



Lunar Resource Mining

Space Resource Utilization

As in the days of the great terrestrial exploration missions, this architecture makes maximum use of available resources to support the space exploration missions directly. It also seeks to develop a large class of available resources for a broader range of transportation, habitation, life sciences, energy production, construction and many other long term activities. The goal is first to reduce the direct expense of going to the Moon and Mars, then to build toward self-sufficiency of long duration space bases and eventually to return energy and resources to Earth.

Strategy

Space is a unique store of resources: solar energy in unlimited amounts, materials in vast quantities from the surfaces of the Moon and Mars, gases from the Martian atmosphere, and the vacuum and zero gravity of space itself. With suitable processing, these raw resources are transformed into useful products. These products,

while increasing exploration efforts, provide bulky materials at a fraction of the cost of transporting huge masses from the deep gravity well of Earth, supply much of the energy needs of pioneering space activities, produce the constituent gases for air and would generate fuel for use by both chemical and nuclear rockets. Eventually, some space resources, especially solar energy and Helium-3 (a potential fuel for future fusion power plants), could be exported back to Earth. This could maximize the return on the investment of going to space, and allow cost effective expansion of space activities.

The implementation of this architecture entails several steps. First, resource extraction processes must be verified on Earth prior to space demonstration. In the case of the Moon, it is possible to use synthetic regolith on the Earth and to simulate other conditions which exist on the Moon to run a prototype plant. In the case of Mars, simulating the carbon dioxide atmosphere at the correct temperature and pressure is equally feasible. In both cases, it is possible to gain a high degree of confidence prior to ever leaving Earth. Next, the location and quantities of resources on the Moon, Mars and other bodies must be assessed. Some of this characterization is done remotely from Earth, but the general plan is to conduct robotic missions to map the Moon and Mars, emphasizing resource location and quantification.

An early lunar experimental plant is established to demonstrate the feasibility of extracting hydrogen and oxygen, other related volatiles, and industrial feedstocks from the lunar regolith. This experiment also demonstrates an ability to operate such a process from Earth remotely and verifies that the gases produced can be separated and stored for lengthy periods on the Moon.

The focus on Mars is similar; prototype facilities demonstrate extraction and production of hydrogen,

methane and oxygen from the Martian atmosphere autonomously, including storage for later use. From there, the strategy is to develop lunar manufacturing capabilities further to enable production of specific products which are made from the processed regolith. These include items such as solar cells, structural materials, formed metals, various fuels and other pure gases. These strategies are pursued with the goal of achieving lunar self-sufficiency, then build toward eventual production of export quantities of Helium-3 and electrical power. On Mars the goal is to eventually achieve self-sufficiency.

Finally, an infrastructure is needed to store, transport and use lunar-produced fuel to power rocket vehicles landing on the Moon, moving in Earth orbit and moving between the Earth and the Moon. This phase highlights the powerful effect of using space resources to greatly reduce cost and dependency on Earth. Fewer heavy lift launches are then required to support lunar and Martian activities.

Summary and Schedule

The Moon is emphasized because it is nearby and has known valuable resources which are extractable with relative ease from the regolith. Mars is secondary because its distance from Earth is much greater.

Lunar activity begins with a pair of site reconnaissance orbiters in 1999. A telerobotically operated rover verifies site suitability two years later. In preparation for the first human return mission, an experimental resource processing plant is landed at the selected site in 2003. In 2004, a crew of six arrives for a 14 Earth-day (one lunar daytime) stay. They live out of the lander and bring a small, unpressurized rover for local exploration. The next three piloted missions, in 2006, 2008 and 2010, are all to the same site and continue the expansion of resource processing capability, base infrastructure, habitats, exploration and science. The crew size remains constant at six, but the stay duration grows progressively from 45 to 180 days. In 2010, a small base exists which is capable of supporting up to

Lunar Boulder Near Taurus Littrow, Apollo XVII



12 people at a time. After a Mars dress rehearsal mission is performed on the Moon in 2011, the Mars mission is conducted. Special resource utilization experiments on Mars are featured in keeping with the theme of this architecture. In each phase, buildup of capability is highly dependent upon the success of the preceding activity.

Lunar Phase

Lunar Precursors. Lunar activity begins with a pair of reconnaissance orbiters in 1999. Data from these satellites allow selection of a site which has excellent resource potential, but which also has superior characteristics for exploration, science and habitation. A telerobotically operated rover verifies the suitability of the site two years later. Then, in preparation for the first human mission, an experi-

mental resource processing plant is deployed at the selected site in 2003. Operating autonomously, this small plant produces and stores oxygen as its main product, lesser amounts of hydrogen and solar wind-implanted gases, and demonstration amounts of other materials.

Lunar Initial Operational Capability.

The goal of the Initial Operational Capability in this architecture is to return safely to a site on the Moon with excellent resource potential for a stay of a lunar daytime while demonstrating in situ fuel production for use in a surface rover and in ascent/descent vehicles. Human activity on the Moon begins in 2004 with the arrival of a crew of six, with five crew members going to the lunar surface for a 14 Earth-day stay. They live out of the habitat and bring a small,

1998 2000 2002 2004 2006



▲ Proposed Mission

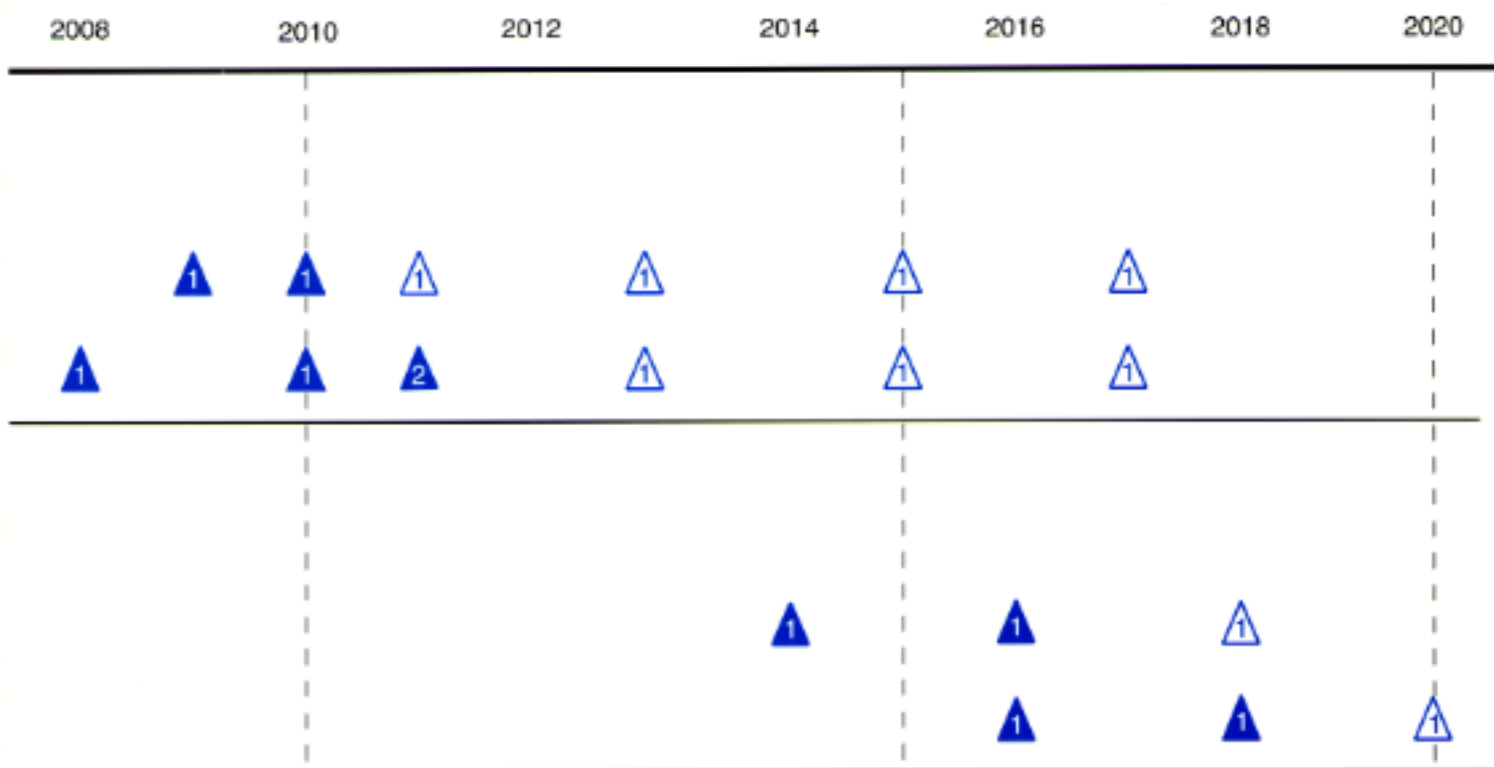
△ Optional Mission

unpressurized rover for exploration. The rover is designed to operate on fuel cells so it can be refueled by the products of the resource plant, verifying that lunar resources can be used and that such operations as fueling can be done safely. With those basic capabilities verified, the crew explores the local area and assesses the site's suitability for future expansion. The reliability and degree of automation of the processing and the feasibility of continued operation are evaluated at this stage for a decision to proceed to the Next Operational Capability. The reusability of the lunar ascent/descent vehicles is evaluated.

Lunar Next Operational Capability-1. In this phase, a small base capable of expansion to a permanent facility is developed. Production of key lunar-derived materials such as fuel and a

demonstration test of power beaming are performed. The next three piloted missions are sent to the same site and continue the expansion of resource processing capability, base infrastructure, habitats, exploration, science, and the broad range of operations associated with human presence.

Each of these three subsequent missions is preceded by a cargo flight which delivers expanded capability to the resource plant, power systems, habitats, science instruments, rovers, site construction equipment, tools, food and other supplies. The crew size remains constant at six, but the stay duration grows progressively from 45 to 180 days. At the end of 2010, a small base exists which is capable of supporting up to 12 people at a time. This capability is expanded to a permanently occupied base, but the initial concept is for periodic stays



of varying lengths over the long term. Each mission provides a measurable increase in capability and a logical decision point for determining the final configuration of the Next Operational Capability.

Throughout this period, the focus of the increasing activity on the Moon continues to be resource development. The intent is to produce, store and use a wide variety of lunar materials including gases, for fuel and air, fused silica sheets and beams for construction, solar cells (made from lunar material) for power, and experimental quantities of Helium-3 to be exported for use in the Earth-based fusion program. Other experiments take place at the Moon site such as beaming power back to Earth or to an orbital cargo transfer vehicle to test the usefulness of that technology, trial export of limited quantities of construction materials and solar cells to evaluate their usefulness, and testing of processed regolith as soil for growing food in reduced gravity.

The earliest potential payback is to use lunar-derived fuel — in the form of hydrogen or methane, plus oxygen — first to power lunar vehicles such as rovers and utility equipment; then to refuel lunar ascent/descent stages to or from lunar orbit or a Lagrange point with cargo; and finally to fuel transfer vehicles between the Earth and Moon. The Lagrange point staging area may prove attractive. The initial propulsion is conventional chemical, employing liquid oxygen and liquid hydrogen or methane, but because liquid hydrogen is an excellent working fluid for a nuclear thermal rocket or a plasma thruster, it could be eventually used in these applications as well. Methane may be manufactured on the Moon and Mars, and is storable, which may prove attractive for local transportation.

The feasibility of beamed power is tested using power generated on the

Moon and beamed to a vehicle in space. A further test beams power to Earth to demonstrate the potential of importing energy from space. This test establishes the operational limits of beamed power and determines if transmission to Earth can be accomplished economically.

The basic features of this concept call for continuously expanding production and storage capabilities for fuel gases on the Moon. Development of transfer and landing vehicles which are reusable and refuelable on the lunar surface, in Earth and lunar orbit, or at a Lagrange point, would follow. These vehicles transport fuel from the Moon to both lunar and Earth orbit. There are both cargo and personnel transport vehicles, and the cargo transport type is configured as a conventional cargo carrier or tanker. The result is a lunar-based transportation infrastructure.

The above applications are far from being an exhaustive list of the uses of lunar resources. The concept is to encourage the development and use of resource categories not specifically stated or envisioned at this time. More opportunities may arise, innovation is encouraged and eventual transition to commercial activities is stimulated. Three things are certain: using resources near at hand potentially lowers the long term investment in space activities, broadens the range of human activities in space, and provides a large payback in later years.

Lunar Next Operational Capability-2.

This Next Operational Capability will perform the dress rehearsal for a mission to Mars. The fifth piloted mission to the Moon in 2011 returns to the established site, but is planned as the dress rehearsal of the Mars mission. The total mission duration is 500 days, with only 40 days to be spent on the lunar surface; the rest is spent in lunar orbit, 200 days before landing and 260 days after leaving

the Moon and before returning to Earth. This simulation mission uses the full suite of equipment to be used for the actual Mars mission as much as practical, including the equipment supplied by a separate cargo flight in 2010 as in Architecture I. When the crew of six lands on the lunar surface, their activities parallel those planned for Mars. An additional six crew members launched earlier are available on the surface assist the next crew upon landing. Because this simulation mission takes place close to the existing lunar base, there are extensive additional equipment, living quarters, and resources available in an emergency. Finally, the Mars prototype equipment left behind at the end of the mission augments the infrastructure of the lunar base.

Human habitation on the Moon after the simulated Mars mission continues on either a periodic basis or evolves to permanent presence. If the promise of resource development and use is realized, extensive human presence is feasible.

Mars Phase

Mars Precursors. The precursors for this architecture are the same as those denoted for Mars in Architecture I: two site reconnaissance orbiters and two surface rovers to certify and characterize the landing sites on Mars.

Mars Initial Operational Capability. The Initial Operational Capability in this phase is similar to the one described in Architecture I with the addition of some resource utilization experiments on the Martian surface. Preparation for the first human mission to Mars begins with the launch of a cargo mission to Mars in 2014 for this architecture. This flight emplaces a pressurized rover, a habitat and an atmosphere reduction plant at the selected site. The atmosphere reduction plant takes in the carbon dioxide, reacts it with an initial store of hydro-

gen brought from Earth and generates and stores modest quantities of methane and oxygen, gases which would be used as sources of energy.

A rover, powered by methane/oxygen fuel cells, is used for local exploration, and is refuelable from the products of the resource plant. The verification of using in situ fuel and the refueling operation itself are major activities next to the primary activity of exploration. The first human mission to Mars is in 2016, two years later than the other three architectures, to allow sufficient time for development of a lunar resources capability. Once on Mars, surface exploration, as described above, will be the theme of operations.

Mars Next Operational Capability.

The Next Operational Capability in this architecture emphasizes tests and demonstrations of in situ resource use on the Martian surface to support long term human presence. The second expedition to Mars follows the pattern established by the first; a cargo flight leaves in 2016 and places an expansion unit to the resource plant and a small greenhouse, all at the previous site. This provides a significant food and fuel production capability. The Martian greenhouse is provided to augment the food supply and improve the quality of life for humans on the surface. It is also important as a test of whether human activity on Mars could become self-sufficient. This second expedition is the last specifically detailed in this architecture, and it provides a Next Operational Capability.

Near-Earth Asteroid Option. As in Architecture II, an exploratory visit to a near-Earth asteroid is an option. The emphasis in this case is not primarily exploration but the characterization and examination of an asteroid as a source of valuable, useful material.



Exploring the Moon