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SUBSELENE: A NUCLEAR POWERED MELT TUNNELING CONCEPT FOR HIGH-SPEED LUNAR SUBSURFACE TRANSPORTATION TUNNELS

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Summary

High-speed lunar surface transportation between manned scientific, commercial, or logistical facilities will require subsurface tunnels because humans must be shielded from Galactic Cosmic Ray and Solar Proton Event irradiations. We present a concept called SUBSELENE in which heat from a nuclear reactor is used to melt rock and form a self-supporting, glass-lined tunnel suitable for Maglev or other high-speed transport modes. We argue that SUBSELENE is an optimal approach to forming transportation tunnels on the Moon because: (1) it uses a high-energy-density, high-efficiency, nuclear power supply; (2) it does not require water or other rare volatiles for open system muck handling or cooling; (3) it can penetrate through a mechanically varied sequence of rock types without complicated configurational changes; (4) it forms its own support structure as it goes; and (5) it is highly amenable to unmanned, automated operation. We outline the R&D needed to develop a SUBSELENE device and give a cost estimate based on experience with small-scale, field-tested, rock-melting penetrators.

Introduction

Current conceptual planning for a permanent return to the Moon early in the next century is focused on the establishment of a lunar base envisioned initially as a scientific outpost but eventually also as a resource base for a broad human advance into the space frontier.[1] The scientific focus is likely to be in the areas of astronomy[2] and planetology[3] with mining and processing facilities established for production of oxygen[4], structural components (e.g., glass[5]), and radiation shielding. Thinking about how all this might evolve leads us to the conclusion that, even though a single base might be established where human activity on the Moon is concentrated, there will also be a need for numerous fixed sub-bases such as launch facilities, mines, processing plants, and large astronomical telescope arrays, all of which will need to be physically separated to avoid mutual interference. For example, the dust raised by extensive rocket launch or mining activities would pose a serious source of pollution to sensitive optical instruments and other scientific equipment.[2] Thus, we envision the evolution of numerous fixed logistical nodes on the lunar surface that will require some form of rapid, non-polluting transportation system for frequent human visitation and material support.

Several transport concepts readily come to mind such as rockets, wheeled surface vehicles, or a rail system; however, few people realize that all of these concepts must face a common constraint if human cargo is to be a major item on their manifests--namely, shielding from the radiation environment on the Moon. The radiation environment on the lunar surface is harsh. Galactic cosmic rays (GCRs) produce a relatively constant radiation background in free space of about 50 rem/yr, consisting mainly of high energy protons but also containing higher atomic number particles such as iron nuclei that are particularly damaging to human tissue. Self-shielding on the lunar surface reduces this dose by about a factor of two,[6] but GCRs represent a long-term hazard to people outside the shielding provided by the Earth's atmosphere and magnetic field. In addition to the constant GCR background, people on the lunar surface will be periodically exposed to the radiation attendant to solar proton events (solar flares). These intermittent radiation storms can produce huge amounts of high energy protons for short periods of time (hours to days) representing doses of thousands of rems that would be promptly fatal to an unshielded astronaut on the lunar surface.[7] Effective warning time of these events is estimated to be no more than 30 minutes[8] and, thus, they represent a serious hazard to lunar workers.

On Earth, radiation exposure standards have been established that require doses of no more than 5 rem/yr for "radiation workers," and newly established NASA standards for astronauts propose a lifetime limit of 200 rem.[8] Thus, it is clear that any long term human usage of the Moon involving duty tours of months or years will require extensive use of radiation shielding and operational procedures that minimize exposures to the radiation environment. How much shielding is required? Estimates of 500 g/cm^2 have been proposed[6,7] representing 1-2 m of lunar regolith. However, continuing analysis of the problem seems to be in the direction of lower dose limits and, for the long durations associated with a lunar base, we believe that lunar regolith shielding equivalents of 10 m or more are likely to be established. This leads us to the conclusion that most lunar base facilities that are used frequently by humans such as living quarters, laboratories, and logistical nodes will be underground. Furthermore, fixed transportation facilities of the type discussed above that are frequently used by people would also logically best be placed underground. Thus, we are led to the conclusion that subsurface transportation tunnels featuring Maglev or other high-speed vehicle technologies will evolve as an essential requirement of permanent human exploitation of the lunar environment.

How might these tunnels, which would need to be hundreds or even thousands of kilometers long, be produced? On Earth, tunneling based on blasting and mechanical tunnel boring machines are well established technologies. Consideration of how to extend these terrestrial techniques to the lunar environment quickly exposes several potential difficulties. First, there is the question of the energy source needed to produce the tunnels. Explosives, for example, are a very compact and efficient way of storing (chemical) energy that can be released in a controlled way to effect rock breakage needed for tunneling. However, the energy needed to break rock is only a fraction of the total energy requirement for the production of tunnels. Generally, about equal amounts of energy are expended in the tunneling process for (1) rock fragmentation, (2) rubble removal or "mucking," and (3) tunnel support. We discuss these three aspects below in more detail, but it is easy to see that the latter two aspects, in particular, will be problems because of the special lunar environment. Efficient mucking for tunnels on Earth usually involves some sort or transport fluid such as air or water for the rock fragments; both of these volatile fluids are absent on the Moon and would need to be imported at great expense. Because of the extensive history of impact cratering on the Moon, the near surface region is extensively fragmented to produce a so-called regolith. Tunneling through this material will require extensive support of the tunnel walls and roof to prevent slumping, even in the reduced gravity field of the Moon. It is difficult to see how to overcome these special lunar tunneling problems by adapting conventional terrestrial tunneling technology.

Instead, we propose a new tunneling technology, subsequently termed SUBSELENE, that we believe is particularly well suited to producing large transportation tunnels in the difficult lunar environment. SUBSELENE is a concept based on rock melting to produce self-supporting tunnels with strong rock-glass linings and muck removal without using any volatile, imported fluid. We present a brief discussion of the basic concept, point out some engineering problems that will need to be solved for its realization, and make a rough estimate of development and delivery costs.

Tunneling Technology

Tunneling technology has traditionally evolved with the mining and transportation industries. For many years the construction of tunnels was primarily a mining process, consisting of three distinct phases: (1) breaking the rock or soil from its in situ state, (2) removing the cuttings (mucking) from the tunnel vicinity, and (3) providing support for the tunnel opening to achieve long-term tunnel stability. Until the mid-twentieth century, the rock breakage was accomplished using explosives; the mucking was accomplished with the aid of fluids (air or water); and the support liner was fabricated from wood, steel, or concrete.

Over the past thirty years, significant advances have been made in all three phases of tunneling technology. The rock breaking has been mechanized by the development of large-diameter tunnel boring machines (TBM). These machines have rotating cutting heads that chip the rock away and bore a full-diameter circular hole along the desired path. Mucking is accomplished by scraping the cuttings onto a conveyor belt which carries them to mine cars and thence out of the tunnel. Since the tunnel is bored to full diameter, there is sufficient work space to erect the required tunnel support system, either steel or concrete, behind the TBM. A big factor contributing to the improved tunneling performance of TBMs over previous construction methods is that the TBMs have steady, continuous performance. Previous to TBMs, the three phases of cutting, mucking, and lining were not carried out simultaneously as they are with TBMs. Currently TBMs are capable of boring 7-m-diameter tunnels at rates of 20 m per day in medium hard rock.

TBM's and other traditional systems are very equipment dependent and require a considerable labor effort to deploy. An automated tunneling system, an obviously major goal on the Moon, requires selection of a system that is independent of the details of the rock and soil conditions and types and can include all three functions of the tunneling system. An additional interesting aspect of the lunar application is that there is an opportunity to fabricate the spoils or debris into useful forms and minimize the need for materials supply and structural fabrication from sources outside the tunnel. One approach that meets these goals is a system concept developed and set forth[9] to solve advanced tunneling and excavation problems on Earth. This technique involves melting of the rock and soil, forming melt-glass liquids, and processing the debris into useful forms. A compact, nuclear reactor powered system with extensive automation of control and operation was termed a SUBTERRENE; applied on the Moon, we term such a system a SUBSELENE.[10]

Advantages of Subterrene Technology on the Moon

The rock melting SUBTERRENE technology was invented at Los Alamos National Laboratory for making vertical and horizontal holes by heating and melting rocks and soils. The three major facets of excavation—rock fracturing, debris removal, and soil stabilization--are accomplished in an integrated operation. This approach depends on the fact that rocks have relatively low melting points, about 1200°C, compared to refractory metals such as molybdenum and tungsten. Furthermore, the rock melt that is produced can be chilled to a glass and formed into a dense, strong, firmly-attached hole lining, which is particularly useful when excavating in fractured or loosely compacted soils or rocks. The SUBTERRENE technology developed at Los Alamos in the early 1970's used rock melters powered by electric heaters, but the thermal power requirements of a large-diameter tunneling machine could best be supplied by a compact specially-designed nuclear fission reactor.

The SUBTERRENE technology that was developed at Los Alamos demonstrated many characteristics that could be turned to good advantage for excavation work on the Moon. The lunar environmental characteristics such as no atmosphere, low gravity field, lack of free water and oxygen, and plentiful quantities of loosely consolidated soils, are all advantageous to operation of the rock melting system.

The three major phases of excavation are still required for lunar excavation using the rock melting principles. The rock cutting phase is easily accomplished by applying the hot refractory metal-melting body to the rock or soil. The melting body turns the rock or soil into a liquid. Part of the liquid is configured into the glass lining, while the remainder is extruded backward out of the hole and further processed into a variety of structural building materials. The refractory metal-melting body should have a very long service life on the Moon because no water or oxidation corrosion will occur. The glass lining has more than sufficient strength to provide completely adequate structural support for the tunnels.[5]

The SUBSELENE rock melter is very insensitive to the type of rock, hard or soft, dense or porous, that it encounters. All tend to turn into liquid melt at approximately 1200°C and are processed into dense, strong glass in a similar manner. A major advantage of the rock melting technology for lunar tunneling is that the removal of spoils does not require the use of fluids or gases as does mechanical tunneling on earth. The melted rock can be extruded or pumped mechanically and no fluids or gases are required to handle the melt. This constitutes the entire mucking operation. In porous materials, the rock melting results in a consolidation process also. In many cases, this consolidation is a great advantage in providing strong structural support to the hole.

SUBSELENE Design Concepts and Options

Figure 1 is a sketch of a proposed 5-m-diameter thermal lunar tunneler. On this SUBSELENE tunneler are 134 individual rock melting heaters. Each heater requires 3 Mw of thermal power, provided by a liquid metal heat pipe which is connected to a nuclear fission reactor. A smaller, 3-m-diameter tunneler would require approximately 50 of the 3 Mw heaters. The total thermal power requirements are approximately 400 Mw for a 5-m-diameter lunar tunneler and 150 Mw for a 3-m-diameter tunneler. These thermal powers are based on a very fast advance rate of 80 m/day. Projection of power requirements for SUBSELENE applications at more modest tunneling rates is relatively straightforward. The energy to melt soil and rocks is not sensitive to large variations in subsurface condition. Therefore, a direct statement of tunnel diameter and productivity (rate of progress of tunnel construction) gives the required thermal power levels. Table I shows these projections for 3 and 5 m tunnels; the operational values essentially scale linearly with both diameter and progress rate.

TABLE I

THERMAL POWER REQUIREMENTS

Advance rates m/day	30	50	80
Power for 5-m-diameter tunnel, Mwt	150	250	400
Power for 3-m-diameter tunnel, Mwt	56	94	150

The thermal power for the tunnelers would be supplied by suitably-sized nuclear fission reactors, a reactor being positioned immediately behind the melting head of each tunneler. Each reactor could be a basic graphite cored design, fueled by UO_2 dispersed pellets. The reactor core fuel element matrix would include spaces for insertion of the required number of heat pipes. Surrounding the core will be a beryllium reflector that will include reactivity control elements. The reactor thermal power will be transmitted to the rock melting bodies by liquid metal heat pipes. Either lithium or sodium-potassium type of heat pipes should be satisfactory.

The control functions of the nuclear reactor and the thrusting/gripping functions of the tunneler, as well as all other auxiliary functions will be accomplished by electrical/mechanical systems powered by conversion of waste heat from the main reactor to elec-

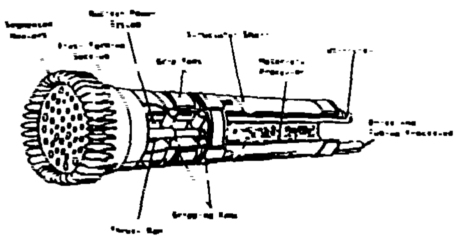

Figure 1. Trimetric View of Proposed Thermal Lunar Tunneler.

tricity. An alternate approach to this dual mode operation would be to provide another nuclear reactor located outside the tunnel and electrical power distribution via superconducting transmission lines. However, the latter is likely to be an unnecessary complication since, as we indicate below, there is so much waste heat associated with a SUBSELENE that electric power is likely to be an important by-product of its operation.

The thermal balance of the SUBSELENE poses interesting problems in heat transmission and rejection. Since the lunar soil is a very poor thermal conductor, most of the thermal energy in the rock melt must eventually be carried back out of the tunnel and rejected by radiation. The sequential transmission of the thermal energy will be accomplished by a liquid metal convective loop, Na-K being a candidate. Figure 2 shows a block diagram of this system, the function that the system accomplishes, and the temperatures throughout the loop. The physical makeup of the loop will include sealable high-temperature metallic pipe. The sealable feature is necessary so that the thermal distribution system can keep up with the advancing tunneler. Regulation of the optimum temperature at each functional block is accomplished by metering bypass Na-K flow at each block. Overall heat rejection is self-regulated because the heat rejected by the radiation is proportional to the fourth power of the temperature. The waste heat rejection system is probably the limiting aspect controlling the size and advance rate of a SUBSELENE, since we estimate that at 400 Mw about one [illegible] kilograms of Na-K per second would need to be pumped to the radiators

Operation of the SUBSELENE is carried out completely remotely and automatically. Most systems are self-regulating, such as reactor power by thermal power demand, advance rate by constant thrusting force, distribution of thermal energy by the heat pipes and Na-K convective loop, etc.

The rock melt output deserves further consideration. The rock melt, when properly processed by careful cooling and tempering, can comprise the strong, dense structural lining around the tunnel opening. The structural reinforcement will be enhanced by the very fluid melt flowing into and filling up any crevices in the lunar soil. The strength of this high-quality glass exceeds the strength of concrete, more than adequate for supporting tunnels in the reduced gravitational field of the Moon. Normally, an excess of rock melt over liner needs will be available. This excess can be cooled under controlled conditions and formed into useful structural shapes such as bricks and cylindrical tubes.

Cost

Cost estimating of large, high-technology development projects or construction of civil structures in new, hostile environments is a difficult undertaking. Here, we are faced with both aspects at once in attempting to estimate the cost of a SUBSELENE system. At best, we can only point out some aspects of the problem to stimulate discussion. First, we can only begin our estimate within the context of a lunar base development plan, the outlines of which are just now beginning to be established.[1,11] We will need to know the number and separation of base transportation nodes and the quality of any supporting infrastructure. Lacking such detail, we guess that somewhere between one and five SUBSELENE tunneling devices will be needed with several thousands of kilometer life capabilities.

Next, we estimate that each SUBSELENE device will mass 120,000 kg, equally divided between the tunneler and the waste heat rejection system, and will have a unit development cost of $50M. This is based on experience with small diameter rock-melt drills and study of a conceptual SUBTERRENE tunneling system.[12] It is hard to be certain about the development cost, but we guess that our estimate is within a factor of five on the high side. Such a gross estimate is probably good enough at this point because we judge that the total cost of using a SUBSELENE system is likely to be dominated by the delivery cost of the hardware to the lunar surface rather than the

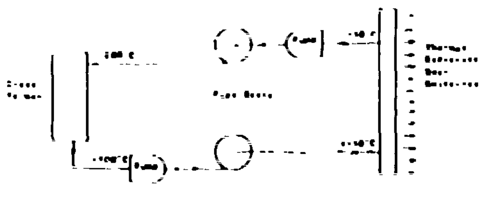

Figure 2. Na-K Heat Rejection Loop.

capital cost of the device itself. This has been the case in most recent analyses of large-scale orbital structures[13] and facilities such as lunar bases[11] or Mars bases,[14] and is the reason why there is so much interest in using extraterrestrial resources for rocket propellant (e.g., lunar oxygen extracted from the regolith silicates or oxygen and fuel from the Martian atmosphere). Much of the cost in moving mass out of the near Earth region is the cost of lifting the propellant to low Earth orbit. If a substantial fraction of this propellant can be obtained outside the Earth's deep gravity well, then substantial transport cost savings seem possible. The same reasoning can be used to argue that lunar materials should be used to construct a portion of the tunneling devices rather than lift the mass from Earth. Trade studies are needed to find the break-even point where the cost of local production is less than the cost of transport from Earth. It is not clear at present where that point might be for a SUBSELENE system.

In any case, we estimate that the bounds for transporting a single SUBSELENE system from Earth to the lunar surface are \$155M to \$2,323M The upper bound is based on experience with the Space Shuttle (\$3000/lb[15]) and the lower bound on a goal recently expounded by the National Commission on Space (\$200/lb[11]). Thus, our guess for the total cost of building and placing a SUBSELENE tunneling system on the Moon is \$205M to \$2,373M. Clearly, much needs to be done to refine these estimates; however, this magnitude of equipment costs is felt to be consistent with the infrastructure investment associated with an extensive lunar subsurface transportation system.

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