Tunnel Boring Machines for Off-World Colonies

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Abstract - Inflatable or 3D printing lunar facilities have been proposed for sustainable off-world colonies. They, however, will become uninhabitable after the first meteorite, quake, act of war, or cosmic ray burst. We propose the idea of landing a Tunnel Boring Machine (TBM) on the Moon to create multi-kilometer long 8.5-meter diameter tunnels. We would start by boring deeply (~60- to 600-meter deep) within the planetary body until surrounding rock is insulating and can hold an internal gas pressure of 100 kpa. A 2-megawatt parabolic solar dish collector with a Stirling engine would power the facility during 2-week long days. A hot rock geothermal power generator from waste heat would power facility during the 2-week long nights. Most importantly, a TBM based colony would give the venture a reason for being there and expanding, mining minerals.

Numerous concepts have been proposed for building the infrastructure for sustainable off-world colonies. They vary from landing complete Lunar facilities using 100% Earth materials (e.g., inflatable) and covering them with Lunar regolith for solar protection. Some have proposed landing 3D printing machines that would build igloo-like structures out of the Lunar regolith, using adhesives from earth. Advocates of 3D printing machines claim this technology requires 80% less material than the first option. However, in this paper we are advocating the idea of landing a Tunnel Boring Machine (TBM) to bore deep into the planetary body. The largest 16-meter diameter TBM requires up to 10 Megawatts of power while traveling 50 feet per day. Less power would be required for a smaller diameter TBM or less travel per day.

Power Source Options

1, 2, or 3 megawatts may seem like a lot of power, especially since the ISS only generates 160 kilowatts. However, any option to construct a Lunar colony will require power of some sort. Not only is power needed for the TBM or 3D printer, but the Lunar base will need electrical power after it is inhabited. It is just a matter of which power source makes the most sense.

Sunlight based systems must store sufficient energy during the 2-weeks of daylight to power all the equipment during the 2-weeks of night.

Power Options

In the following section, we take a quick survey on different means of powering a space colony. A nuclear power plant was not considered since launching nuclear fuel would require an Apollo-type effort in regulations that must be met. Nonetheless, planning an off-world colony with only KW instead of MW of power is the same as starting a manufacturing business with cents of working capital, when you need $Millions.

1. Solar Panels and batteries are the most common power option used in aerospace, to date. But batteries are heavy and solar panels are only ~21% efficient and will overheat with little means of dissipating waste heat since the back sides of the solar array will face the Lunar surface, which will become a poor heat sink over the 2-Earth week Lunar day. The International Space Station solar array produces 120 kw of electrical power, but they can more easily get rid of heat from the solar array as the back side of the array faces the black-body of space, which is a perfect

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heat sink for radiation heat transfer. Single layer solar cells will require 4,762 square meters of solar panels to produce 1MW of electrical power.

2. Radioisotope thermoelectric generator (RTG, RITEG) are the second most common power option used, to date. In order to generate 1MW of power, we would need 1.85 metric tons of Plutonium 238 isotope. Currently, some USA agencies have a desire to produce 400 grams per year; RTG's are not a long-term solution.
3. We advocate a 3rd option. A Parabolic Solar Dish Collector or Dish Stirling and an alternative energy storage device. Dish Stirling have a stand-alone parabolic reflector that concentrates light onto a receiver placed at the focal point of the reflector. Although Stirling Energy Systems of Phoenix, AZ filed for bankruptcy in 2012 due to falling photovoltaic prices caused by Chinese subsidies, this remains the best power source on the Moon. What is the alternative energy storage device?

    a. Excess electricity produced during the 2-week long Lunar days would need to be used in the electrolysis of water to produce hydrogen and oxygen gases. These gases would be use in fuel cells to produce electricity during the 2-week long Lunar nights. The water is constantly being reused.
    b. Most fuel cells are 50 to 60% efficient without recovering the heat of operation (steam is a fuel cell's exhaust). Additional energy (for a total of 90% efficiency) could be obtained by recovering steam heat from the fuel cells via the same Stirling engines on the parabolic dish collectors. Such a system would require 1,100 square meters to produce 1MW of electrical power.
    c. Fuel cells are a well-established technology. California plans to operate over 7,000 Fuel Cell Electric Buses by 2040, many of the fuel cells from Ballard Power Systems. The buses are to compete against 280 hp diesel and 85KW lithium-ion battery buses with 100 kwh of energy storage. The Fuel Cell buses carry 37.5 kg of hydrogen on-board.
    d. Ballard Power Systems already has a 1MW stationary fuel cell module that fits in a standard shipping trailer.

4. The tunnel colony could be self-sustaining, energy-wise. During the day, we would use a solar parabolic dish collector/Stirling engine. Waste heat from the Stirling engine is discharged via radiant reflectors. The initial plan was to have twice the required solar dish systems in order to operate at night. The excess energy during day would be used to make hydrogen and oxygen that would be stored until used in fuel cells at night. However, after boring 200 to 2,000 ft under the surface, we wouldn't need the fuel cell system. Heat from base activities and the planetary body interior could generate electrical power during the 2-week long Lunar nights (reference how electrical power is generated by Hot Dry Rock Geothermal Energy Power Generation). We would pipe a gaseous cryogenic refrigerant to a condenser on the surface (radiant reflectors) and send liquid refrigerant underground to expand through a turbine to generate electricity.

Roof Support

For very hard and very strong substrate, no additional support is needed to support the roof. Hydraulic actuators for tunnel head would merely push against the tunnel wall. For strata that is less firm, steel rods (brought from earth) will need to be driven into the walls and the hydraulic actuators would push against them.

Tailings (or Spoils)

Tailings from the TBM will need to be transported out of the Lunar tunnel via a battery powered Lunar Rover Truck. The tailings could feed a 3D printer that prints buildings on the surface. As the tunnel becomes 1,000's of feet long, it will become more important that the tailings are removed so that a raised floor is installed that will house the colony's electric, HVAC, filtration, lighting, water, and plumbing.

Figure 1 shows a Boeing 747 cross-section; it only has a 6.1-meter cabin width for a size comparison. We hope to bore a 16-meter-diameter lunar tunnel. This is a really telling example. Any view of the interior of the ISS or MIR space station and you will notice ductwork or flexible air tubes routed down corridors and into different compartments. If a space colony is 3D printed, how are they going to route the HVAC, electricity, water, sewage, communications and controls? In this picture you should realize that all of those items can easily be routed in the bottom portion of the tube (where the car is located) along with anything that needs to be easily stored.

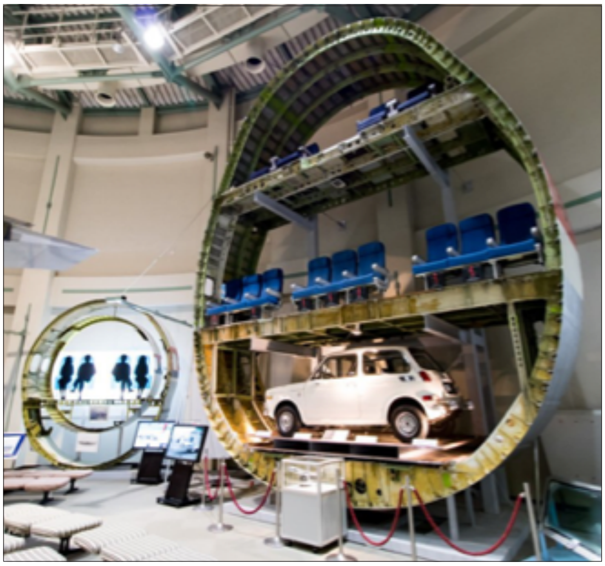

Figure 1. A Boeing 747 cross-section.

Electrical power

Electrical power to the TBM could be a safety problem. We could extend a high voltage (~500KV) electrical wire from the tunnel entrance to the TBM. The silicates that make up the Lunar strata and lack of moisture in the ground make for a very good electrical insulator. At the same time, this lack of humidity could cause electrical shock.

Do the advantages of the proposed concept outweigh the disadvantages? In the following section, we try to put forth several of the major PROs and CONs of using a Tunnel Boring Machine to establish Off-World Colonies.

The PROS of this concept

1. Safer from bombardment. Colonists deep in the tunnels would be perfectly safe from a random meteorite bombardment, acts of war, or cosmic ray flare up, unlike 3D printed or inflated structures. Even life on earth is susceptible to large meteorites.
2. Gives colonists a purpose. One purpose could be to mine for minerals, especially while they are mining their own living spaces. If colonists can find and develop metals and minerals, the colony can be self-sustaining. The metals can be used to create more TBM's and other structures. Concepts that don't use a TBM must have a separate operation and equipment for mining.
3. Colony can be self-sustaining, energy-wise, as delineated above.

The CONS

1. A TBM is heavy. An 8.5 meter-diameter TBM would weigh 828,000 lbs, if all of the parts are needed and not just the cutting head.
2. A TBM requires a lot of energy. An 8.5 meter-diameter TBM requires 3,150 kw of

power at full speed operations. However, the TBM does not need to be operated at full speed and the same energy source that powers the TBM will power the colony after the tunnel has been completed.

3. A TBM requires some human operation. This can be a CON or a PRO. The TBM gives the colonist a reason to be there. Removing the tailings by a separate vehicle would only be needed after the TBM has penetrated deep under the surface.

A Robbins HP open hard rock TBM can bore tunnels up to 8.5 meters in diameter. It was used to bore the fresh water supply for New York City. It needs 3,150 kw of power.

Table 1 shows the 5 major TBM components for an 8.5-meter TBM. The cutterhead is only 21% of the total mass of the TBM and is the only component that must be launched from the earth until such minerals can be mined on the moon and Mars.

With all the promises of a self-sustaining Lunar colony, a TBM-based colony could merit serious investigation.

Table 1. The 5 major TBM components.

Components	Tons	Lbs	Percent of total
Main beam	85.2	188,000	22.70%
Cutterhead support main bearing, and seals assembly	110	242,000	29.20%
Gripper carrier	67	148,000	17.90%
Rear support	34	75,000	9.10%
Cutterhead	79	175,000	21.10%
Totals	375.2	828,000	