling for suspended lighting tracks, platforms, overhead crane.
9) make an opening large enough for a freight elevator (passenger too while we are at it)

**Challenges**

√ achieving a thermal balance. Activity generates heat, but without lot's of insulation, we may need supplemental heating. Habitat heat leaks will slowly raise the internal temperature. Not sure where the balance point will be.

√ achieving comfort and ambiance. Sky blue ceiling & sunlight will help. The tube will have a slight downward gradient. So a central pressurized passageway could support a recirculating stream, intermittent waterfalls and fountains, fish, water plants, etc.

At this stage of the game, until we do a lot more (none yet!!) exploring of actual tubes and engineering tests on site, schemes of pressurizing lavatubes are where terra-forming schemes still are: “garbage in, garbage out.” I.e., nice to think about, no small stunt to pull off, no grounds for can-do confidence that we understand how to go about it, what will work, or won't, what will help, or hurt, etc.

Nifty topic, however. Great subject for artists.

## MMM #172 –

# Lavatubes

## By Blacklight Fantasy Excursions

By Peter Kokh

In the previous article, we spoke of blacklight-lit fantasy out-vac surface gardens on the Moon's Farside where truly dark nightspan conditions exist. Yet despite the glaring presence of the Earth in the Nearside night-span skies, there is opportunity galore for this kind of fantasy lit fantasy gardening on Nearside as well, within lavatubes open for public excursions and tours. It is not impossible that without the addition of anything artificial or human-altered, just with blacklight, lavatube surfaces may include spots and streaks that shine brilliantly in blacklight. We won't know that until we go there.

We can test if that is the case in terrestrial lava tubes. Our friends in Oregon L5 who have spent so many hours in a pair of lavatubes outside Bend, Oregon may have already thought of this and tried it. In the summer of 1992, with Oregon Moonbase team members Bryce Walden and Cheryl York as my hosts and guides, I had the chance to explore these tubes, much to my delight and fascination. I was amazed by the diversity of texture in the walls and ceilings of the tubes, testimony to the varying temperatures and viscosities of the flowing hot lava that formed them thousands of years ago. It had not occurred to me to bring along a black-light flashlight.

**Preparing preexplored Lavatubes for Blacklight Excursions**

If the surfaces of lunar lavatubes prove to be sensitive to blacklight, a host of practical questions remain before installation of a blacklight system can become a technically and financially feasible project. The tubes are vast in size and a lot of power, lamps, and wiring would be needed. For "dayspan-only" tours, power could come from solar collectors on the surface. This site could operated by a commercial concession in a prime tourist traffic area. We are talking about an era well into the future when there will be a substantial resident population and industrial infrastructure in place and when tourist excursions from Earth are popular and affordable. But even if none of us live to see that day, the possibilities can excite us and motivate us.

The blacklit lavatube could include fantasy forests and sculptures, all glowingly and beautifully revealed by blacklight. There are no limits, and like many tourist facilities, the manmade features of this site would likely grow as profits from tourists were plowed back into the investment. Why not an Earthside enterprise analog? </MMM>

NOTE: for more on fluorescence in rocks, visit: Tozour Family's Fluorescent Rocks Links and Updates Page - http://mywebpages.comcast.net/jtozour/links/links.html

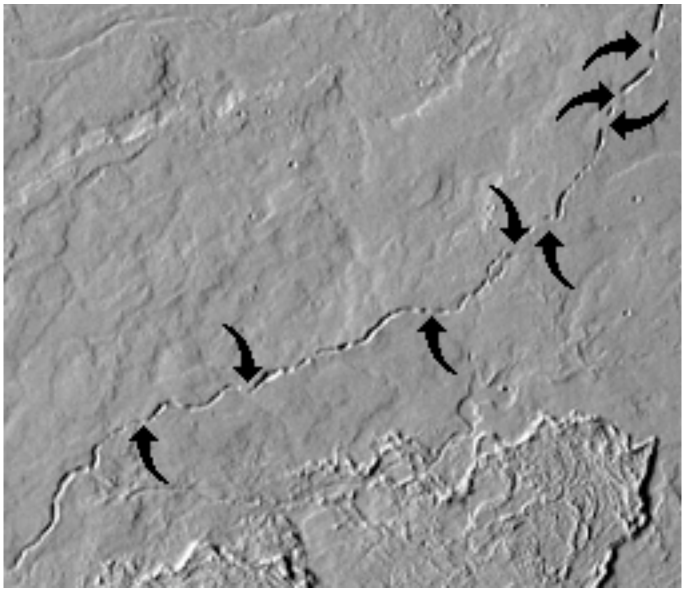
**MMMM #198 -**

## Eureka! Mars Lavatubes

From Bryce Walden <moonbase@comcast.net>

To: <orl5rt@yahoogroups.com> August 19, 2006

Check out this THEMIS "Image of the Day" for 2006 August 18, "Tharsis Lava Flows". There's a long, long interrupted sinuous rille running SW to NE in the top half of the long vertical image. The TIFF file would be best for study, if you can afford the 4 MB download. It's only barely visible in the "thumbnail" image on this page; download choices for the larger image are at the bottom of the page. http://themis.asu.edu/zoom-20060817a



Crop of original TIFF file by Editor = **Arrows** indicating uncollapsed sections added by Editor.

**Editor's Comment:** Uncollapsed sections of should-be-continuous rilles are at present our only real evidence that lavatubes exist on the Moon and Mars. The Oregon L5 Society's Tom Billings has been working on a concept dubbed the "Radar Flashbulb" that would illuminate and map intact whole lavatubes that geologists expect to abound in the maria, lava sheet flows on the Moon, Mars, and possibly the dwarf planet Vesta in the asteroid belt. Lavatubes are natural features formed in the process of lava flows spreading out from their point of origin and are commonly found in lava flows on Earth and also in the gentle slopes of shield volcanoes such as Mauna Loa and Mauna Kea on the Big Island of Hawaii and elsewhere.

A workshop to advance the Radar Flashbulb concept was held at ISDC 1998 in Milwaukee. Financing to advance the project further has been the stumbling block. A preview of the project is outlined in the second section of this online paper:

www.lunar-reclamation.org/papers/lavatubes_ccc.htm

"Remote Mapping of Lunar Lavatubes: Teleo-Spelunking on the Moon"

A more complete explanation was published in MMM # 115, May, 1998, p. 14. "A Radar Flashbulb on the Moon" by Tom Billings. This article has been reprinted in MMM Classics #12, in pdf format, freely downloadable at:

www.moonsociety.org/publications/mmm_classics/

also download the following:

www.lpi.usra.edu/meetings/moon98/pdf/6049.pdf

www.lpi.usra.edu/meetings/robomars/pdf/6062.pdf

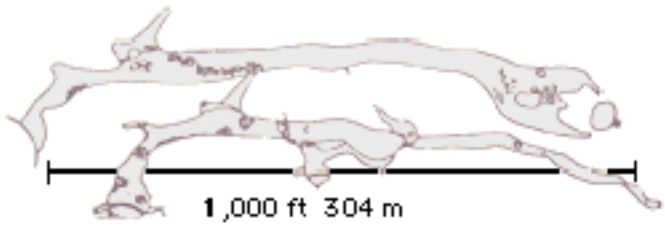
**MMM #201 - December 2006**

## Usefulness of Terrestrial Lavatubes in a Lunar Analog Research Station Program

By Peter Kokh

In August 1992, I had the wonderful experience of a personal guided tour of the pair of lava tube caves outside Bend, Oregon that the Oregon L5 Society was using for outpost simulation purposes. My guides were Bryce Walden and Cheryl Lynn York of Oregon L5.

Oregon Moonbase Photo taken during a simulation. The PVC tube frame would be covered with a tarp to serve as a makeshift base for students. The cave floor is flat due to the invasion of volcanic ash from the explosive eruption of Mt. Mazama 4,800 BC that formed the jewel known as Crater Lake, 85 miles to the WSW of Bend.




**Above:** Young's Cave complex outside Bend, OR.

Above: Young's Cave complex outside Bend, OR.

Lavatubes on Earth are much smaller in scale than those on the Moon, probably in some inverse relationship to gravity. The widest portion of the Young's Cave complex is 79 ft., the greatest ceiling clearance 26 ft. but these dimensions are uncommon. Because of their much smaller scale, they are hardly simulation stand-ins for those on the Moon. But we can put them to some use. And, on July 20, 1989, NASA granted the Oregon chapter $25,000 to do a thorough site characterization.

The Geological survey was done by Stephen L. Gillett, a consulting geologist now in Carson City, Nevada with U-NV-Reno. Century West Engineering of Bend did the engineering analysis. A series of 5 borings, in roomy locations specified by Oregon L5, showed the roof to be generally from 10 to 20 feet thick with 7-19 ft of hard basalt overlain by 0-3 ft of loose soil. Except for a few transverse cooling cracks, the ceiling is relatively intact and rock quality analysis shows the roof could support from 2-60 tons suspended weight per linear foot, depending on varying roof thickness and the presence presence or absence of fractures. For this, a system of rock bolts will do. In weak areas, roof-shoring supports are advised. Some 6000-7500 cubic yards of sand forms a floor 0-6 ft thick. This could be removed, if desired, by vacuuming. Rock debris could also be removed, if desired, by backhoe or by hoists through openings made in the roof, thereafter available for installation of equipment.

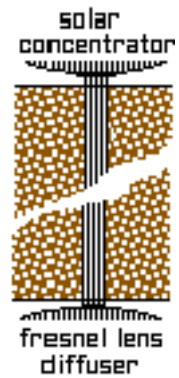
But creating such openings whether by blasting, jackhammer, or rocksaw would be a major undertaking.

The variations of surface terrain was also surveyed. The estimated cost of preparing the site as a major lunar analog facility as outlined by the Oregon Moonbase team was over $6 million

1990 dollars. The Phase II grant never came. Eventually, the chapter decided to let the renewable 5-year lease on the facility expire.

But on the basis of what we learned about this pair of lavatubes during the study, we think that this facility, if we could regain access, or a similar tube elsewhere, could support unique simulation exercises. If the main moonbase facility was up on the surface nearby and only limited simulations done in the lavatube, the cost could be significantly lower, with a very modest initial presence expanded on a pay-as-you-go basis.

The five 60 mm (2 3/8") bore holes through the tube roof-ceiling could be used to drop in miniaturized survey equipment designed to demonstrate how we can robotically map the interior of lunar lava tubes, profiling their complex shapes and cross-sections. These tests finished, the bore holes could be filled with fiber optic bundles to let in sunlight concentrated up to thirty times. One bore hole could be used for communications access.




A small Habitat complex could be put together out of small inflatable units or of EZ assemble-disassemble semi-prefab structures. At such a facility, where, within the lavatube, lighting would be totally controllable, we could more easily simulate the lunar dayspan/nightspan cycle. We could examine ways of dealing with the two week long nightspan that would let a crew remain productive throughout. We would try to determine how little power we could get by on and still be productive, concentrating on repairs, maintenance, inventory,and other power-light, manpower-intensive tasks, so as to better use the 15 days of dayspan solar power available to store up power to tap after lunar sundown.

**Activities Ideal For Dayspan (abundant power available)**

- **Energy-intensive activities**
  - construction
  - soil moving
  - materials processing
  - manufacturing
  - power storage

**Activities Ideal For Nightspan (reduced power available)**

- **Energy-light activities**
  - routine equipment maintenance
  - equipment overhauling
  - inventory & warehouse work
  - energy-light product finishing
  - packaging
  - design work
  - bulk of free time, long weekends
  - arts & crafts
  - extra time in the gardens

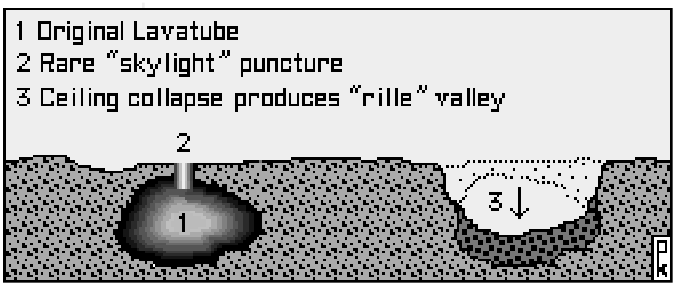
Meanwhile, a nearby surface conventional outpost complex would investigate and demonstrate other things: teleoperations; in situ resource utilization; shielding options; and many more lines of investigation. While it would be ideal for the companion analog surface outpost to be very close to the lavatube entrance, a separation of a few miles should not hinder operations. Crew would go from one to the other in a "pressurized vehicle." This allows room for latitude if it is not possible to have both outpost components closely collocated.

If the access to the Bend, Oregon site can't be recovered, we might do something similar at lavatube locations at Craters of the Moon National Park, ID; El Mapasis National Monument, NM; or Snow Canyon State Park, UT. The advantage of Bend is that the lavatube complex there is well known and studied, and familiar to a number of Moon Society members. <MSJ>

## MMM #231 – December 2009

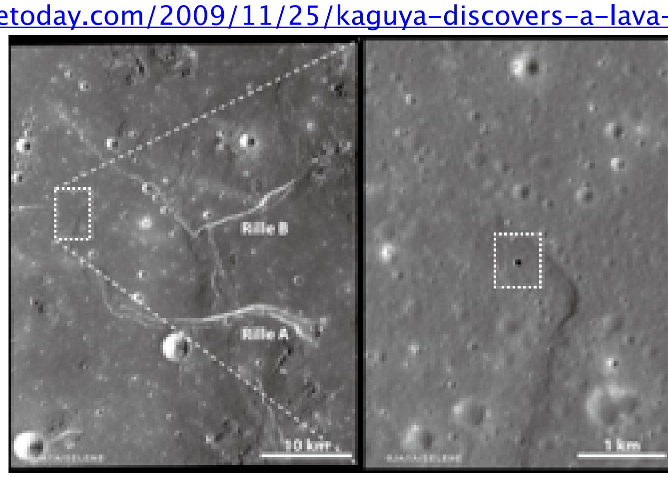
# First Lavatube "Skylight" Discovered

Ever since Apollo 15's visit to Hadley Rille, the Moon'a numerous winding valleys, dubbed "rilles", have been interpreted as collapsed lavatubes of surprising size. For Lunar advocates, the Moon's "Hidden Valleys" promise thousands of linear miles of readymade shelter for settlements, industrial parks, warehousing, and more. But most people continue to see the Moon as no more than a dusty "rubble pile." With Kaguya's recent discovery, that perception will hopefully change.




**Size of the Lavatube whose "Skylight" was discovered by Japan's Kaguya orbiter?**

http://www.universetoday.com/2009/11/25/kaguya-discovers-a-lava-tube-on-the-moon/




**"The hole is 65m [213ft.] in diameter"**

"Haruyama's team observed the hole nine separate times, at various illumination angles, and even when the sun was almost directly overhead it looked mostly black, suggesting that it is very deep. They calculate a depth of around 88m [289 ft.], so the hole is deeper than it is wide." [ **Location:** 13.36°N / 56.27°W ]

"Their calculations based on the multiple images of the hole show that the tube could be 370m [1215ft] accross."

[**Editor:** this is very much in keeping with expectations and back-of-the-envelope calculations based on the size of Hadley Rille (Apollo 15) and of other sinuous rilles that are now interpreted as collapsed lunar lavatubes. That they are so much bigger in scale than well-known terrestrial tube would seem to be an inverse relation to gravity. The lighter the gravity on a world, the larger naturally forming lavatubes might be. Thus tubes on Mars should be of an intermediate scale.]

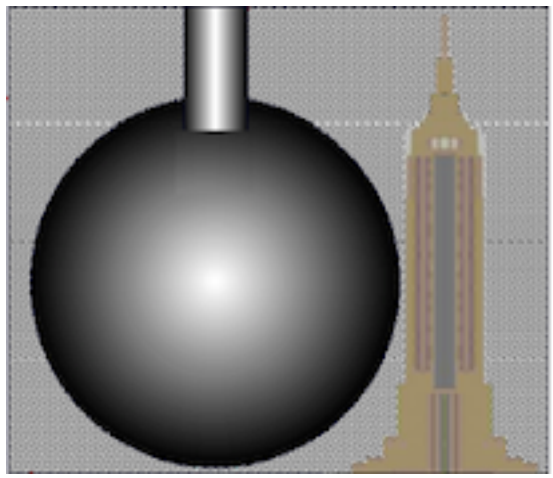


Illustration © MMM - the Empire State Building to scale

[**Editor:** Space enthusiasts have long speculated on the major role lavatubes could play on the Moon. Now with Kaguya's discovery of an actual lavatube "skylight," the vision of the Moon's "Hidden Valleys" is receiving long-overdue public attention.] **MMM**

## Lunar Analog Stations Without "Moonlike" Terrain

By Peter Kokh

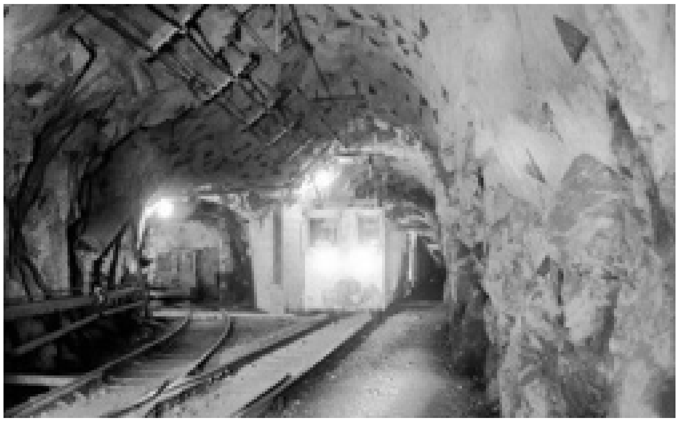
Not every organization that would like to start its own lunar analog research station program, is going to be able to find an ideal "vegetation-free picturesque desert" location, especially one located to minimize the logistics costs of frequent visits and support. In such a case, what are the options?

**Situation:** You want to do analog research on activities at a Moonbase that would we confined to the outpost complex interiors. And/or research that would be applicable to an outpost constructed within a Lunar lavatube but do not have access to a terrestrial lavatube. Most lavatubes within the United States are protected from any kind of alteration, and only temporary access might be granted.

**You have in mind experiments with**

- **Life support systems; experimental agriculture** under lunar dayspan/nightspan sunlight availability constrictions; you want to experiment with operations scheduling that tries to reserve energy-intensive chores for the two weeks of abundant lunar sunshine; with energy-light, manpower-intensive chores preferentially put off until the two-week long nightspan period: sunlight unavailable.
- **Architectures for a lunar settlement** that is free to grow in length but constricted in width.
- **Robot explorer teams** that map the "tube/gallery" and report to a surface command station

As a stand in for a terrestrial lavatube, you might look for abandoned mine galleries that are above the water table and thus dry. Below is a photo of an abandoned copper mine in northern Chile.)



MMM #240 – November 210

# From Lava Tube Skylights To Lava Tube Settlements

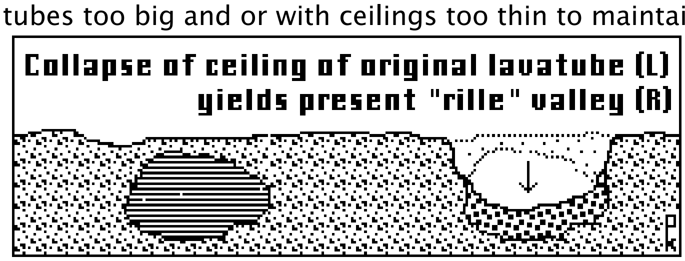
By Peter Kokh

**Where we're at**

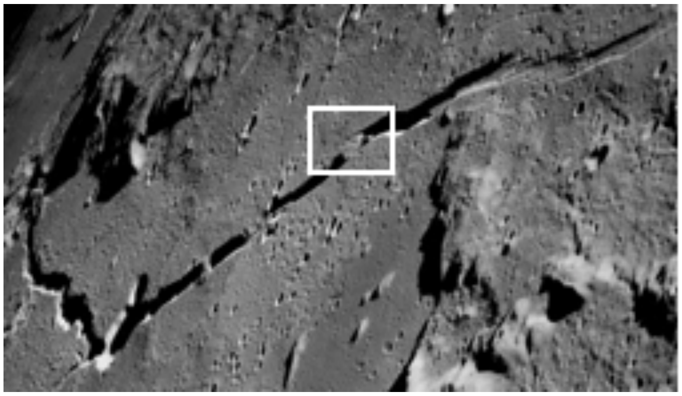
Chuck Woods (Lunar Photo of the Day, creator of http://the-moon.wikispaces.com) keeps track of all confirmed lunar lavatube skylights. To date (10.26.2010) there are 5 such sites, the first 2 found by Japan's Kaguya lunar orbiter, the last 3 by Lunar Reconnaissance orbiter. It takes very high-resolution photography to confirm such a feature, and LRO has found ten more dark spots around the lunar globe that need to be revisited with higher-res photography before they can be added to the list. Chuck suspects many more will be confirmed.

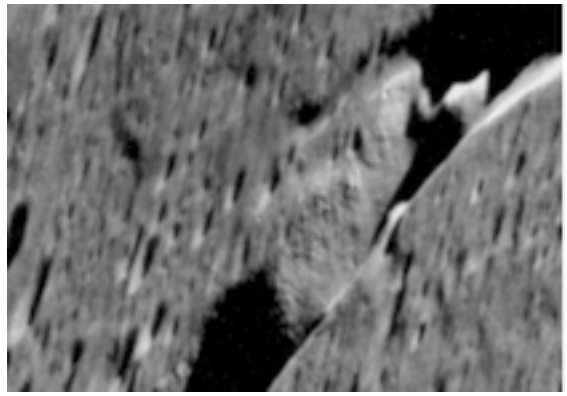
All of these locations are in lave flows, which spread by rivers of lava that soon crust over and as the lava flows out, create lava tubes. So we are finding these features in the lunar maria, frozen "seas" of lava. As the maria occupy 39 of nearside, and only a much smaller part of farside, we expect to find many more of these features on the nearside.

They are formed when a chance meteorite of sufficient size happens to hit right over a hidden tube, causing the tube ceiling to collapse. The reason we have been confident for decades that lunar lava tube networks pervade the mare areas, is twofold: that's the way lava sheets spread on Earth; and on the Moon we find many "sinuous rilles" for which the most logical explanation, given the basaltic nature of the terrain, is that they are the remnants of collapsed lava tubes: tubes too big and or with ceilings too thin to maintain their integrity.




This argument is strengthened by the existence of long sinuous rilles that are "interrupted" by gaps miles long, interpreted as intact segments of the original tube.



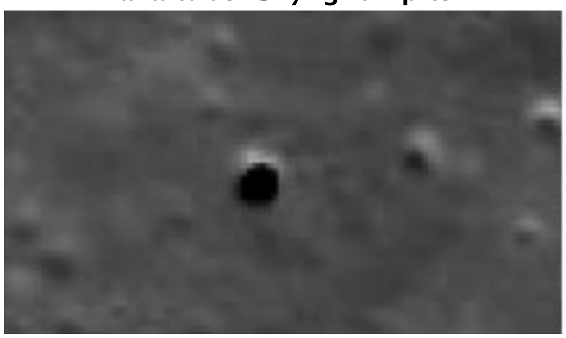


**Left:** Starting at the bend to the left, 4 "bridges" are visible in this Apollo 10 photo of Hyginus Rille, central nearside. A very high-res 4.4 mb image of the above is at:

http://spaceflight.nasa.gov/gallery/images/apollo/apollo10/hires/as10-31-4650.jpg

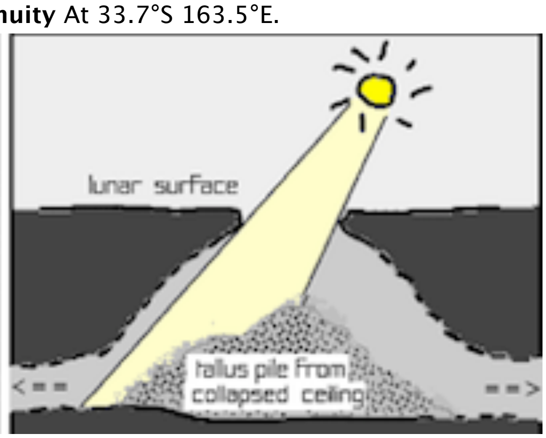
**Right:** the area centered on the "bridge" interruption furthest right.

**Lava tube "Skylight" "pits"**



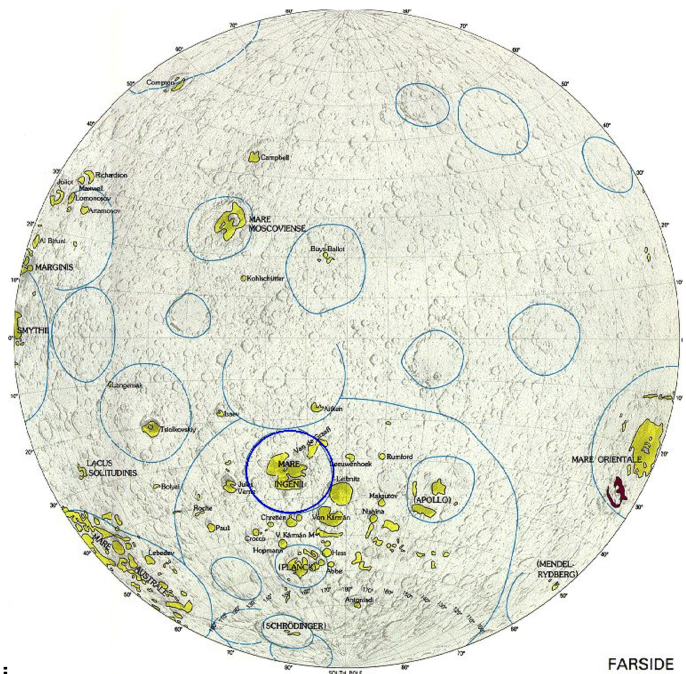
The first discovered, by a camera aboard JAXA's Kaguya (Selene) Orbiter is in the Marius Hills region of Oceanus Procellarum (Ocean of Storms) in an area known to have not only lava flows but also volcanoes.

**The Skylight found in Mare Ingenii, Sea of Ingenuity** At 33.7°S 163.5°E.




**Right Above:** Discovered by the LRO team, this skylight pit is the first such feature discovered on the the Moon's farside. In this superb high resolution photo, what we are seeing lit by sunlight, is not the lavatube floor, but the tallus rubble pile from the collapsed lavatube ceiling.

**Above Left:** This sketch, enhanced by to show the talus collapse pile, shows how these pit photos are to be interpreted. This webpage, maintained and updated by Chuck Wood, gives the current inventory of confirmed skylight pits. **http://the-moon.wikispaces.com/Skylights**




**Location of Mare Ingenii**

**Three skylights found by LRO in M. Tranquilitatis** Yes, in the very mare in which humans first set foot on the Moon in the Apollo 11 mission July, 1961. The location of the first of the three found by Lunar Reconnaissance Orbiter is approximately 2° SE of the Sinas Crater and some 230 mi (380 k) to the Northeast of the Apollo site. This skylight has been unofficially named 'Sinas" by Danny Caes.

**Looking Forward**

All those captivated by the implications of these recent discoveries look forward to the positive identifica-tion of more lunar lavatube skylights. Meanwhile, we must not deduce that these skylights mark the Moon's only lavatubes! These are lavatubes that, from a human point of view, won the cosmic lottery by being impacted just right to cause a local collapse. It would be more realistic to believe that we will find lavatube networks wherever there are lava plains. There may be hundreds, if not thousands of these features.

**What's next – lunar lava tube skylight probes**

The Moon Society is working on a design competition, which will be previewed at the **SEDS SpaceVision 2010** Conference at the University of Illinois Champaign-Urbana the weekend of November 5-7, 2010.

One design competition will be about modifying NASA's AXEL experimental rover (Google NASA AXEL for information and videos) which can winch itself down a crater rim, explore and then winch itself back. For our purposes, we need a much longer lighter weight cable, as well as some instruments that do not need sunlight to map and explore.

We will have a complementary competition for designs of probes that can enter the skylight and return data by means other than a cable and winch.

We are doing this in the hopes that NASA will consider fielding such a probe on both Moon and Mars. At stake is our need to modify public perception of both worlds as **dusty boulder-strewn rubble piles** to worlds with extensive networks of fascinating "**Hidden Valleys**" – the pre-shielded lava tubes ready for industrial parks, agriculture, warehousing, sports arenas, and archiving!

And, oh yes, lava tube Settlements!

## Lavatubes: the possibilities

Please do check our earlier 1995 paper: "The Use of Lunar Lavatubes" – 2 parts [http://www.moonsociety.org/publications/mmm_papers/lavatubes_ccc.htm](http://www.moonsociety.org/publications/mmm_papers/lavatubes_ccc.htm)

A favorite vision for many members who were with us during the Artemis Society days (1995-2000) was that of settlements inside pressurized lavatubes. But this does not appear to be a near-term option for 2 reasons:

1. **Breathable atmosphere is 80% Nitrogen** – at 1 ATM – Earth-normal pressure. Of all the volatile elements most needed for biosphere purposes (Hydrogen, Carbon, and Nitrogen), Nitrogen if by far the

least abundant in proportion to the amount needed. In the near term this will mean low ceilings and few pressurized “open spaces.” One thing we can do to alleviate this somewhat is to try to make do with 0.5 ATM pressure, with all the hit (reduction) taken by Nitrogen, keeping the Oxygen partial pressure normal. Some point to disadvantages of this solution. But on the pro side, by simply reducing the partial pressure of nitrogen, the same tonnage of nitrogen will let us provide 2.73 times as much pressurized volume. For an article on this point, see pages 21-24, MMM Classic #16, a PDF file that you can download without username or password from **www.moonsociety.org/publications/mmm_classics/**

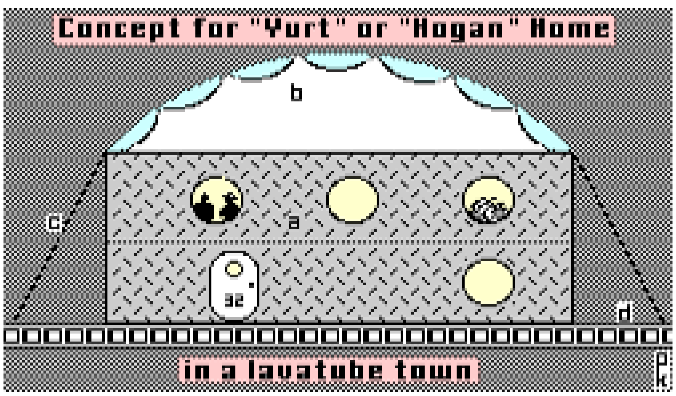
2. **Lavatube walls and surrounding basalt is most likely fractured.** If air moisture gets into these fractures and goes through repeated freeze-thaw cycles as the temperature inside the tube fluctuates, material is likely to spallate, break off and fall. We can probably deal with this on the lower walls, but spalla-tion from the upper walls and tube ceiling could be a problem. So why not seal the walls? **Sealing a lavatube will not be easy.** Most suitable sealants involve scarce volatile elements. And they will be expensive for the pioneers to pruduce and use.

We are not saying “never,” we are saying not in the near term. Our best bet and most practical nearer term option is to put pressurized structures inside the unpressurized lava tube. These “buildings” need not be shielded, unless we choose to do so for insurance against material breaking off the tube ceiling.”

We should keep in mind that the most urgent need for pre-shielded space will be for industries and industrial parks, for protected warehousing, and maybe for extensive soil-farming. None of these uses will need the visual delight that would be provided by pressurizing the whole tube rather than the functional volumes inside. Residential areas can be more compact, but eventually we will move them into protected lavatube networks as well.

**Brainstorming an early lavatube town**

http://www.moonsociety.org/publications/mmm_papers/lavatubes_ccc2.htm

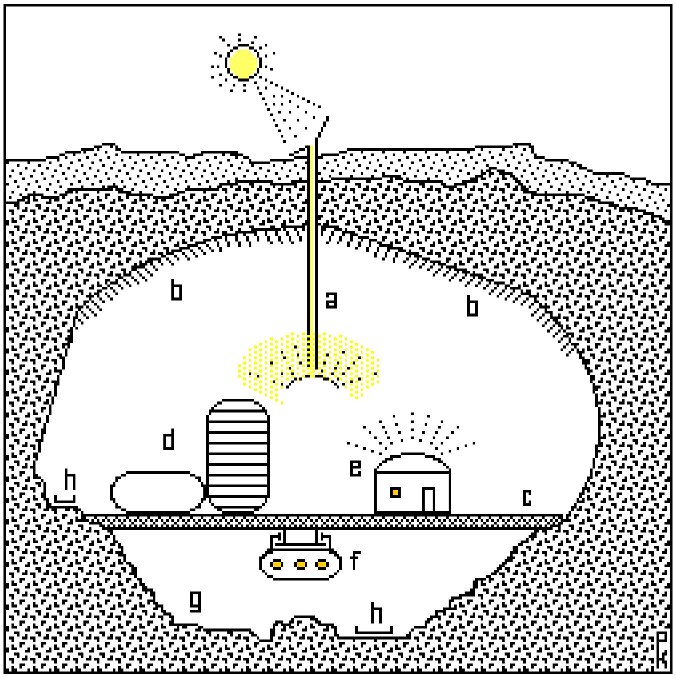



Concept for a lavatube single family home

KEY: (a) 2-story vertical cylinder section, bedrooms on the lower level; (b) lunar translation of the geodesic dome for a high translucent ceiling vault over the family room and other common areas including a central garden atrium; glass panes are neither flat nor concave, but convex; (c) cable stays prevent internal pressure from literally "blowing off the roof"; (d) the residential deck of the townsite, leaving the tube floor ungraded.

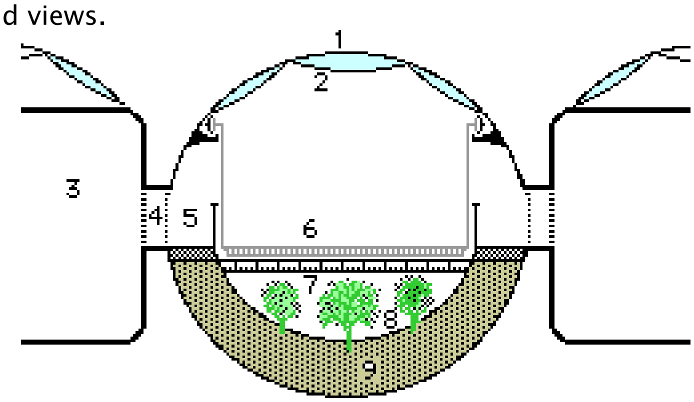
**NOTE:** upscaled, the yurt/hogan design will make a fine church, synagogue, or meditation chapel, with the simple use of stained glass convex panes in the roof dome. A dedicated shaft of directed sunshine on such a dome would surely help set the mood.

**A variety of structures inside a lavatube**




KEY: (a) sunshine access and defuser system; (b) white-washed "firmament" for best sunlight reflection; (c) "town deck" on tube-spanning beams; (d) assorted structures; (e) "yurt/ hogan" type home with translucent dome to flood interior with firma-ment-reflected sunshine; (f) monorail transit system; (g) lavatube floor left natural; (h) nature walks.

The early lavatube settlement will not be an assembly of individually pressurized buildings, but rather, like the in-surface burrowings, a maze of structures conjoined by pressurized walkways, streets, alleys, and parkways. In the netherspaces, roadway cylinders can be generously paned with convex windows to flood their interiors with ambient reflected and diffused sunshine and views.




**Fast forward to a can-do future:**

Some maria experienced multiple episodes of lava sheet flooding. **The walls of lower level lavatubes may be less fractured, and more easily pressurized.**

We did a thorough Google Images search for “lavatube settlements” and found nothing. There are sketches, from the pre-internet era, which apparently have not been posted online. However, our lunar lavatube cross sections are pretty much the same ballpark, size-wise, with cross-sections of Stanford Torus type space settlements. Two illustrations below to whet your appetite:


If you find some suitable sketches, color artwork or just black and white line drawings, please send them to us, electronically at kokhmmm@aol.com or by mail to:
Moon Miners' Manifesto, c/o Peter Kokh, 1630 N. 32nd Street, Milwaukee WI 53208-2040

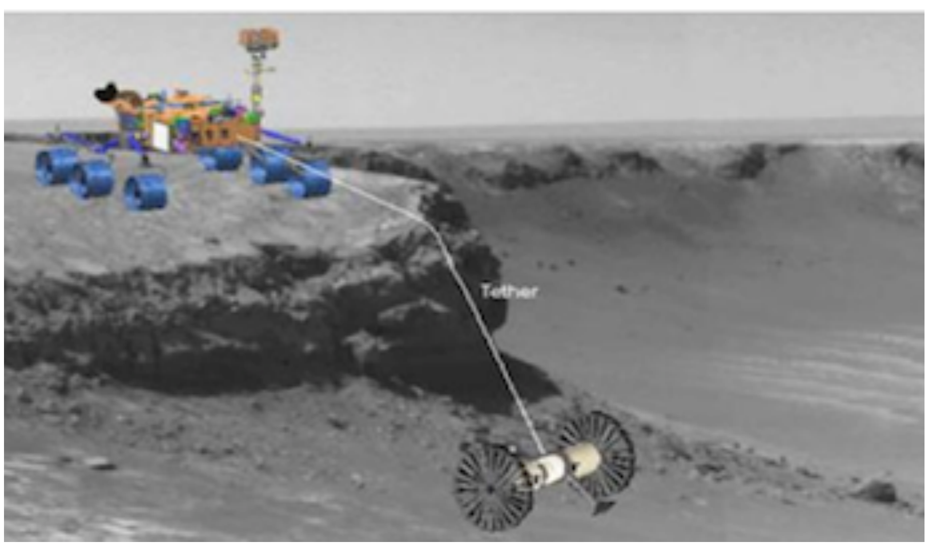
We need more appropriate artwork to enthuse the public at large about the possibilities that the confirmation of lavatube networks on Moon and Mars imply.

In the coming months, Moon Miners' Manifesto, and/or The Moon Society, may announce an art competition with several categories and attractive prizes. In the meantime, we look forward to additional confirmations of lava tube skylights on both Moon and Mars. We also hope for great entries to our AXEL-type probe design contest as well as for a wide open contest for practical lave tube skylight probes that NASA or other national space agencies may pick up, and build and fly.

To young people in the future, the possibilities of life on the lunar frontier will seem that much more interesting. There is more to the Moon than "magnificent desolation!" The Moon, and Mars too, have extensive and spacious protected Hidden Valleys that will one day be home to thousands, tens of thousands, and more pioneers. Keep the faith! **PK**

**MMM #241 - December 201**

## Our Lavatube Skylight Explorer Engineering Concept Competition




NASA-JPL's "AXEL" winches itself down into a crater
Next, one that can descend into a lava tube Skylight?

By Peter Kokh

When I first saw the image JPL AXEL probe, I knew right away that this was a concept that might be adapted to probe into the several lavatube "skylights" we have been finding on both Moon and Mars these past few years! There would have to be design changes and adaptations. The cable, in order to allow the probe to winch itself down some hundreds of meters into a lavatube skylight, not just down a few meters into a small and shallow crater, would have to be lighter weight, thinner, and stronger so as not to increase the AXEL-probe's weight. And it would have to carry data, sending back measurements and readings taken to the rover anchored above on the skylight rim, should the probe not be able to winch itself back up to the surface.

The winch has to be on the probe, not on the surface rover, to avoid the cable rubbing and possibly fraying on the skylight's rugged edge. And quite a bit is at stake. In the public mind, both the Moon and Mars are barren, dusty rubble-strewn worlds with no "safe harbors." Such a modified probe could send back data providing glimpses of the vast underground sheltered spaces that exist on both worlds, ready to house acre-hungry industries, warehouses, farms, archives and settlements, - that both worlds had extensive, safe, and friendly "**Hidden Valleys.**" This might change public perceptions to the point that the idea of human exploratory expeditions and even permanent outposts, would receive much more support. And we all know that public indifference is the core problem we face.

The weekend of November 5-7, Moon Society Director of Project Development David A. Dunlop and I drove down to the University of Illinois' campus at Champagne-Urbana to take in the annual **SpaceVision** conference of the **S**tudents for the **E**xploration and **D**evelopment of **S**pace - **SEDS**. NSS was on hand as well. We had a chance to present our idea of a Lavatube Skylight Explorer Engineering Concept Competition to a room full of students and the reception was terrific.

You can download our PowerPoint presentation from

www.moonsociety.org/competitions/engineering/

The Moon Society, the Lunar Reclamation Society, and the National Space Society have each pledged $500 in prize money towards this project, and we hope to bring other sponsors and co-sponsors online as well. As we have to time this with the fixed academic school year, we expect to have the competition rules and constraints ready by the spring to allow faculty to line up what support they need, aiming at demonstrations and prize awards in the following spring of 2012. This seems a long time to wait, but we want results that will catch NASA's interest, encouraging them to fly this mission! ●

**MMM #261 - December 2012**

## (lava)Tubers and (lava)Tubophobes

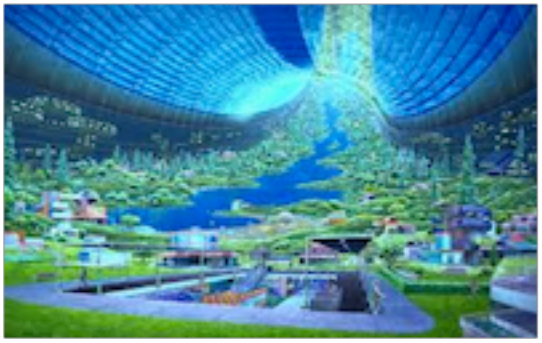
By Peter Kokh

Here on Earth we have people who live on a farm and wouldn't dream of living anywhere else. The same holds true for those who live in small crossroads towns, in downtowns of major cities, or in their suburbs. Ditto for some who live inland rather than along Great Lake or Ocean coasts, or in the hills or mountains as opposed to the plains. Likewise for those who live in high-rise apartments or condos and those who live in single homes, each on its own lot. Yet perhaps most people can adapt to anywhere so long as they have a job.

Some space enthusiasts dream of living in a space settlement island rather than on a surface of a planet or Moon, floating free in the void. Others, described by the latter as "planetary chauvinists" prefer a planetary surface with natural scenery rather than fake zoo-type mini-mountains. Count me as one of those planetary chauvinists!

Many Moon and Mars enthusiasts foresee life inside a large spacious pressurized lavatube as the ideal. Paradoxically, that dream may be realized on Mars before it is practical on the Moon, for the simple reason that Martian tubes are smaller, thus taking less to pressurize them, as well as the much sooner availability of the needed buffer gas Nitrogen on Mars in comparison to the Moon.

While pressurizing a lavatube to create an Earth Like Eden down under is a gargantuan undertaking, building modular settlements within a lavatube, with the same kind of construction we will use on the surface, minus the shielding overburden – the thick ceiling-roof of the lavatube supplies that function – is a relatively near term option. Certainly, lavatubes are ideal where extensive acreage is needed e.g. for warehousing, industrial complexes, and agriculture.



Artist's view of the inside of a Stanford Torus or Island II type Space Settlement. "Unroll" this scene, and you have the kind of settlement inside a lunar or Martian Lavatube that many would-be "tubers" envision. Such a dream may be realized someday, but it is not realistic in the near term on the Lunar or Martian frontier.

But it is a mistake to believe that all lunar and Martian settlers will check (√) a lavatube town as first preference. After all, while "tubers" will not have the burden of "shielding" their living and working spaces, and thus the architecture of the homes and other buildings in a tube settlement will be much more visible, and have much more attention given to them. But tubers will pay a penalty, almost as stiff as those who live in space settlements. The will not be able to look up and see the heavens (at least not spinning by once a minute!), nor the "magnificently desolate" Moonscapes or Marsscapes.

Now for some lifelong city dwellers, where nighttime light pollution has gotten to such an advanced stage that many never get to see more than the Moon, Jupiter, Mars, Saturn and a few dozen of the brightest stars, that might not be a big loss. But for those raised in the countryside, or who have split their time between the country and the city (as myself), giving up the nighttime sky, and the beautiful rural landscapes, will be much too much to bear. We need the beauty of nature, both as expressed in planetary surfaces and in the heavens as soul food.

I myself could visit, but never live in either a space settlement or a lavatube. I prefer living on the shores of space – such as places on Earth with natural scenery, not designed by landscape architects (or zoo architects) and be able to look up, at least now and then, and be sucked up into the star-spangled heavens.

It takes all kinds of people to make a world, and all kinds of places too.

Lavatube settlements will come, and urban undergrounds such as PATH in Toronto and RESO in Montreal, give some idea of what they may feel like. I'll settle for these previews and take a pass on the real thing. But by all means, those of you who want to shrink the universe to the confines of a "spacious" lunar lavatube, be my guest.

**Links:**

**Toronto PATH:** http://en.wikipedia.org/wiki/PATH_(Toronto)

Google images "Toronto PATH"

**Montreal RESO:** http://en.wikipedia.org/wiki/Underground_City,_Montreal

Google images "underground city Montreal"

**For Previous MMM articles on Lunar Lavatubes**, read the online report:

http://www.moonsociety.org/publications/mmm_papers/lavatubes_ccc.htm

**Or check out** http://www.moonsociety.org/publications/mmm_themes/**mmmt_construction.pdf** **PK**

# Lavatubes on Mercury
# Could we put an Outpost on Mercury? If so, why would we?

By Peter Kokh

**For previous articles on Mercury, check out our Solar System Theme issue:**
http://www.moonsociety.org/publications/mmm_themes/**mmmt_solarsystem.pdf**

**Mercury is significantly closer to the Sun:**

- as a result, its surface temperature range is much higher
- a trip from Earth's surface to Mercury's surface takes more energy than to reach any other planet surface

**The Mercury Slingshot:**

So why would we want to go there? By the same token, a solar power satellite of given size in orbit around Mercury would produce 4.6x as much power as it would in Earth orbit when Mercury was furthest from the Sun and 10.6 as much power when Mercury was closet to the sun. That power could be used to **decelerate arriving space ships and accelerate departing ships**, more than neutralizing the disadvantage of Mercury being deeper down the Sun's gravity well. Such assistance could make Mercury the Grand Central Station of the Solar System with the added benefit of the shortest interval between launch windows to and from anywhere in the Solar System. A ship bound from Earth to Callisto around Jupiter might get there faster and with less fuel by using this "**Mercury Slingshot**." Trips to Jupiter, Saturn, Uranus, and Neptune would be shorter.

Read "**Mercury Gateway: Grand Central to the Outer Solar System**" in MMM #78 Sept 1994 reprinted in
http://www.moonsociety.org/publications/mmm_themes/**mmmt_solarsystem.pdf**
and in
http://www.moonsociety.org/publications/mmm_classics/**mmmc8_Jan2006.pdf**

These advantages provide ample economic incentives to establish a settlement on Mercury whose primary purpose would be to ramp up the volume and frequency of interplanetary travel and trade in the Solar System.

**But isn't Mercury too hot to live on? (on the surface, yes, but ....**)

**Not only are the polar areas significantly cooler on the surface, but extensive thick lava flows** (maria, like those on the Moon) ("enough to bury the state of Texas under 4 mi/6.4 km of once-molten rock" **have been found "at high northern latitudes"** i.e. near the North Pole – and that means that there must be lavatubes whose interior temperatures may be more than cool enough to support human activities in comfort. Human and industrial activities produce heat, so we want those "tubes" to be on the cool side.

Mercury's axis is tilted even less than the Moon's. **Mercury could have double or more the total floor surface of permanently shaded craters**, and yes, **radar has detected water ice deposits in those craters**.

http://news.yahoo.com/blogs/sideshow/**nasa-says-enough-ice-mercury-encase-washington-dc**-194415297.html

So we have **a quadruple bonanza:**

1. **Water ice**
2. **Lavatubes: Extensive and cool underground sheltered living spaces**, enough to house a considerable population
3. **Basalt**, a key industrial resource as it is on the Moon
4. **Iron and other key elements** in abundance

**The Rhythm of life on Mercury:**

● **Mercury's axis** has the smallest tilt of any planet, but its orbital eccentricity is the largest.

- As a result the seasons on the planet's surface are caused by the variation of its distance from the Sun, rather than by the axial tilt, which is the main cause of seasons on Earth and other planets. At its closest to the Sun (perihelion) the intensity of sunlight on Mercury's surface is more than twice the intensity at than at its farthest distance (aphelion)
- Because the seasons of the planet are produced by the orbital eccentricity instead of the axial tilt, the season does not differ between its two hemispheres.


**Mercury's day-night/year follows a totally different paradigm:**

- Radar observations in 1965 proved that the planet has a 3:2 spin-orbit resonance, rotating three times for every two revolutions around the Sun**. As a result, its dayspan/nightspan cycle is twice as long as its year,** 176 Earth days long vs. 88 Earth days. And Mercury's set of seasons coincides with the that cycle.
- Image Link: [http://www.eso.org/public/outreach/eduoff/vt-2004/mt-2003/mt-**mercury-rotation**.html](http://www.eso.org/public/outreach/eduoff/vt-2004/mt-2003/mt-mercury-rotation.html)

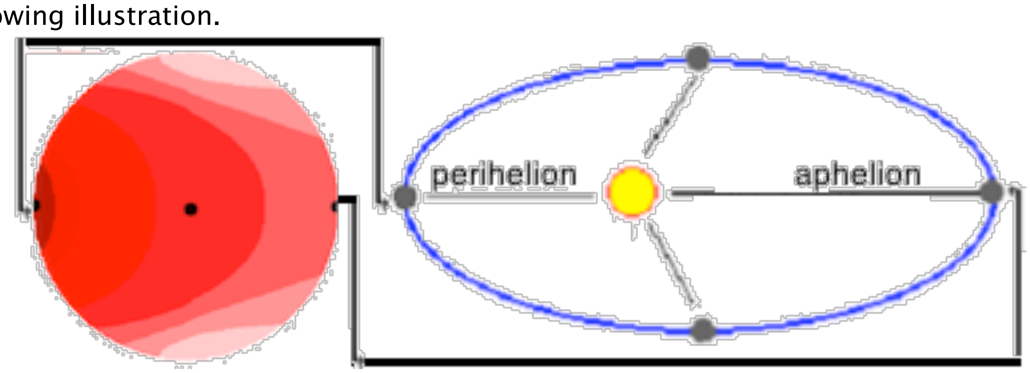
**A "logical/practical" Mercury "Calendar"** for settlers and temporary personnel should then be 176 Earth Days long, not 88. But, as 2 such cycles come very close to our year, **352 Earth days** (vs. our 365), settlers on Mercury may want to use a calendar that is two day/night = two season cycles long. Such a calendar would be similar in length to our Jewish and Muslim 12-Moon-cycle calendars (354 dates).

These 352 dates could be subdivided into 8 "seasons" of 44 dates each. As to weeks, a sequence of 2 seven day weeks, one 8 day week (x2=44 dates) with the 8th day being part of a 3-day weekend every 22 days - this could be very popular with the Mercury's settlers.

- Link: [http://www.eso.org/public/outreach/eduoff/vt-2004/mt-2003/mt-**mercury-rotation**.html](http://www.eso.org/public/outreach/eduoff/vt-2004/mt-2003/mt-mercury-rotation.html)

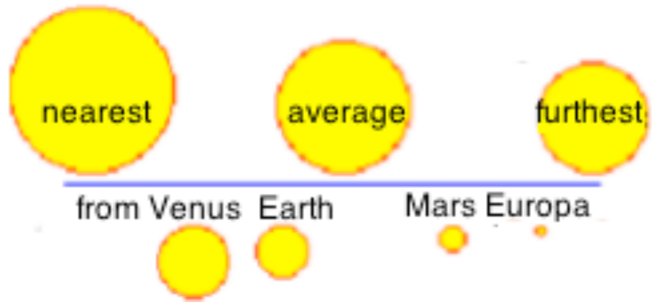
**Climate Zones on Mercury**

As one face of Mars is always facing the Sun when Mercury's distance from the Sun is at its minimum, and the antipodal face is always facing the Sun when Mercury distance is at its greatest, the planets thermal climate zones are unique. I have tried to get the point across in the following illustration.




**Above:** The deeper the shade of red, the hotter the climate zone - Graphic by the author.
Note that northern and southern climate zones are the same.
The lightest pink areas are where we want to be.

In these two circumpolar areas **we have the four things needed**
**"**water, basalt, **lavatube**s, benign temperatures" – all in close proximity
Trips outside these areas would be practical only in most benign conditions (seasonal darkness)




How big the Sun appears from Mercury in comparison to from other planets – PK graphic

**How far in the future is any such development?** The best way to answer such a question is to list **missions** and **technology developments** that must come first.

**Missions:** Currently, NASA's Messenger probe is in orbit around Mercury giving us an enormous amount of knowledge that we did not have previously. Messenger is photographing Mercury from various altitudes at various resolutions.

What we need is **a Mercury Reconnaissance Orbiter** on a par with the Lunar and Mars Reconnaissance Orbiters, able to photograph the innermost planet at a resolution great enough to reveal any lavatube skylights in this "far northern latitude basalt sea." Finding one or more such skylights would help pin down candidate locations for a subterranean outpost.

Next, a "**skylight explorer**" on the model of JPL's Axel probe, able to winch itself down into the skylight and scan what it sees to give us an idea of the cross-section size of the lavatube in question, and a sense of what would be involved to set up an outpost within the tube.

Meanwhile, sampler missions could analyze on location samples of the surface regolith around the skylight area and at various distances from it.

**Technology Development:** We will have accumulated extensive experience in design and construction of modular outposts on the Moon, and maybe on Mars by this time. What else? We need to be already building upgrade versions of **Solar Power Satellites**, as they will be key not only to supplying power to the outpost, but for using to decelerate incoming craft and then accelerating them in a new direction. SPS units could also spot-illuminate areas of Mercury's surface currently in darkness for exploration of the rest of the planet under the best conditions.

Yes, these developments are a long time off. But we have taken step one: <u>exposing the possibilities</u>! **PK**

**MMM #266 – JUNE 2013**

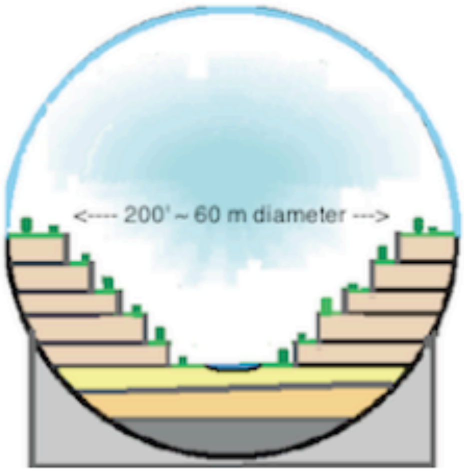
## Surface vs. Lavatube Settlements: Pros & Cons – a place for both

By Peter Kokh

### Designing and Assembling a "Lava Tube Exhibit" leads to new insights and questions

As the Moon Society is hosting a "Lave Tube Track" at this year's International Space Development Conference ("ISDC") hosted by our affiliate, the National Space Society, in San Diego, May 23-27, I decided to create a "Lava Tube Exhibit. The constraints I set for myself were: occupy half of a standard display table, lightweight, made of inexpensive materials and post-consumer items when feasible, have a lighting system, compacts for shipping, etc. Now lavatubes can be many miles long, but here we are talking about a short, typical section. Thus, I could not model all the many things we could do inside these spacious tubular volumes, but had to highlight some key ideas:

- **Housing:** a pressurized cylinder that could house say 500 settlers
- **A tower** set on the tube floor that rose above the lunar surface through a “skylight” opening. It would provide surface access through airlocks, personnel and cargo elevators, an above surface “conning tower level” and shielding for the portion that rose through the skylight above the surface. The tower’s base would be connected to the “town” housing unit by pressurized walkway tube that could also handle airport type open
- A warehouse area: I chose to model containers of various kinds of liquids

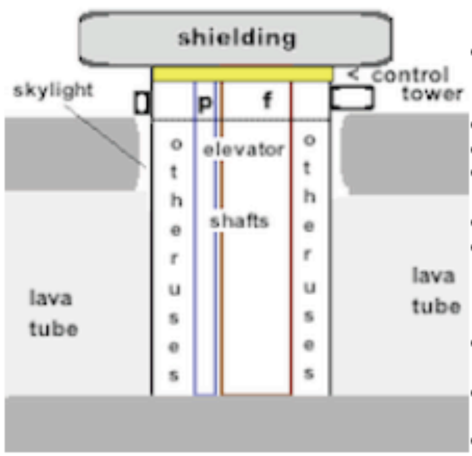



**Concept for Small Lava Tube Town (500 people 100 units)**
**(Cross section illustration at left)**
- Construction materials – not specified
- Musts: blue sky, green spaces incl. private gardens

**Concept particulars:**
- Uplit sky blue bright “firmament”
- multiple tiers stacked atop one another in step back fashion so exposed “roof” of one tier is garden space for one above
- Each unit has windows opening to garden space, valley
- Curved side wall elevators at intervals, access to rear doors
- Trout stream, lagoon, picnic space, play grounds, in plaza
- Yellow level: commercial space, shopping
- Pale orange level schools, meeting rooms
- Gray level utilities, maintenance, subway to other in-line towns

**Pressurized walkway** (airport type 3-6 person carts?) access to multipurpose tower with surface access via existing skylight

**Nb: Residential space can have various architectures.**
- The one illustrated suited the scale of this exhibit
- Design by Peter Kokh, Editor Moon Miners’ Manifesto`




**Lava Tube Skylight Control Tower**
- First, the “talus” rubble pile from the collapsed part of the lava tube roof must be cleared away, and/or used for other construction purposes
- Next in importance are personnel and freight elevators
- **A conning tower observation room above surface level**
- This activity area should be adequately shielded with moon dust – and have a generous overhang.
- Airlock-docks for people/freight form the tower support core
- Extra space surrounding the elevator core can be divided into floors for operations offices, and other management operations. Extra space can be rented to trucking firms, and other companies doing business with this outpost
- Skylights can be quite large, and the original tower is unlikely to occupy all that space, but be placed against one side
- Power transmission lines from surface solar power arrays will also enter the tube through the skylight.
- Here, the width is exaggerated, the height minimized


**The exhibit plan:** a section of a lavatube with a bend in it, with just enough of the bend cut off to allow views inside at mid-point as well as from each side of the exhibit.
**Notice** the "town" area at left, the skylight/tower area to right of center, and the warehouse area at far right.

**Exhibit Construction materials**
- A 24” x 36” lightweight white dry erase board for the base (a cork board would do)
- 11 layers of standard 14” x 48” x 3/4” insulating foam board
- PL 300 construction caulk for foam board
- Gray latex flat paint (first coat) followed by gray tone “Fleck” spray paint (Krylon)
- Complete instructions available on request to kokhmmm@aol.com


**What more I would have liked to do**

For personal reasons, I was not able to attend this year's ISDC. But in retrospect, if that were not the case, I would have liked to have conducted an all morning, or all afternoon brain storming workshop with breakouts for 3-8 persons each, each group tackling something different:

- **Design and construction options for "towns" inside lava tubes**,
- **Design options for a lava tube skylight tower,**
- **Design options for lava tube industrial parks and comprehensive warehouse areas, etc. etc.**

We have conducted such workshops at ISDCs and science-fiction conventions past and the results were amazing. Perhaps we can do something like this at a future ISDC.

**Insights gained from this exhibit planning and construction exercise**

Of course, I attempted to design something within which I could picture myself living. I tried to identify aspects that were gratifying, which left me cold, and which would have frustrated me as a "tube-dweller." And as a result of this exercise, identified some advantages and some drawbacks of Lava Tube Living.

________________________

**Advantages of Living and Working in a Lava Tube Settlement**

- Temperatures are stable, relatively moderate
- Maximum Shielding from Cosmic Radiation and micrometeorite rain and impacts
- Earth Calendar 24-hour-day-friendly
- Three job shifts with neutral day/night schedules (no reason to want one over the others) unless the tube itself was lit, and not lit on a schedule that favored a "day shift."

**Disadvantages of Lava Tube Environments**

- Loss of benefits of a "lunar" calendar: the unique 14.75 day "Dayspan" and equal "Nightspan" with welcome twice a "sunth" change of pace (energy-intensive activities during dayspan; energy-light tasks during nightspan)
- Less opportunity to personalize habitats (lot size, design and shape, other things). Looking like a "company town"
- Town architectures are constrained: long narrow towns in lavatubes many, many times longer than they are wide)
- The basalt surfaces are very dark and light absorbing. It would be difficult to uplight the overhead portion of the tube to create a semblance of "daylight" without installing a hanging "sky blue" faux ceiling fabric or screens.

**A More Ideal Arrangement? Splitting 'what goes where' might give better results**

- **Lava Tubes:** Acreage-hungry manufacturing industrial parks, warehousing operations, agriculture, archiving
- **Surface Moondust-Shielded:** Settlements and Outposts that blend into the moonscapes, open to the stars
  Surface towns could arise around the entrance to a lava tube: integrating residential and industrial areas.

**Lava Tube "Networks" are certain to be established and grow**

The Moon's maria, or frozen lava seas, are likely to be doubly riddled (horizontally and vertically in successive lava flow layers) with lava tubes and we can expect various kinds of interconnections, such as artificial (bored) lateral connections as well as elevator shafts where a tube in one layer overlays a path crossing tube in the lava sheet below. Just as on Earth where two rivers join, or fork as in deltas, such spots are more likely to become metropolitan tube complexes, attracting more residents. Some lower level tubes may have collapse created blockages.

Surface roads will also connect neighboring lava tubes as surface access will be much cheaper to build than boring connections through fractured but otherwise solid basalt.Those such confluences nearer to neighboring highlands will have the advantage of access to complementary sets of resources, and likelier to become major industrial centers. ###

## MMM #267 -AUGUST 2013

# Residents of Lava Tube Towns May Need Regular Surface Contact

By Peter Kokh

## Importance of Exercising and Maintaining Contact with the Moon's Surface

Without planned regular contact with the surface, possible psychosis (fear of the open sky, of the outvac, of the universe at large could develop not only in children, but in some adults. This could lead to unhealthy cults. Some measures that might be considered:

√ **Children would go on surface excursions from an early age.**

- Psychological risk of being cut-off from the lunar surface, from the star-filled heaven, and from Earth

Such "outings" would introduce them to the starry heavens, to Earth as our home world (if they lived on the Moon's nearside or limbs); to the Sun, Mars, and other planets. But they would also learn to appreciate the great variety of scenic vistas out on the Moon's surface.

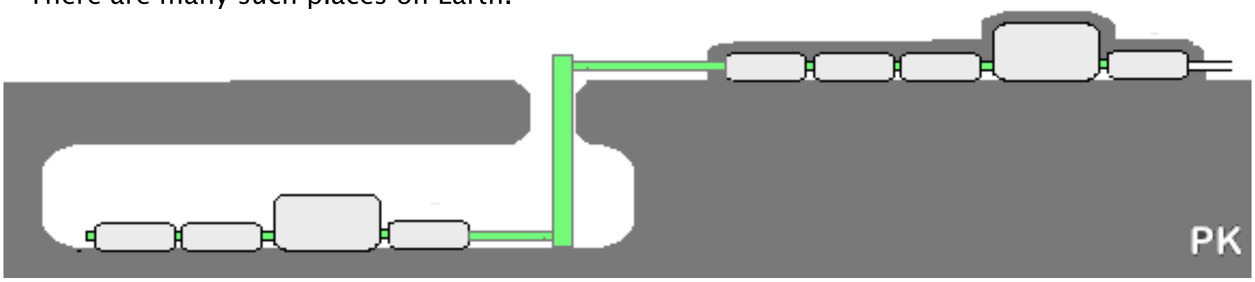
They would go on rover excursions; engage in fun surface sports and activities, visit surface communities. They would also see for themselves the surface world that they might otherwise have seen only in cinema, television news, or on the Solar System Internet. They could take fun space hopper trips, go to surface amusement parks and more. They would visit their own settlement's skylight or rille entrances. They would begin to appreciate the greater "context" in which their lava tube mini-world exists.

√ **It will be important for adults to maintain contact with the "outside world" as well, like many city dwellers retain connections to the surrounding countryside.** But the difference in culture and experiences between tube dwellers and surface settlement residents may be greater than those between city and country people on Earth.

**They can do this on v**acations; in temporary service in "out top" works well as job- and continuing education-related assignments. But to avoid a shift to the opposite extreme, viewing their lave tube town as a kind of cult, they should visit other lava tube towns as well as their own. Stressing how the two kinds of communities, surface and in-tube, complement each other and increase personal options, will cultivate a balanced outlook.

- Tube dwellers may visit "country cottages" and other vacation attractions on the surface.
- Some people may have jobs or occupations that have both in tube and out on the surface components. Among these will be those who work in an access tower protruding through a skylight entrance.

- Others may seek recreational outlets on the surface.
- Access to the surface may be improved by adding artificial skylights or elevator shafts at intervals along the tube away from the main access, be it a natural (impact-created) skylight entrance off of a collapsed ("rille") segment.
- There will be some analogy between tube settlements and linear cities and towns here on Earth, such as those in narrow river valley canyons or pinched between a river and mountains. There are many such places on Earth.




**Many layered Maria:** In Mare Crisium, the many layered lava fill is several kilometers deep. If there are lava tube flows in each layer, there will be a lot of exploring to be done, possibly over many years, even centuries. Any intact tube has been so for over 3.5 billion years. Will we find anything surprising or extraordinary in the early era flows? Possibly not, but this will surely be the subject of many Lunar Science Fiction stories. No similar place on Earth is likely to remain intact for even a million years. Our geology is way too active. What might we find out of the ordinary? Most likely, nothing. It is possible that some tubes in deeper layers may be collapsed by the sheer weight of the layers above. But we won't know until we explore.

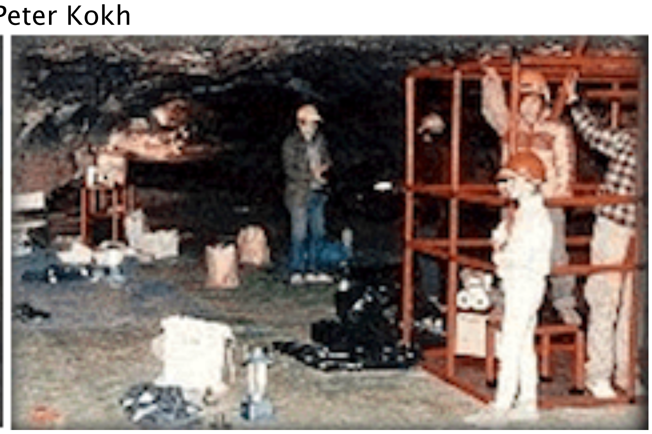
But for humor and fun fiction sake, read "**It Came From the Bowels of the Moon.**" MMM #210, November 2007, pp. 7-8. http://www.moonsociety.org/humor/afd_news.html#hh

There is a lot (actually 99.99%!) that we do not know about lunar lavatubes, or those on Mars. All we have seen is a few skylights and a few rille entrances, and these from a distance that shows scant detail. We are a long ways from being able to plot lavatube networks. We need to prioritize orbiters equipped to detect and map them, as far-fetched as that seems. We need to send probes down into the few skylights we have found. And eventually, we will have to send future Arne Sagnussen's down to explore them. The future looms endlessly exciting! PK

## Exploring Lavatubes on the Moon will be unlike exploring them on Earth

By Peter Kokh

OREGON MOONBASE



**Above: Oregon L5 exercises 1987-88 Young's Cave c. 5 mi NE of Bend, Oregon**
http://www.moonsociety.org/images/changing/OregonMoonbase.gif

## Moon Society plans: skylight “axle” probe instruments, insect armies, command systems

### Factors that make terrestrial lavatubes dissimilar to lunar ones

- **Terrestrial lava tubes are more irregular in course and in vertical profile in fist and second lava flow layers** because they hug a preexisting non-level surface shaped by other occurrences such as mountain building, water carving, impacts, etc. Like river channels formed by water trapped under an ice sheet, that can flow up and over obstacles, this can happen in lavatubes as well, which flow downhill in general, but not necessarily in mid-course.
- On the Moon, we are likely to find **irregular tubes** near the basin periphery, forming on the basin “benches”
  and in the earliest basin basement levels
- We are likely to find **regular, relatively smooth bottom contours in lava flow layers overlaying a number of previous floods and in maria many lava sheet layers thick**
- **In terrestrial tubes, we can use** buoyant probes to map the tube features from just under the ceiling – we can’t do this **on the Moon where there is no atmosphere “to be lighter than.**” Where “buoyancy” does not allow mapping from above, bouncing kangaroo probes may, where the floor is flat. Bouncing probes are obviously easier and cheaper But the height and direction of the bounce must be controllable. Can we develop a probe whose bounce height and distance can be altered?
- Drilled holes in the ceiling will take much more effort and expense on the Moon where we will be dealing with ceilings hundreds of feet thick not a few feet thick.
- Terrestrial tubes often have areas where the floor has been “smoothed” by post=formation of sand layers transported by rain and flooding. **“Post formation smoothing” of tube floors is most unlikely on the Moon.**

### Challenges of Lava tube exploration on the Moon

- Insect-like explorer robots might have **feet that can change in shape with each step to avoid getting stuck between rocks.**
- The “axel” type skylight explorer is a start. All skylights on Earth and on The Moon and Mars will have **talus piles** below. The collapsed material has to go somewhere and smack in the middle of the skylight opening is where.
- **Tallus debris slopes will also characterize openings to lavatube**s at the beginning of rilles. Adjustable tank type treads may be a solution. They can be lightweight. By making them wide and long, they will be relatively ground-hugging and less likely to fall over sideways or in line of movement.
- **Safety in numbers – insect armies, platoons, squads will be more successful,** some attrition in ranks is to be expected – side reporting as well as up-reporting “communist cell style”
- Some **tenuous “atmosphere” is to be expected in tubes with no open outlets to the surface,** but with gradual loss by attrition through fissures. Such atmosphere is most likely to be lava volatiles, some from radiation. Tubes with skylight or rille openings will have negligible gas.

### What it makes sense to simulate and test here on Earth

- Mapping instruments lowered thru a skylight
- Insect army scouts and reporting systems
- Lighting systems
- Freight elevator-limiting modular designs for various purposes ##


"Oops! This lavatube seems to be occupied!"

**Want to read more about how Lavatubes on the Moon, Mars, and even on Mercury may someday shelter future off-Earth Settlements?**
**Stay tuned to Moon Miners' Manifesto!**

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**It is also available to members of the following National Space Society Chapters**

**Milwaukee Lunar Reclamation Society - the publishers**
**Chicago Space Frontier L5   NSS-Philadelphia Area Space Alliance   OASIS (Los Angeles)**
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**Contact information for the above chapters: http://chapters.nss.org/a/lists/#US_Chapters**