Lavatube Entrance Amelioration on the Moon and Mars

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Abstract

To explore and utilize lavatube caverns, a negotiable entrance is vital. Lavatube entrance amelioration includes clearing debris, establishing a transportation right-of-way, and preparing for and installing various access aids. There are four main types of entrances to lavatube caves: a "rille entrance," a "skylight," a "hornito," and an engineered, artificial skylight.

A rille entrance should be easiest to improve. In rare cases it may be possible to simply walk or drive into the lavatube. More likely, the rille entrance will be choked by initial rille collapse and eons of weathering. A mucker and cable assembly used to clear the entrance might become a cablecar. Later, a suspended road may be built.

A skylight forms when a small portion of the cave ceiling collapses. The skylight entrance is prone to further collapse. Given their great age, unstable areas will probably have collapsed already. Beneath the skylight, there is most likely a chaotic pile of collapse debris ("breakdown"), covered with regolith. Dangerous slopes of regolith lead into the hole. Survey and stabilization are the first steps of entrance amelioration. Mechanical aides from nets and ladders to A-frame pulleys and small elevators can then be emplaced. Later development could include large freight elevators up to a skylight-spanning "Maxivator" suitable for lowering entire ships into the lavatube shelter.

Hornitos occur where temporary blockage within the active lavatube causes molten lava to burst out to the surface, leaving a surface cone of solid basalt with a central hole leading to the cave. There may only be minor debris below this hole. A hornito provides a strong lip and solid foundation for devices to lower material and people into the cave.

Where a cave lacks a handy entrance, an artificial skylight could be created. The edges of the hole would be engineered, and the roof is not necessarily weak in its vicinity. Utility holes of various sizes could be drilled directly. Larger holes could be created by direct blasting, or precision blasting to result in a removable plug.

The improvement of lavatube entrances will require a range of engineering solutions. Since lavatubes on the Moon or Mars are expected to be vast, the effort of entrance amelioration is small relative to the sheltered space it makes available. The cost is low compared to the payoff.

Introduction

Entrance Types. Lavatube caverns are large voids in bedrock with massive shielding and virtually no weather. They offer many advantages for lunar and planetary bases, including cost-savings and reduced risk (Walden *et al.* 1998). Once a candidate lavatube is located (York *et al.* 1992), the next task will be gaining access. There are three types of natural entrances to lavatubes: a "rille entrance" at the end or beginning of a collapsed lavatube trench, a "skylight" formed by a spot failure of the lavatube roof not extensive enough to have become a collapse trench, and a "hornito"

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which is a type of skylight formed not from collapse but from eruption of lava through the lavatube roof. Where a natural entrance is not available, an engineered, artificial skylight could be created.

General Considerations. A survey and geotechnical plan will be necessary before and during the process of lavatube entrance amelioration. Each entrance type has advantages and disadvantages, and calls for different engineering approaches for stabilization and improvement.

Companies with an eye to safety and the bottom line will want to gain access to shelter and emplace revenue-producing base elements as quickly as possible. The immediate work area should be wide enough to permit a base construction and operations pathway in parallel with ongoing entrance amelioration activities. This suggests a primary stabilization width on the order of 20 meters.

Robots should be considered for survey and stabilization of unimproved lavatube entrances. Robots can be hardened and optimized for high-risk work. They could perform surveys, stabilize entrance features, and drive initial anchors for equipment and base components. Loss of a robot is preferable to loss of living workers.

We anticipate a 5-step stabilization process for lavatube entrance amelioration:

1.) Survey and planning
2.) Lavatube ceiling stabilization
3.) Regolith clearing
4.) Regolith and breakdown stabilization
5.) Installation of mechanized access systems

Entrance Types and Solutions

Rille entrances. Entrances from a collapse trench will require varying degrees of amelioration. The simplest would be an open trench transitioning smoothly into the shelter of a lavatube with a pooled lava floor flat enough for walking or driving. This may also have the advantage that the trench may function as a naturally bermed landing site on the same geographical level as the entrance. Debris spread ballistically from a landing or launching ship could be blocked by simply placing the landing pad around a bend in the rille, out of line of sight from the lavatube entrance. A lunar railroad might enter here to serve bases within, and even preferentially choose lavatubes to provide as much shielding as possible along its route.

More commonly, entrances from the collapse trench will be choked with breakdown debris: large angular boulders up to twenty meters on a side (Burke 1986) in a huge pile that tails off steeply inside the lavatube. The cave entrance may be completely blocked from the outside by regolith formed in the usual way: weathering and rains of debris from meteorite strikes near and far. Regolith may also form weak bridges over interstitial voids between breakdown blocks that could collapse unexpectedly, like a snow bridge over a crevasse. Inside the lavatube, this regolith cover should extend only a short distance from the entrance. We recommend a sounding survey to identify these hidden hazards, perhaps by ground penetrating radar (GPR).

To clear a path through this regolith, we suggest a simple "mucker" such as designed by Rockwell's Steven Kent: an assembly of cables, posts, pulleys, a dragline bucket, and a small motor (Kent 1990) (*Figure 1*). Beginning its cut at the top of the obstruction, probably near the ceiling of the lavatube, this system would open and stabilize the entrance only as much as needed for humans and equipment to access the lavatube shelter. Large obstacles may require blasting to reduce them to manageable proportions. After clearing the right of way, the cabling and motor of the mucker system may be reused to create a suspended transport system over the steep breakdown slope inside the entrance. Later, a cablecar system, suspended road, or suspended railroad may extend deep into the cave, perhaps serving bases suspended over chaotic boulder fields.

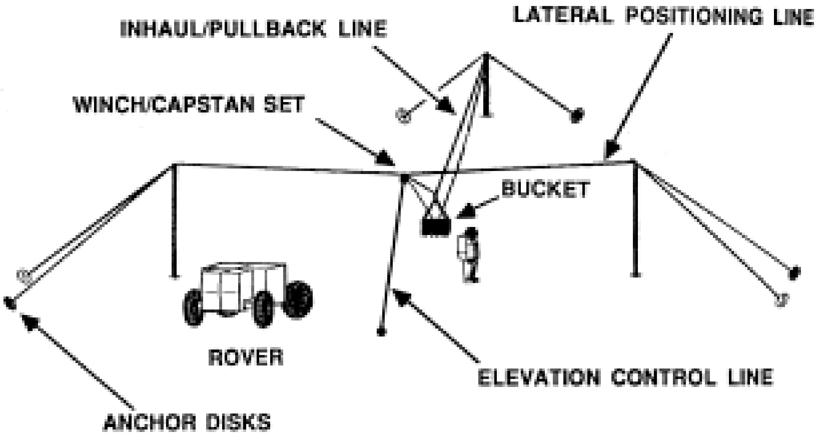

Figure 1: Efficient Early Excavation Machine, from Kent (1990).

Skylight entrances. The skylight may be the most common form of lavatube entrance. A rille represents a span too wide or ceiling too thin to persevere when underlying lava is withdrawn. A skylight forms from a similarly weak area of ceiling collapse that is not lengthy enough to form a rille. A direct meteoroid strike of sufficient force could also create a skylight (Hörz 1985). In any case, the margins of the skylight would be ragged, weak, and have a high likelihood of further collapse, particularly with weights and vibrations from human activity. Four to five meters of surface regolith (McKay *et al.* 1991) will form unstable funneled slopes into the void, perhaps as steep as 40° (Carrier *et al.* 1991). Beneath the regolith at the skylight entrance, the basalt roof of the lavatube will be broken in rough vertical walls several meters to tens of meters thick (Hörz 1985). Below the skylight, a chaotic pile of collapse debris probably lies on the cave floor, covered with unstable regolith. If the roof collapse happened while lava was still flowing in the tube, breakdown might have been swept away leaving a relatively clear floor, still regolith-covered with age. Skylight diameters can range from a few meters up to the width of the underlying cave, perhaps hundreds of meters (Coombs and Hawke 1988). Depth to the floor will depend on the nature of the cave and could be a few hundred meters, less the height of breakdown debris. Even in low lunar gravity, an accidental fall could be fatal or result in serious injury (a 300 m fall on the Moon results in a terminal velocity of 31 m/sec (70 mph)).

Immediate access through a skylight entrance can be gained by building a traveling crane offsite then bringing it in to straddle the entrance or subtend a chord, or constructing a luffing cableway (Bernold 1992). The end support pylons and truss or cables between them could remain mobile or become a semi-permanent fixture. Cargo and personnel would be loaded on stable ground beyond the unstable zone, lifted and carried over the void, then lowered into the cavern. Activities could thus commence in the sheltered lavatube beyond the skylight entrance while the entrance itself is still being stabilized.

Stabilizing a skylight entrance would be an iterative process. Extensive surface work should not be attempted until the underlying cave roof is geotechnically analyzed and loose rocks either cleared or stabilized by rock bolts (Herbert 1990). A small area of the funneling lip might have a runner of cargo net thrown over it, where engineers or teleoperated machines would work attached to belays or to an overhead crane well-secured beyond the immediate danger zone. Loose pieces on the skylight's vertical basalt walls would be secured by rock bolts or removed. The crew would then install a ladder or even a small elevator from the surface to the ceiling of the lavatube, secured at several points along the basalt wall. From there, they would stabilize the cave ceiling in the immediate area of interest, and perhaps leave a hanging work platform behind to serve as a future base of operations on the cave ceiling. If a traveling crane as described above is not used, extending a ladder, pulley cable, or tiny elevator to the floor of the cave would allow a team to begin preliminary site surveying and preparation.

Once the underlying bedrock is stabilized, work may begin on clearing and stabilizing the regolith around the skylight. This can start with the use of a mucker suspended by its cables at the lip of the skylight. To minimize further contamination of the cave, the mucker will scrape loose regolith up the slope to the level area beyond the skylight lip. Initially, only a small portion of the skylight rim need be cleared to provide access to the main lavatube construction volume. Once the initial (≈ 20 m wide) access is completed, the process repeats section by section around the rim even as construction and operations proceed within the lavatube.

To prevent slope failure and the raining of debris into the cave, the entire circumference of the skylight requires stabilization. At the same time, we would like to improve the entrance at least to the extent of being able to reach the vertical bedrock walls of the lip. The mucker would be used to clear all regolith from the immediate area of the lip, and beyond this, to reduce the regolith slope from its natural angle of repose to a lower, more stable angle. The regolith scraped from the surface could be formed into a berm around the skylight. This barrier of loose regolith, being difficult to negotiate (Carrier *et al.* 1991), would hinder accidental running or driving into the hole. A net could be draped over the prepared regolith and down the side of the opening, then secured inside along the cave ceiling. On the surface, such a net will help stabilize and spread loads on the regolith; along the vertical basalt walls it could act as scaffolding to allow inspection, stabilization, and maintenance; and by securing it on the lavatube ceiling, it can serve as a safety net in case rocks work loose from the wall. Where it is placed over regolith, the net should be recessed or covered with a thin layer of additional regolith to prevent wear and hazards to navigation. As a final stage, the regolith would be sintered to a depth of several decimeters to a meter or so, depending on expected load, further stabilizing the surface and sealing the net within the sintered matrix. Sintering might be accomplished by direct solar energy (Khalili 1985) or, to achieve the necessary depth, by a solar-energized microwave projector (Meek *et al.* 1985). Nets could be made on Earth from light but strong space-rated fibers. When lunar industries have started, nets could be made from strong lunar glass fiber protected from regolith scoring by a lunar metal sheath (Blacic 1985).

From the start of construction, access will be needed for humans, light construction equipment, and power. A simple kit of low mass access equipment would consist of a closed-loop cable-suspended system with anchors in the stabilized slope of the skylight lip, and a “bat tent” rest/equipment platform, opening onto a suspended catwalk, from which suspended base construction can begin. The cabling system could extend to access the cave floor.

Ladders are not very useful for space-suited people, so varieties of elevators are proposed. Lower lunar gravity acceleration allows a greater elevator safety margin. An A-frame wire cable and pulley system could lower payloads, or personnel, to the floor of the lavatube. Initially this could be as simple as a winched rope or cable with a boot loop at its terminus, or a long closed-loop cable and pulley arrangement with boot loops/handholds spaced every so often. Using a system of several A-frame pulley assemblies and handheld guy wires below, even habitats and other large components could be lowered into cave shelter early in the project.

Soon thereafter a larger, more formal and heavy-duty construction elevator would be built. A suspended-cable open construction elevator, or “Minivator,” would be lowered into the lunar lavatube, rested on the ground below, and bolted to the skylight wall (*Figure 2*). Lightweight scaffolding and ballistic cloth or nets could protect the device and personnel from spallation caused by vibration or wobble of the working Minivator, which should still be designed to keep dust and pebbles out of cable and gear assemblies.

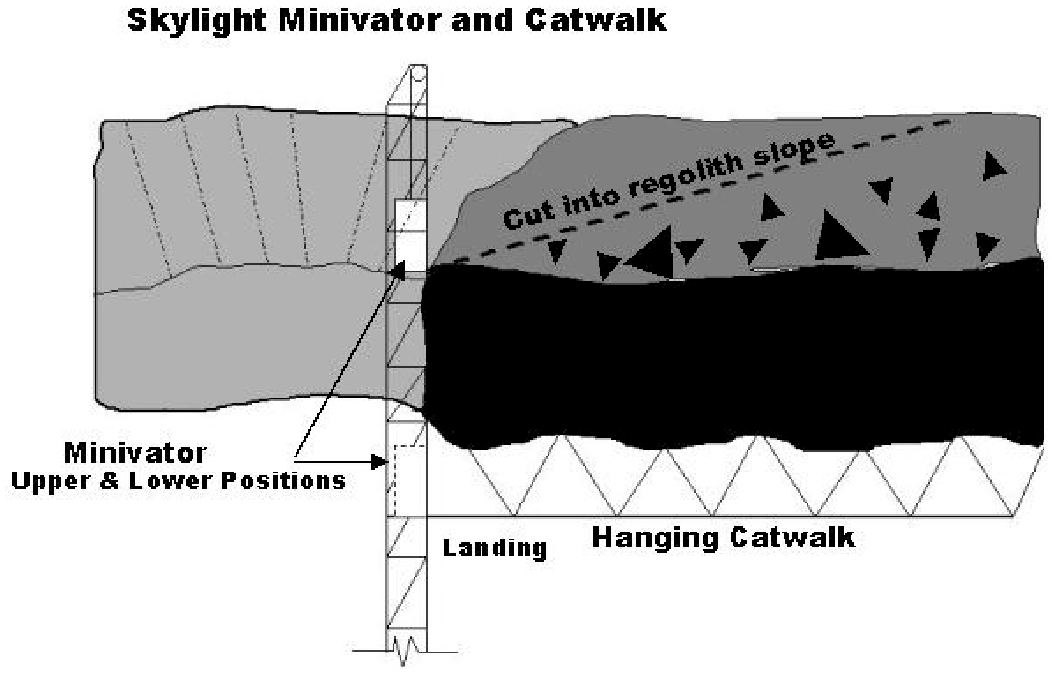

Figure 2: “Minivator” in box truss at a lavatube skylight.

Transferring materials and personnel between an operational base and the surface will require elevator systems more capable than this construction elevator. The initial cargo Minivator can be replaced by a pressurized module traveling between pressurized “shirtsleeve” environments in the cave and on the surface. A larger open-sided freight elevator may be built around the stabilizing box-truss of the Minivator to accommodate a variety of requirements, from resupply to moving large pressurized rovers into and out of the protective cave.

The ultimate extension of these systems would be the “Maxivator,” a disc-shaped assembly larger than the skylight itself, built in place or “dropped in” to place like a kitchen sink. A large central area of the disk would be the elevator, with suspension cabling and motors in the outer ring-shaped section. The Maxivator could be large enough to serve as a rocket landing platform, which would then lower the ship into the shelter of the lavatube for passenger and cargo transfer and servicing, after which it would be raised to the surface again for takeoff (Billings *et al.* 2000).

Hornito entrances. Hornitos occur where temporary blockage within the active lavatube causes molten lava to burst out to the surface. Eventually lava pressure overcomes and carries away the blockage, leaving a surface cone of solid basalt with a central hole leading to the cave. Since it is not formed by collapse, only minor debris is expected under the hole. Although weathering will have comminuted the original surface into regolith, the hornito provides a strong lip and solid foundation for devices to lower material and people into the cave. There is most likely a slope leading uphill to the lip, which provides a built-in safety factor over funnel-shaped skylight collapse entrances. Machines as simple as an A-frame pulley or as complex as an overhead crane or an elevator can be used.

Artificial entrances. A lavatube entrance could be created by artificial means. At first, holes could be drilled through the lavatube roof for power cables and communications. As greater expense is justified, the size of these holes could be expanded to include lightpipes directing daytime illumination into the cave. When sufficient numbers of people must commute between the surface and the lavatube interior, shafts large enough for personnel elevators could be cut through the rock.

The simplest way to create a larger skylight entrance would be by direct blasting. However, this would require evacuation of structures and people from a wide area of the cave around the target zone, and dump a large quantity of rock and debris in the otherwise pristine cave.

An alternative would be to create the skylight as a removable, monolithic rock plug. Although exceptionally challenging technically, creating an entrance this way would prevent most debris from dropping into the cave. Depending on the condition of the ceiling, preliminary stabilization treatments may be required. Drillholes would outline the proposed entrance and measured charges placed in them to fracture the basalt in a controlled way between the drillholes. Additional drillholes could hold suspensory cables that would “catch” the large lava plug when the charges are set off, preventing it from falling into the cave. This “plug” might be set aside on supports to shield a surface area for activities, or lowered into the cave to become a relatively flat floor beneath the skylight. The large size and massive weight of the plug makes these options difficult. On the Moon, the low gravitational acceleration of 1.6 meters/sec^2 would help to make plug removal, as well as installation of large mechanical devices, more manageable.

An artificial entrance can be placed for optimal service with surface operations and enhance the flow of people, goods, and construction material into and out of the lavatube base. The walls of the hole and the ceiling nearby would be more stable than around a naturally-occurring skylight and therefore require less preparatory work. The artificially-created skylight also has the advantage of being located where we want it, and sized according to our purposes.

Summary

We expect to encounter lavatube entrances with a wide range of forms and sizes, most of them requiring improvement for our use. Their amelioration calls for a variety of engineering techniques adapted to the specific geography, availability of *in situ* and Earth-sourced resources, and the level of base development. Even where considerable effort may be necessary, improvement of a suitable entrance to the shelter of a lavatube will be worthwhile.

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