

Lunar Underground Mining and Construction: A Terrestrial Vision Enabling Space Exploration and Commerce

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ABSTRACT

As the Space Shuttle, Candarm and Space Station end their useful lives the question “What next?” needs to be considered. Several countries including the USA and China are looking to the future through exploration of the solar system, thus the NASA logo “Earth, Moon, Mars and Beyond”. The moon is the first major target for NASA and the recent discovery of water has many eying the moon with new vigour. The reason, it now seems likely that a permanent lunar base is possible by using the natural resources available, in particular recently found water. The ability to break water into hydrogen and oxygen for providing the main necessities of life, rocket fuel and air to breathe make this permanent base feasible. Furthermore, several significant environmental issues will force this permanent base underground. These issues include lunar radiation, solar flares, temperature extremes and micro-meteorites. Lunar radiation alone will force this move to rock shielding protection of astronauts as at least 10 metres of

rock cover will be required to protect human, animals and plants.

As early as 1959 the US army considered a permanent underground base on the moon. While the original underground idea has merit space pioneers have strayed from this sensible safe concept. Furthermore, advances in proven telerobotic mining technology for terrestrial purposes can provide the opportunity for the space programs such as the Canadian Space Agency (CSA) to concept, design, build and implement an underground lunar habitat and a mining and processing operation.

This paper discusses a Canadian concept behind a permanent manned outpost on the moon. The paper will discuss the need for an underground outpost, how it might be constructed and the terrestrial technologies that can enable this base to be made and used to construct a mine on the moon.

INTRODUCTION

The discovery of water on the moon recently and NASA's interest in using the moon for exploration and potentially the manufacturing of fuel to explore the solar system, has many contemplating how to live and work on the moon. Astronauts will concentrate on three major activities: survival, exploration and mining including processing. As this mission progresses the focus will change from science based to commercial work. Further mission lengths will change from sortie type short term missions to semi-permanent to permanent with long term manning of the mining and processing operations.

Safety of astronauts will be of prime consideration. Hazards need to be identified and designed out where possible. The main hazards to be considered are:

- Short Term
 - Oxygen
 - Water
 - Shelter
- Long Term
 - Radiation Protection
 - Solar Flare
 - Temperature extremes

- Micro-meteorites

The design of any lunar base will need to address these issues so astronauts are able to survive and be protected from the environment. These environmental considerations will drive many decisions. The type of base, construction techniques, equipment needs and physical layout will all need to be considered closely.

Current NASA plans, as shown in figure 1, may suffice for short term sortie missions, however long duration stays appear unfeasible due to environment conditions. The blocking of radiation and solar flare activity and protection from the other extremes need to be adequately designed. As all these factors are considered an underground base with suffice depth appears to be a feasible solution. The key questions are:

- How would this be built?
- What technology will be needed?
- Has this type of facility been built before?
- What would the timing of such a base?

These questions are all addressed in this paper.

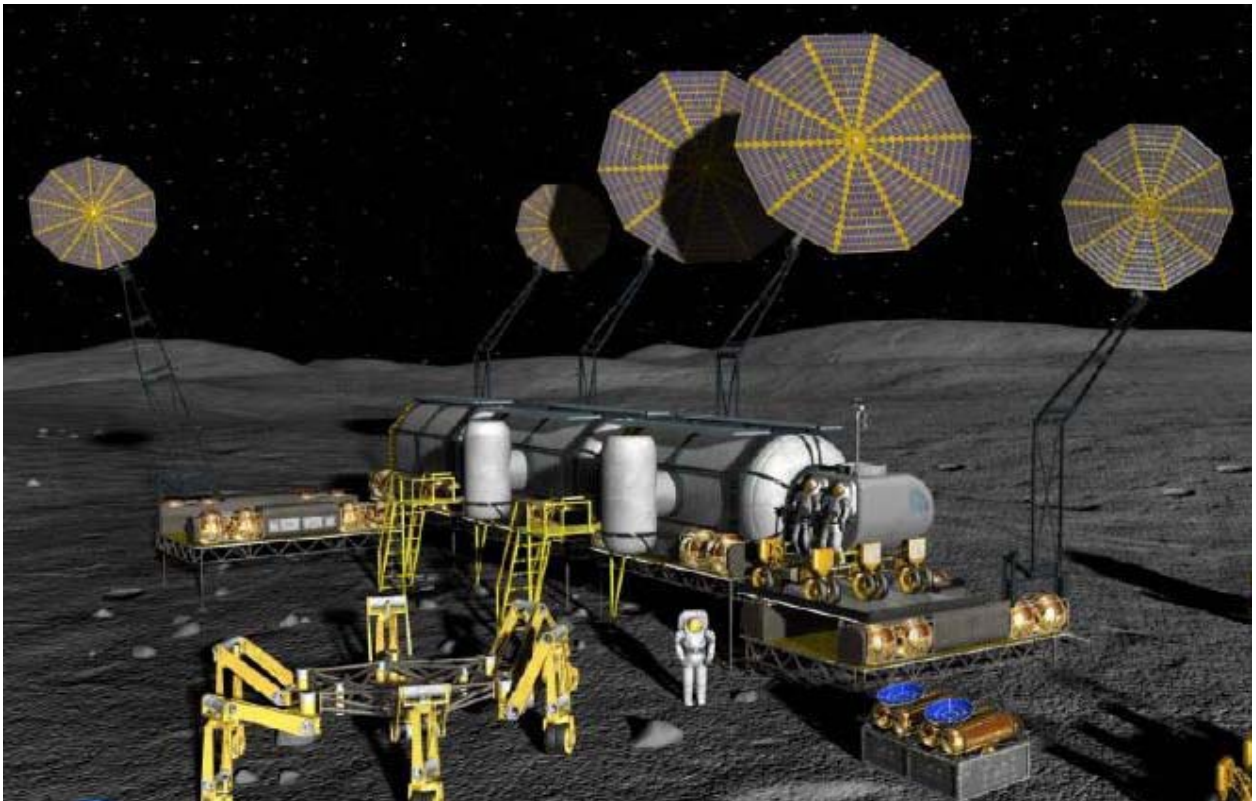


Figure 1 - CxAT Habitation emphasis showing hard-shell habitats [Gruener, 2009].

State-of-the-art in Robotic Mining and Construction

Robotics for terrestrial robotic mining and construction has been the topic of a large portion of public and private research over the last 2 decades and today remains a hot topic for major changes in the way mining is done. Inco Limited's Mines Research group first demonstrated that long distance teleoperation of multiple mining vehicles was possible in 1994 at the Canadian Institute of Mining and Metallurgy Annual General Meeting. This demonstration had a teleoperator running two LHDs between the stage of the John Basset Theater at the Toronto Convention Centre and

Copper Cliff North Mine in Copper Cliff, Ontario a distance of over 400 kilometers and 4000 feet underground is shown in figure 2. The demonstration was done with unnoticeable latency. What made this possible was an advanced telecommunications network that provided 600 Mb/s of wireless bandwidth developed by Dr. Baiden. The success of this demonstration proved that the systems developed were technically successful through improving safety, increasing productivity and lowering costs. This demonstration led to the approval of a far reaching program called the "Mining Automation Program" or MAP.



Figure 2 – One Teleoperator running two LHDs at the CIM Annual General Meeting 1994 (courtesy Dr. Greg Baiden)

MAP was a joint program led by Dr Baiden, involving Inco Limited, Tamrock OY, Dyno Nobel Explosives and Natural Resources Canada. The objective of this program was to build on the research originally developed by Inco – Mines Research. This program would develop Operation Center concepts for the teleoperation of mobile mining machines and developing the economic case for this transformational rework of mining operations. Mines Research had developed an extremely high bandwidth telecommunication system that could support fleet operation of mining equipment. And, a second development was the ability to provide the equivalent of GPS positioning for underground mining. MAP using these developments targeted building tele-robots for exploration drilling, tunnel drilling, explosives loading and ignition,

material removal and transport, rock stabilization, longhole drilling and ore transportation systems.

Two examples of the outcomes of MAP are shown in Figure 3 and 4. The first figure 3 shows a teleoperator running three LHDs from the safety of a centralized control centre in an industrial teleoperation workstation. Figure 4 shows a similar scenario where the teleoperator is running three longhole production drills from a centralized control room. The machines operating in these scenarios operated in production for 2 years regularly from distances of 25 kilometers away with unnoticeable latency to the operator. This was all enabled by an innovative broadband telecommunication infrastructure developed by Dr. Baiden.



Figure 3 – Teleoperation Control Chair to teleoperate multiple Load-Haul-Dump mining machines from an Operations Centre (courtesy Dr. Greg Baiden)



Figure 4 – Hardrock Driller running three long hole drills from a Central Operations Centre (Akerman, Flynn, Baiden 2000)

The outcomes of this research work is currently being applied around the world at mines in Canada, USA, Chile, Brazil, South Africa, Australia and Sweden. The accomplishments of this research is of prime importance to the undertaking of lunar mining as the hostile environment will necessitate the use of these technique for mining for water and other chemicals on the moon.

Hazards

Current surface lunar outpost concepts are risky due to unmitigated environmental hazards. Mission risks could be significantly reduced by advance telerobotic preparation of safe haven shelters, fuel, water and power caches, and underground facilities. Primary lunar environmental risks that are expected to directly influence astronaut safety include vacuum, radiation, extreme heat & cold, isolation (distance from rescue and logistics) and environment-related equipment failure.

Show stoppers include:

- Fatal solar proton radiation events
- Accumulated cosmic radiation dosage due to insufficient shielding
- Sudden loss of pressure for spacesuits, rovers or habitats
- Overheating or freezing of astronauts or critical infrastructure elements
- Failure of logistics to deliver sufficient consumable oxygen, water or food
- Failure of transportation or infrastructure systems (i.e., Apollo 13)
- Loss of or insufficient fuel for a safe return

As illustrated below, cumulative radiation damage will become the limiting factor in

length of stay for astronauts at a human lunar outpost. A key enabler for long stays is access to facilities with deep cover. Thus, an underground lunar facility would qualify as an enabling capability.

"Radiation exposure is THE SHOWSTOPPER for lunar or planetary exploration missions that do not make a realistic assessment of this hazard to health and safety."
[Cohen, 2002]

Radiation protection could be addressed by either robotic pre-fabrication of “solar storm” shelters from locally available regolith, or by using imported water or polymer based shielding for vehicles and structures. As shown in the figure below, galactic cosmic radiation (GCR) exposure is actually *increased* by shielding material, and only starts to decrease after more than two meters of burial depth or shielding thickness. In other words, the amount of shielding that will save astronauts from solar proton events (SPE) actually increases the exposure level due to GCR. Current lunar base concepts are challenged to overcome this problem. The primary solution offered to date is to limit the total exposure of astronauts by limiting the number of missions they can participate in and the duration of those missions. The solution proposed by this paper is to go underground. Underground lunar facilities offer mitigation modes that offset many show-stopping environmental problems. In addition, the possibility that an astronaut-friendly thermal environment could be maintained in very cold places due to the highly insulative nature of the regolith provides added rationale for going underground on the Moon. This would enable

a storm shelter to be created in polar craters to protect human visitors from the extreme cold.

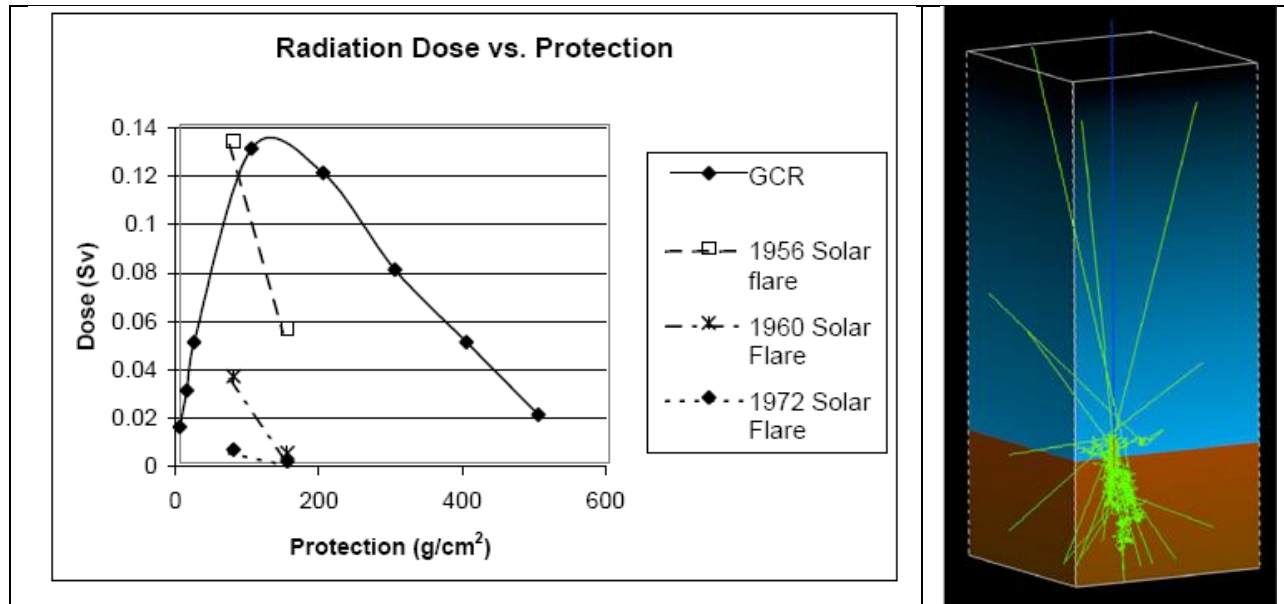


Figure 5. Estimated GCR dosage vs. depth of burial (left), and visualization of secondary particle production dynamics [Dartnell, 2007 and Jablonski, 2005].

Development of an Underground Lunar Base

Establishment of an international underground lunar outpost and mining facility could activate Canada's leadership for next-generation robotics, leveraging experience gained during the CanadaArm project for the international space program. This type of early lunar outpost could easily expand to support multiple large science projects as well as commercial operations. In addition, the work has many terrestrial spin-offs such as underwater mining and construction. The underground habitat layout and construction sequence are shown in the figure 6. In this series of images the underground outpost

starts with collaring a portal into the side of a crater to establish a garage, sleeping quarters and research facility. The excavation of all these initial requirements will be done from the earth based operation centre. Once these are complete, the first major component to install is a collar airlock. At this point the outpost can begin to be habited by astronauts. Initial lunar base pre-development work will require an Earth-based control centre for teleoperation of construction and mining robotic equipment. Several Teleoperation workstations optimized for managing the latency between earth control and lunar operation would run from a control room in Canada.

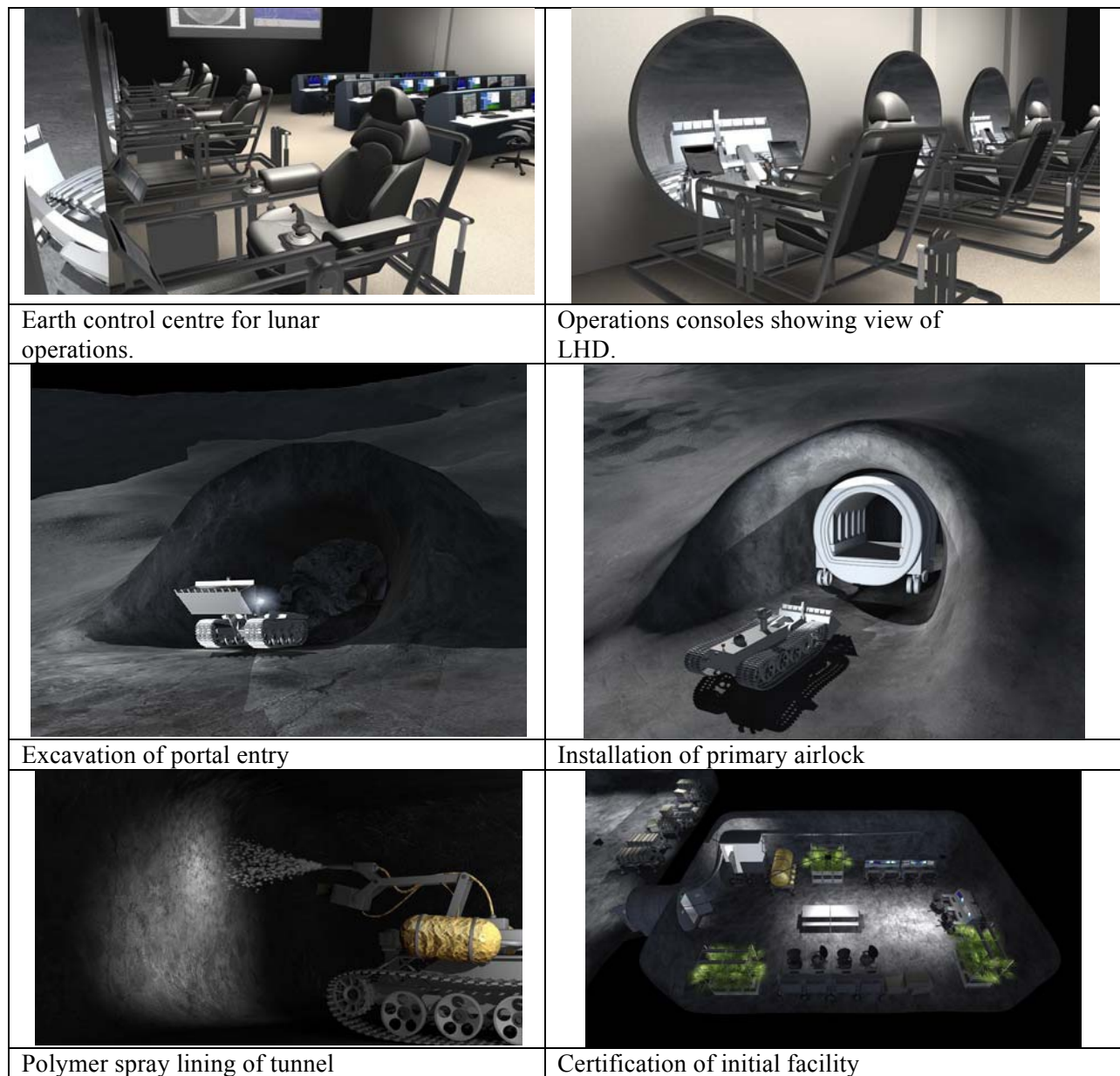


Figure 6. Construction sequence for early shelter habitat.

Preliminary analysis indicates that these systems offer a feasible solution to building and certifying a radiation safe underground lunar facility. Unit energy (kW per cubic meter) for lunar excavation is expected to compare to that used in analogous terrestrial mining, tunnelling and drilling operations, enabling time, volume and equipment productivity estimates to be derived from mining practice and modified as needed to suit

the lower gravity, etc. It is assumed that a majority of operations will be conducted in a sealed and partially pressurized environment, reducing the wear and abrasion of equipment and enabling the use of standardized dust management practices. Estimates of the amount of microwave energy required to sinter lunar regolith [see Wingo, 2007] enable calculation of the power required for structural tunnel support

and sealing. Sealing will be augmented with a polymer coating used in the Canadian mining industry.

As habitation is beginning the construction machinery can continue to advance facilities deeper underground. This can be followed by the building of science experiments such as astroparticle observatory and/or infra-red telescope. Construction scenarios shown above can be used to generate a detailed view of the “concept of operations” typically associated with space mission planning. These operational scenarios should be based on terrestrial mining industry experience for the underground construction of development and production drifts, ramps and block mining operations by the mining industry.

Underground Lunar Mining and Processing

The recent discovery of water in the quantities appears to be in scale with the styles of mining

that are currently used in terrestrial scenarios. Small scale mining may be able to provide basic survival for astronauts and plant life, however, in following on with NASA's mission to explore the earth, moon, Mars and beyond the scale will need to change significantly to turn the moon into the fuel generator of the future.

The achievement of this larger commercial goal will see large scale mining and processing of water for oxygen, hydrogen and fuel. Techniques such as “Block Caving” (figure 7) in a totally underground environment linked to the outpost would support the manufacture of such large quantities. Chemical plants and storage tanks made in the rock would allow the efficient use of lunar gravity for the processing of the water bearing material.

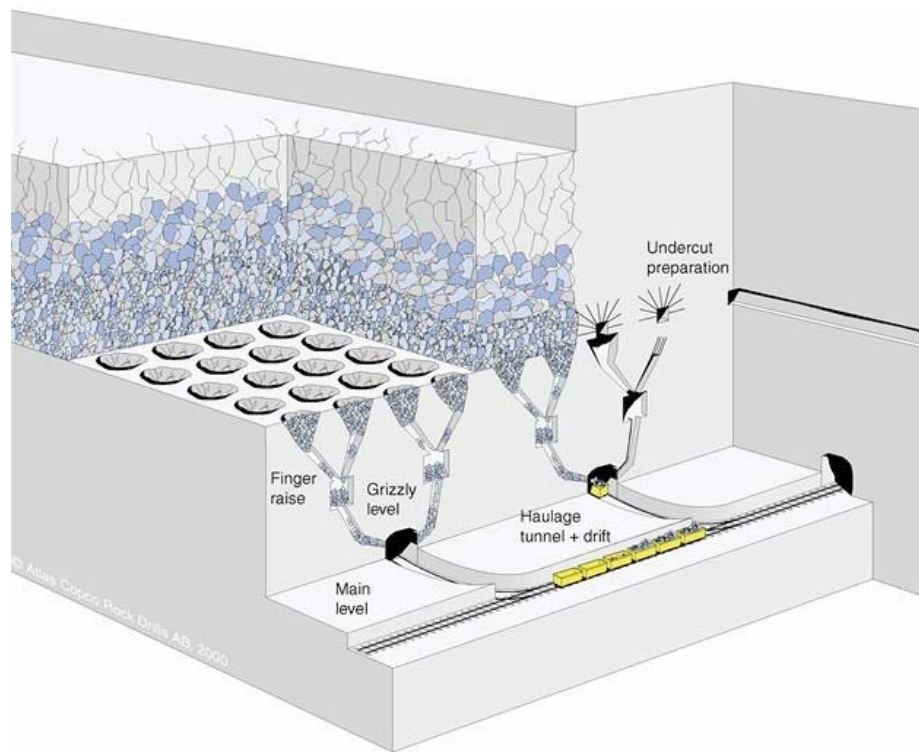


Figure 7 – 3D concept of Block Cave Mining

This technique is feasible of the moon in the gravitational constraints and it minimizes the amount of mining machinery and personnel required to be launched to the moon for performing this work. It is also a technique that can be automated and teleoperated from earth once established.

Economic Leverage of Lunar Resources

Learning to live off the land will add vitality to human space settlement, and will create new jobs, industries, markets and natural habitats as humankind expands its economic sphere. From the potential of Helium 3 (3He) as fuel for future fusion energy, to the production of Hydrogen, Nitrogen, Carbon and Oxygen to support space exploration mission logistics, to future surface manufacturing of system components from Aluminum, Titanium, Iron, Silicon, ceramics and glass, lunar resources pose a significant opportunity for the future.

"The space frontier will inevitably increase the scale of thinking and risk taking by business. When we are dealing with space, we are dealing with a technology that requires a planetary scale to stage it, decades

of time to develop it, and much bigger investments to get across the threshold of economic return than is customary in business today.

Business must now think in international terms and in terms of the next business generation. It must step up to the big risks with the same vision that enabled an earlier generation of builders to push railroad tracks out across the wilderness and lay the foundations of our modern economy." Ralph Cordiner [from Webb, 1964]

Indeed, the visual of an expanding three-part sphere of influence composed of exploration, economic development and mature economic operation, can be used to describe highly successful prior empires from the Phoenicians, to the Romans, to England and finally the USA. As shown in the figure below, this model is also useful to describe our potential future in space, as prospects turn into mines, ore turns into products, and in-space manufacturing feeds an ever expanding space infrastructure.

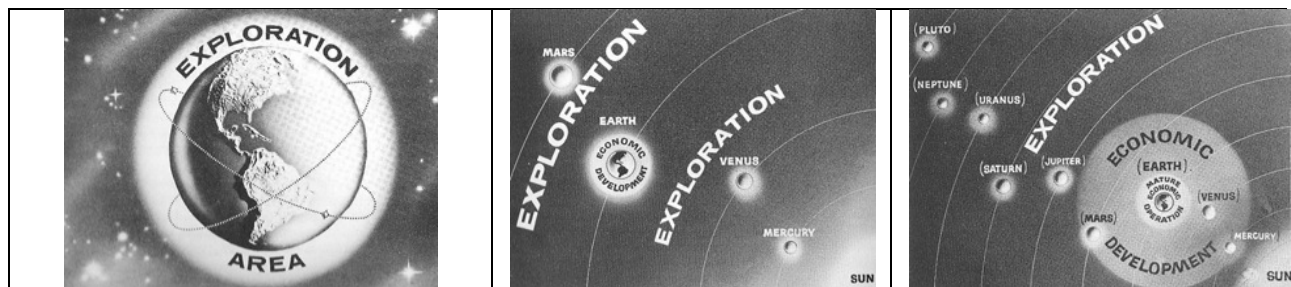


Figure 8. Exploration, development and mature economic operations [Cordiner, 1961]

The first anticipated commercial use of lunar resources is the supply of rocket propellant to government and future private users of the Moon and lunar facilities. The simple addition of an ISRU refueling station to an early lunar surface outpost would dramatically reduce the size requirements for a steady-state cislunar transportation system [Blair, 2002] by

removing the need for the heavier expendable first stage of a two-stage lunar lander. This approach would add robustness and sustainability to current NASA planning. Current expendable vehicle technology could be modified for re-use, collapsing the steady-state hardware requirements for any time lunar access to a reusable lunar lander and upper

stage [Blair, 2002 and Diaz, 2005]. Only the crew capsule would be expended upon re-entry into Earth orbit. Surface mobility benefits for refuelable rover power systems are equally significant. A source of consumable fuel cell reactants on the lunar surface would enable energy-intensive applications such as mining, construction or robust and power-rich human exploration operations using a closed rover. The possible existence of Platinum group metal enrichment among the diverse geologic surface environments of the Moon offers rationale for diversified commercial lunar mining [Wingo, 2004]. Unique features such as the dense nearside mascons that underlie the Lunar Mare offer fodder to the imagination regarding the longer-term potential for underground mining.

Mining the moon is a precursor activity to a much more robust set of long-term mature industrial operations that will take maximum advantage of the unique lunar environment. The list of valuable research activities enabled by the thermal and vacuum conditions on the lunar surface (including permanently shadowed areas) includes materials and metallurgy research, thin film technology (largescale), vacuum welding, coating, distillation and superconductivity research to name a few [Ruzic, 1965]. Access to cold traps and the potential for large-scale (tens to hundreds of meters) passive cryogenic systems could enable a new era in low-temperature science and engineering. Active cooling to micro or milli-Kelvin from one of these cryostats would require orders of magnitude less energy than used today for cryogenic research [Ruzic, 1965].

Summary

Lunar mining or ISRU as it has been called in the space world is about to become a reality. The recent find of significant water on the moon means that the moon as a fuel source will change many of the plans in a positive way. The paper has explored the creation of a

lunar outpost, how mining might occur, how terrestrial techniques will likely become the basis for future mining equipment and systems on the moon, and why these facilities are important for astronaut long term health and safety.

The creation of outposts on the moon and mining and processing appears to be feasible given techniques that have already been explored.

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