LAVA TUBES: POTENTIAL SHELTERS FOR HABITATS

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Natural caverns occur on the Moon in the form of "lava tubes," which are the drained conduits of underground lava rivers. The inside dimensions of these tubes measure tens to hundreds of meters, and their roofs are expected to be thicker than 10 meters. Consequently, lava tube interiors offer an environment that is naturally protected from the hazards of radiation and meteorite impact. Further, constant, relatively benign temperatures of -20°C prevail. These are extremely favorable environmental conditions for human activities and industrial operations. Significant operational, technological, and economical benefits might result if a lunar base were constructed inside a lava tube.

INTRODUCTION

This paper addresses the existence of natural caverns on the Moon in the form of "lava tubes," and it suggests that they could provide long-term shelter for human habitats and industrial operations.

The origin of lava tubes is genetically related to the formation of "sinuous rilles," which represent flow channels of molten lava. Such channels generally form at high extrusion rates of low viscosity magmas. Sinuous rilles are abundantly observed on lunar basalt surfaces (*e.g.*, Oberbeck *et al.*, 1969, 1971; Greeley 1971, 1972; Cruikshank and Wood, 1972; Head, 1976). The distribution of sinuous rilles on the lunar front side was mapped by Guest and Murray (1976).

Lava tubes are well known from basaltic volcanic terranes on Earth (Ollier and Brown, 1975; Greeley, 1971, 1972, 1975; Cruikshank and Wood, 1972; Hulme, 1973; Peterson and Swanson, 1974). A number of processes may contribute to their formation: (1) radiative cooling may cause surface crystallization and crusting-over of the liquid lava. (2) Commonly, such relatively thin crusts break apart and collapse because the melt below continues to flow. Solid but relatively hot chunks of this crust will raft on the lava river and may coalesce into larger and larger aggregates until a solid roof forms. (3) Radiative cooling takes place at the sides of such lava flows, leading to crusting and aggregation of solids and ultimately to the buildup of pronounced levees, which in turn increase channelled melt flow. Additional aggregation from these levees, aided by spattering of lava splashes, can lead to the formation of solid roofs.

Commonly, low viscosity magmas are also very hot. Hulme (1973) and Peterson and Swanson (1974) present field observations that lava tube cross sections may be modified and enlarged by thermal erosion, *i.e.*, by remelting of the tube's ceiling, walls, and floor.

Typical heights and widths of terrestrial lava tubes are generally measured in a few meters; cross-sectional dimensions in excess of 10 m are rare. The length of lava tubes on Earth may reach 10 to 20 km, but most lava tubes are only 1-2 km long. Greeley (1975) points out that the frequency of such underground lava conduits on Earth may have been underestimated in the past and that they are indeed relatively common around terrestrial shield volcanoes such as those in Hawaii.

LUNAR LAVA TUBES

High extrusion rates and extremely low viscosities characterize lunar basaltic volcanism (Moore and Schaber, 1975), conditions very conducive to the formation of lava channels and tubes. Open channels in the form of sinuous rilles are very abundant on lunar basalt surfaces. Their widths and depths are typically hundreds of meters, and they are commonly a few tens of kilometers long. They are, thus, much larger than their terrestrial analogs (*e.g.*, Oberbeck *et al.*, 1969, 1971). Indeed many of the above studies address the problem of how to properly scale the dimensions of terrestrial lava channels and tubes to their much larger counterparts on the Moon. Hulme (1973) argues for increased turbulence and increased thermal erosion during lunar basalt flow. In detail, the highly meandering nature of many lunar rilles is also not observed to the same degree in terrestrial analogs. Increased meandering is probably best explained by reduced gravity and extremely shallow flow gradients.

In contrast to numerous open flow channels in the form of sinuous rilles, bona fide lava tubes are rarely observed on the Moon; they could indeed be rare geologic features. On the other hand, they are subsurface and will therefore generally not show up in lunar surface imagery. The only lava tubes that can be recognized from lunar surface photos are those that have partially collapsed roofs. Thus, little can be surmised about the absolute frequency and global distribution of lunar lava tubes. They may well be more common than can be demonstrated at present. The important point and the crux of this paper is, however, that they do exist on the Moon.

Figure 1 shows a lava tube with large segments of collapsed roof. A modest topographic ridge forms the crest of the tube as pointed out by Oberbeck *et al.* (1969). The elongated depressions must be caved-in portions of this ridge system. Their elongated plane view and the lack of any raised rims distinguishes these depressions from circular impact craters. Note also the highly braided nature of the elongated depressions, in stark contrast to the random distribution of circular impact features dotting the surroundings. This observation in particular lends additional credence to the interpretation that the entire linear feature is a partially collapsed lava tube. Figure 2 represents another feature interpreted by Cruikshank and Wood (1972) as a partially collapsed lava tube. This tube seems to be unusually straight. The width of the open rille is approximately 200 m, and the uncollapsed roof segments are a few hundred meters long. Note the size of impact craters that were suffered by the seemingly intact roof segments.

What do we know about the roof thicknesses of lunar lava tubes, and are these roofs sufficiently massive and structurally stable to provide long-term shelter against

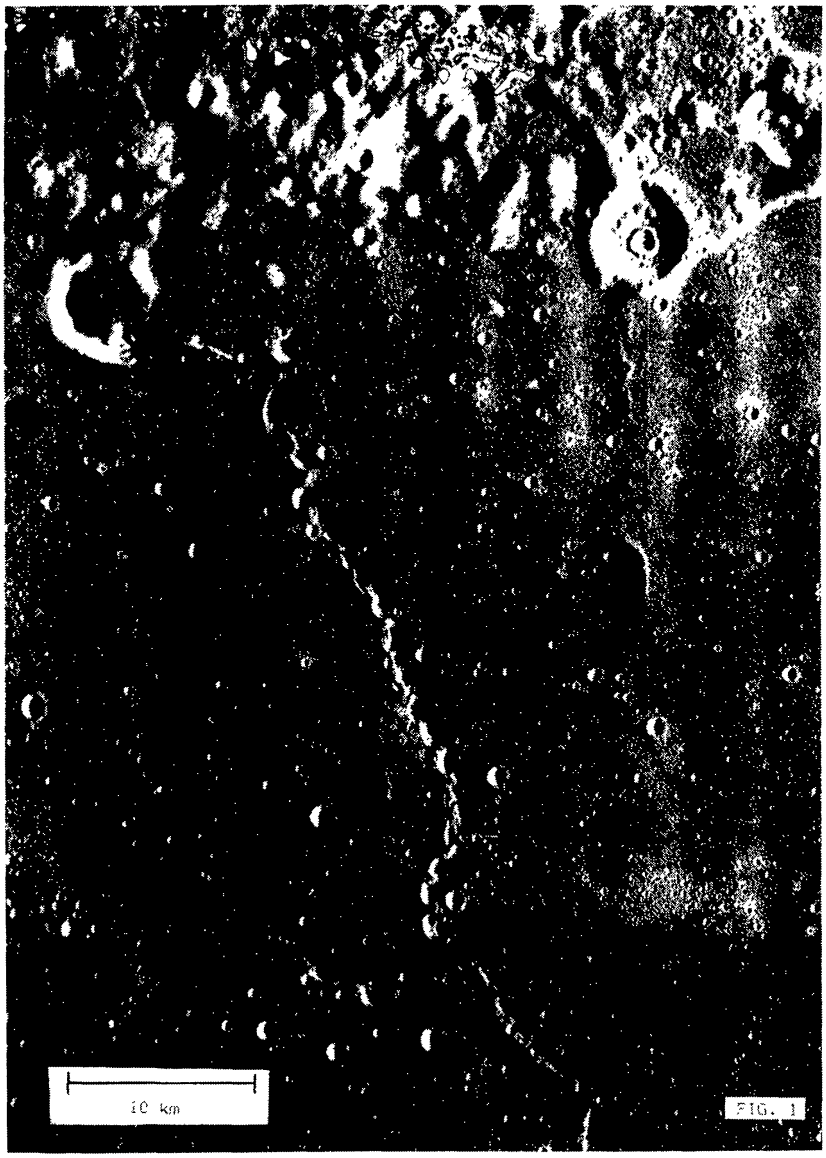

Figure 1. One of the most prominent lunar lava tubes, first described in detail by Oberbeck et al. (1969). The lava tube is approximately 40 km long and up to 500 m wide. Note that some sections of the roof are uncollapsed and that the tube continues underground toward the south (at bottom of picture). Also, note that slopes leading into the rille may be of different steepness; the flatter ones might be negotiated with ease. Uncollapsed sections of the tube are on the order of a few hundred meters long, particularly in the northern part. Dimensionally, these lava tubes would be more than adequate to serve as receptacles for modular habitats and a variety of machinery. Note that this lava tube happens to be within a few kilometers of a highland contact, and it is not inconceivable that access to different raw materials may be possible from a single lava tube (Lunar Orbiter 5, frame 182. Northern Oceanus Procellarum).

radiation and meteoroid bombardment? According to Oberbeck *et al.* (1969), the ratio of roof thickness (T_R) of terrestrial lava tubes relative to typical dimensions of tube cross sections (T_C) ranges from 0.25 to 0.125. Oberbeck *et al.* (1969) also use simple structural beam modeling to calculate that basalt "bridges" spanning a few hundred meters are possible on the Moon provided they are at least 40–60 m thick. These estimates happen to agree with the terrestrial T_R/T_C ratios. Importantly, these estimates are also in good agreement with the following observations: uncollapsed roofs of lava tubes display impact craters a few tens of meters across (see Fig. 2), occasionally as large as 100 m. The diameter/depth ratio of small lunar craters is approximately 4 to 5 (Pike, 1977). Thus, crater excavation depths approaching 20 m can be demonstrated. Using ballistic penetration mechanics (*e.g.*, Gehring, 1970) and associated spallation processes at the rear surface (the roof's ceiling) of a slab-like impact target, one can estimate conservatively that the

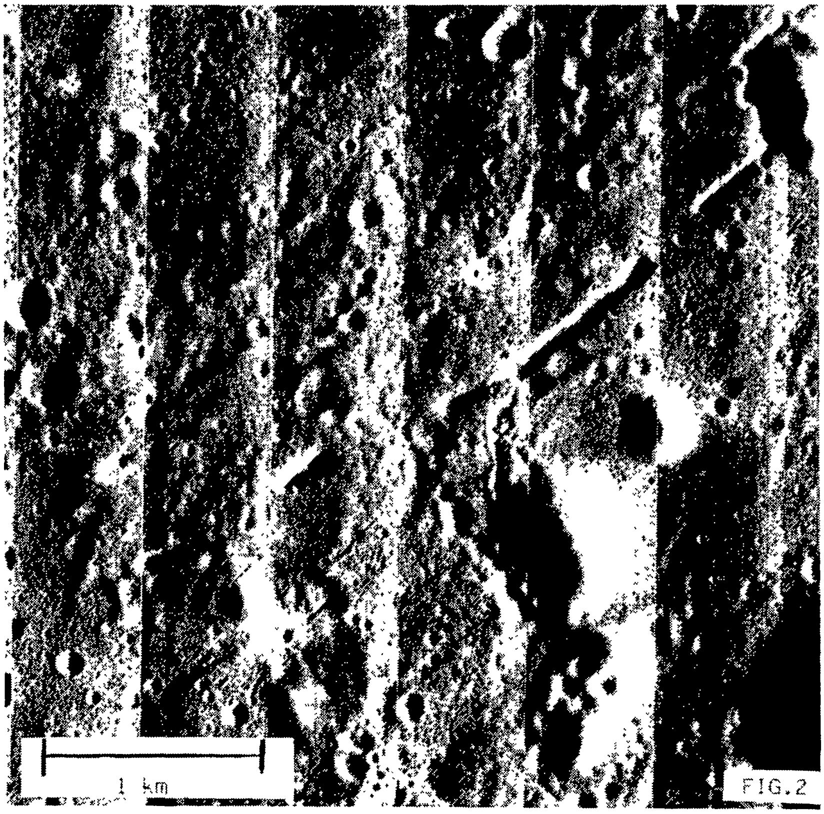

FIG.2

Figure 2. Lunar lava rille with uncollapsed roof sections that measure hundreds of meters. Note that mountains are close by which certainly differ in chemistry and mineralogy from the relatively flat basalt surfaces. This rille was extensively described by Cruikshank and Wood (1972) (Lunar Orbiter 5, frame M-191).

roof thickness must be at least two times larger than any crater depth; otherwise complete penetration of the slab (roof) would have occurred. Following these arguments, the maximum crater sustained by an uncollapsed roof yields a minimum measure of roof thickness. The thicknesses of some lunar lava tube roofs are thus a few tens of meters. In principle, the minimum roof thickness of specific lava tubes could be assessed using the above crater-geometry relationships.

While impact craters indicate that initial roof thickness must have been substantial, the cratering process has also contributed to the erosion and structural weakening of such natural basalt bridges. Judging from the thickness of lunar soils on representative basalt surfaces, the uppermost 5–10 m of solid bedrock (lava tube roofs) are totally comminuted into fine-grained lunar soil. Penetrative cracks associated with this average regolith depth are a factor of 3–5 deeper on the basis of seismically disturbed areas below terrestrial craters (Pohl *et al.*, 1977). Importantly, the above-mentioned spallation process occurs at the tube's ceiling even for impact events that are not penetrative; *i.e.*, it occurs as long as the stress amplitude of an impact-triggered shock wave exceeds the basalt's tensile strength (*e.g.*, Hörz and Schaal, 1981). This spallation-induced thinning and weakening is of more concern for the structural integrity of a given roof than surficial erosion. A few relatively large craters (>50 m) may have done more structural damage than the cumulative effects of many <20-m-diameter craters. Because meteorite impact is a stochastic process, it is difficult to predict the structural integrity and exact thickness of a lava tube roof with great precision. Nevertheless, rough estimates can be made via photogeologic techniques related to crater geometry as outlined above. An obvious strategy would be to select roofs or roof segments that have suffered relatively small cratering events only. Such segments are clearly safer than areas close to, if not directly below, a relatively large impact crater.

What do we know about cross-sectional dimensions of lunar lava tubes, and how do their interiors look? As indicated above, the linear dimensions of sinuous rilles and lava tubes are significantly larger on the Moon than on Earth; collapsed portions of some lunar lava tubes indicate correspondingly large tube interiors (see Figs. 1, 2). There is little doubt that lunar lava tubes have large enough cross sections to house most any habitat. Restrictions and enlargements of cross sections occur in terrestrial lava tubes, but on relatively modest scales. The surface relief of terrestrial lava tube interiors can be highly variable, ranging from relatively smooth to very rough and knobby. However, this variability occurs on relief scales that are extremely small compared to cross-sectional dimensions. We can only assume that lunar lava tubes display similar relief. In addition, the above-mentioned spallation products will have accumulated on the floor; they may possibly make initial trafficability cumbersome until removed or leveled (using readily available lunar soil as fill).

LUNAR BASE INSIDE A LAVA TUBE

Based on the foregoing, it appears that natural caverns of suitable sizes to house an entire lunar base exist on the Moon. Roof thicknesses in excess of 10 m will provide safe and long-term shelter against radiation and meteorite collisions. Creation of similarly shielded environments will constitute a significant and costly effort for any lunar base located at or close to the lunar surface. Substantial operational advantages for a lava tube scenario emerge as outlined below.

The primary suggestion advocated by this report is to use lava tubes merely as receptacles for prefabricated, modular habitats, either imported from Earth (initially?) or fabricated from lunar resources, if not in place (at later stages?). We do not suggest that the lava tube itself may be suitably modified to serve as the primary habitat. There are too many uncertainties related to detailed geometry of the cross section and to the surface roughness of the walls and floors. Indeed, lava tube interiors may be too large, at least initially. Furthermore, penetrative cracks in the roof may exist, which would make it extremely difficult, if not impractical, to render the enclosed volume airtight. Modest site preparation inside the lava tube would consist of leveling the floor with lunar soil, an earth-moving operation similar in scale to site preparation on the surface. The lava tube would then be ready to act as a receptacle for self-enclosed habitats as well as for a large number of industrial operations, all safely protected from radiation and meteorite impact.

The primary advantage of housing the lunar base in a naturally sheltered environment is the potential to use extremely lightweight construction materials. None of the components would have to support any shielding mass whatsoever. Indeed, many components, such as a habitat shell, would not even have to support much of their own weight because they could be supported from the walls and ceilings of the lava tube. Habitats could even be inflatable, supported by air pressure only. In any case, construction and selection of materials would be entirely dictated by expected wear and tear. Widespread use of thin foil materials (metals, plastics?) is possible not only for the habitat itself, but also for a variety of ducts, storage tanks, *etc.* Any lunar base will include a variety of machinery located outside the man-rated, shirt-sleeve environment. Some of this gear will have to be protected against meteorite impact (*e.g.*, all life-support systems). Much of this equipment will also have to be visited occasionally by crews for monitoring, maintenance, and repair. Inside a lava tube, the layout of this equipment could resemble that of terrestrial operations with all components freely exposed and easily accessed for inspection and repair. This seems particularly convenient for a variety of duct work, pipes, valves, storage tanks, *etc.*, used to transfer gases and liquids. It is also possible to house some machinery inside lightweight shells to create an optimum environment for its operation (*e.g.*, bio-processing plant). Such lightweight shells and habitats are easily connected with each other, providing great flexibility for expansion of the lunar base as well as for specific environmental engineering inside individual enclosures and compartments. In summary, numerous structural and operational advantages would present themselves if a lunar base could be designed and constructed without continuous concern for the hazards of radiation and meteorite impact.

Lava tube interiors offer additional environmental differences compared to the lunar surface. These differences may be beneficial for a number of engineering tasks and operational aspects. Being underground and some tens of meters removed from the lunar surface, there is a relatively constant-temperature environment (estimated at -20°C; Mendell, personal communication, 1985). This contrasts with the diurnal temperature cycle of -180° to +100°C at the surface. Temperature management inside a lava tube appears significantly easier than at the surface, where complex thermal insulation and control systems appear unavoidable. Also, the selection of materials functioning properly over a wide range of temperatures is severely limited at the surface; in contrast, a wide range of common materials may be used at the more benign and constant temperatures prevailing inside a lava tube. Furthermore, inside a lava tube, all equipment is well shielded from IR and UV radiation. Materials (*e.g.*, certain plastics) that otherwise deteriorate if exposed to this radiation could be used indiscriminately inside a lava tube. In short, additional environmental differences of a subsurface location may allow widespread use of common materials that may not be suitable for use on the lunar surface.

Some additional advantages for siting a lunar base inside a lava tube come to mind. The front and rear entrances of the tube may be sealed off rather readily to keep a relatively dust-free environment for all operations; loose dust may be a nuisance for a fair number of operations on the surface. It is also possible to conceive of lightweight, highly fexible suits for crews venturing outside the man-rated habitats but remaining inside the tube; neither thermal insulation nor meteorite impact is of great concern for such suits. Heavy, vibrating machinery may be solidly anchored to firm bedrock (a rarity on the lunar surface). The lava tube may serve as convenient "hangar" or "garage" for all kinds of equipment that have low duty cycles and that must be kept in a protected environment.

A major operational drawback in utilizing lava tubes may be their difficult accessibility. Negotiation of perhaps steep slopes and the climbing in and out of a local "hole" appears cumbersome, possibly impractical. Relatively shallow sinuous rilles, somewhat flattened by impact craters, exist however. Also, the Apollo 15 crew visited the edge of Hadley rille and felt that their Lunar Rover could have negotiated the slopes of this rille (Irwin, personal communication, 1985).

Location of a lunar base at the bottom of a hole seems not very economical from an energy point of view, because mass will have to be lowered and especially raised when needed on the lunar surface and when being readied for export to LEO or GEO. These energy considerations are, however, a matter of degree, because most large-scale industrial operations rely heavily on gravity for material transport. Some modest elevation difference between the source of lunar raw materials and the processing plant is desirable even for such simple operations as sieving and magnetic separation. For this reason, a lunar base may be more functional if located at the base of some slope. Why not a sinuous rille/lava tube where chutes or pipes may be laid out such that they terminate inside the lava tube at exactly that station where the high-graded raw materials are needed?

The most serious drawback in the utilization of lava tubes relates, however, to the present status of lunar surface exploration. Only a few lava tubes are recognized. High resolution photography of the entire lunar globe is needed to improve the inventory of lunar lava tubes and to determine their spatial distribution. Detailed imagery appears at present to be the only means for an improved understanding of their dimensions, roof thicknesses, and global distribution. Furthermore, lava tubes are viable candidates for shelters only if desired raw materials are close by. The distribution of specific lunar resources is also largely unknown at present. It appears prudent to further explore the lunar surface and its resources via remote sensing from polar orbit. Lava tubes are viable candidates to house a lunar base if basaltic raw materials are desired. Lava tubes are, however, not excluded if non-basaltic resources were the ultimate choice. As illustrated in Figs. 1 and 2, lava tubes occur within kilometers of non-mare terrains with lithologies that differ substantially from the surrounding basalts.

CONCLUSIONS

Establishment of a lunar base, its construction, its layout, its diverse functions, and its ultimate location will be the compromise result of numerous scientific, technical, and economic considerations. Some of these considerations may be incompatible with housing a lunar base inside a lava tube. The simple purpose of this contribution is to remind everybody that natural caverns exist on the Moon. They provide a natural environment that is protected from meteorite impact, shelters against radiation, and is at a constant, relatively benign temperature. Such a natural environment allows widespread use of lightweight construction materials, great flexibility in the choice of such materials, and it results in improved operational capabilities. If a lunar base were emplaced on the lunar surface, a qualitatively similar environment would have to be engineered with great complexity and cost.

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