FINAL REPORT

on

DEVELOPMENT OF LUNAR ICE/HYDROGEN RECOVERY SYSTEM ARCHITECTURE

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by

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FOREWORD

This document represents the final report on the “Development of Lunar Ice Recovery System Architecture” a NIAC-Phase I study contract (research grant #07600-021) prepared for NASA and the NASA Institute for Advanced Concepts (NIAC), managed by the Universities Space Research Association (USRA). A major output of the study is the recommended "Lunar H_2/O Resource Use Program Plan". The plan that is presented here is considered a starting point for a NASA-funded program that would take full advantage of the lunar resource for the development of a manned base on the Moon. It represents what we believe to be, a well-thought out initial plan that will require continuous updates as work is conducted and new knowledge becomes available. This document is included as Attachment C to this final report.

ORBITEC wishes to acknowledge the excellent communications and support from Dr. Robert Cassanova, NIAC Director. Dr. Eric E. Rice, PI and prime author, wishes also to acknowledge the contributions of Mr. Robert Gustafson (Deputy PI), Mr. Ronald Teeter, Mr. William Knuth, Mr. Matthew Molecki, Mr. Brant White, Ms. MaryAnn Knoke, Ms. Kelley Rice and Ms. Molly Mitten.

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1.0 BACKGROUND

The significant presence of hydrogen in the form of water ice or bound hydrogen in permanently shadowed depressions near the lunar poles will influence both the near and long-term prospects for lunar and Mars exploration and development. In this report the two possible forms of hydrogen (H_2O and H_2) shall be represented by H_2/O. Since the most recent data from Lunar Prospector indicate that water ice or hydrogen is present in the polar regolith in significant quantities (up to 260 million metric tons, if water), it is important to characterize it and how to extract it for beneficial use.

Man's space activity will soon focus on the Moon as the next logical step for human exploration. We must find ways to keep the cost of exploration as low as possible. The Moon is an attractive low-cost source of resources for the development of near-Earth/Moon space because the Moon is close to Earth, it has a small gravity field and most of the chemical elements important in the development of space capabilities (e.g., oxygen, metals) can be readily found on the surface. Previously, the most significant problem with lunar development has been the scarcity of fuel for spacecraft and transport vehicles. Although oxygen is present in abundance in the minerals of the lunar regolith, no concentrated source of hydrogen was known with certainty to exist, prior to the Clementine and recent Lunar Prospector mission. If rocket fuel must be imported to the Moon to launch payloads from the Moon, it is very difficult to devise a low-cost Moon-to-space transportation system. However, if both fuel and oxidizer can be obtained locally and relatively easily, a reusable transportation system that can reach Moon-orbit space at low cost would be very attractive. This is the promise of lunar water or hydrogen. Water can easily be electrolyzed to produce hydrogen and oxygen, be liquefied and used as propellants. If hydrogen is abundant in the polar regolith, it too can be easily recovered and processed. If developed as a supply of propellant, a myriad of other beneficial uses for lunar water or hydrogen can be developed, ranging from life support to construction materials.

Two general classes of resource extraction processes can be considered for removal of ice or hydrogen. In the first class of processes, energy (solar-beamed, nuclear, etc.) is transported into the shadowed regions, hydrogen or water is extracted in-situ, and transported out of the cold trap. Alternatively, a hydrogen/water-containing regolith can be mined in the cold trap, transported outside the cold trap, and the hydrogen/water extracted in a location with abundant solar energy.

The existence of water ice or hydrogen deposits in the cold traps at the poles on the Moon represents an extremely valuable resource future lunar exploration and development. This final report provides the results of our Phase I study to establish the feasibility of the advanced concepts to discover, extract, and use the H_2/O resource to benefit man’s development of an economical lunar base and support space exploration.

2.0 ADVANCED CONCEPT DESCRIPTION

The Moon is an attractive source of resources for the development of near-Earth space because it is close to Earth, it has a small gravity field and most of the chemical elements important in the development of space capabilities (e.g., hydrogen, oxygen, metals, and etc.) can be readily found. Now that hydrogen has been discovered in significant quantities, a reusable transportation system that can operate in Earth/Moon-orbit space at low cost is feasible. This is the promise of lunar water ice/hydrogen (defined here as H_2/O). Water can easily be electrolyzed to produce hydrogen and oxygen, be liquefied and used as propellants. If hydrogen is abundant and water ice is not, there are many processes that could be used to develop an oxygen supply directly from the regolith. If developed as a supply of propellant, a myriad of other beneficial uses for lunar H_2/O would be developed, ranging from life support to construction materials.

Models for the existence of water ice in permanently shadowed polar cold traps have been discussed since the work of Watson et al., (1961). The plausible sources of water ice and hydrogen on the Moon are micrometeoroids, the reaction of solar wind protons with the lunar surface, and comets. Existing lunar ice models consider the rates of accretion of water to the Moon, losses during ballistic migration of water molecules across the lunar surface to the cold traps and losses from the cold traps. None of the published models have explicitly included the gardening of the lunar surface by meteoroids, which can both protect ice by covering it and destroy ice by vaporizing it.

The Clementine mission indicated extensive areas of permanently shadowed terrain at the lunar poles, particularly around the south pole of the Moon. Clementine showed that an area of contiguous permanent shadow in the vicinity of the south pole extended over about 15,000 km^2 (Nozette et al., 1996). The shadow is continuous, because the lunar south pole lies within a large, ancient crater, the Aitken Basin, where the surface lies several kilometers below the mean sphere. This area of contiguous shadow is not the only portion of the lunar surface that is in permanent shadow. Considering statistical analysis and examination of polar terrain images, Watson et al., (1961) and Arnold (1979) estimated that about 0.5% of the Moon's surface (190,000 km^2) is in permanent shadow. They demonstrated that craters as much as 25 degrees from the pole could have their bottoms in permanent shadow. The permanent shadow, therefore, is a more widespread phenomenon and the contiguous shadowed area near the South Pole is only a few percentages of the estimated total area that is in permanent shadow.

The Clementine team also reported a bi-static radar signal received in one pass over the South Pole, which was interpreted to indicate the presence of ice (Nozette et al., 1996).

The Lunar Prospector, launched on January 6, 1998, carried an experiment called the Neutron Spectrometer. This experiment was designed to detect the presence of hydrogen, which is believed to indicate the presence of water ice. The Neutron Spectrometer is designed to detect minute levels of water ice at concentrations of less than 0.01%. The instrument focused on areas near the lunar poles where ice was thought to exist. The original analysis of the data returned from Lunar Prospector indicated water ice mixed in with the lunar regolith at relatively low concentrations. These ice concentrations were conservatively estimated at 0.3 to 1 percent by mass at the Moon's poles, or up to 300 million metric tons (Feldman et al., 1998). Figure 1 shows Lunar Prospector Neutron Spectrometer data showing the concentration of H_2/O for the Moon’s north and south poles.

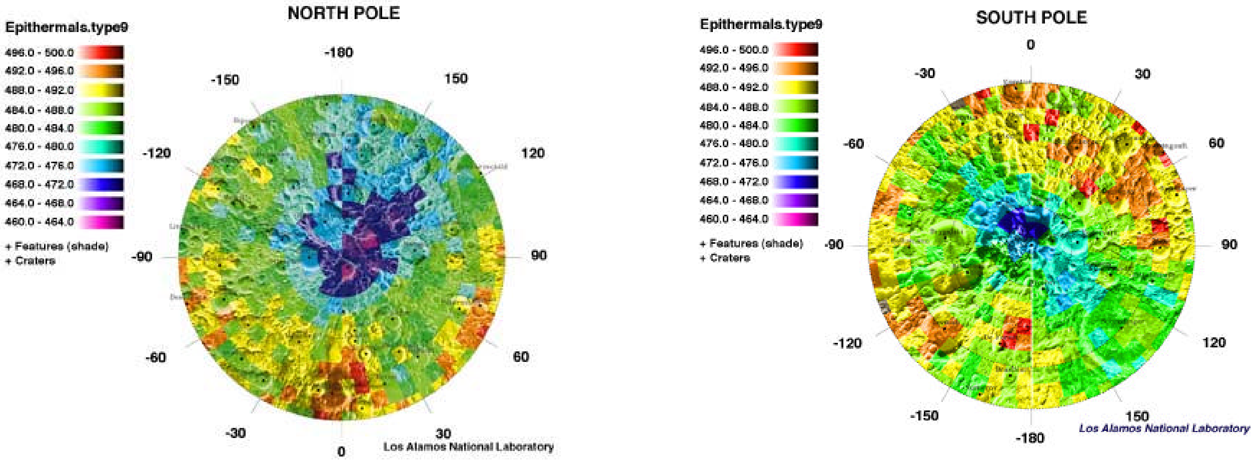

Figure 1. Lunar Prospector Neutron Spectrometer Data Showing the Concentrations of H_2/O

Current data (per Al Binder) indicate up to 260 million metric tons (MMT) of water ice have been predicted to within the first 2 meters of lunar regolith by the science team (July 1999). The current confidence level in this number is not very high, but it is likely the best estimate available until we measure insitu in the cold traps. Estimates indicate 200 MMT at the south pole and 60 MMT at the north pole. Ice is likely in deposits of pure water ice buried beneath ~5 cm of dry regolith in ~1.5% (or 1700 ppm if water ice) concentrations in the permanently shadowed areas. Concentrations appear higher at the North Pole**.** Kulcinski, Schmidt and others have suggested that the neutron spectrometer data are due to increased hydrogen concentration in the regolith, not water. Therefore, we must consider this possibility. Al Binder and Bill Feldman will be constructing a total hydrogen concentration map of the Moon to within an accuracy of 1% that is expected to be complete in 2001. Binder now believes that both hydrogen and water exist in the polar regions. The data and interpretations indicate that both H_2 and H_2O may exist in the permanently shadowed areas and that higher than usual H_2 concentration (by a factor of 2) exist in the colder regolith just outside the cold traps. In approximately 2 years from this report date, the entire Moon’s surface hydrogen concentration should be mapped.

ORBITEC has proposed the development of an overall system architecture for the discovery, extraction and utilization of H_2/O found near the north and south poles of the Moon. The architecture has been described in an initial overall program plan document (see Appendix C) that identifies many of the key elements of the ISRU architecture and defines what work should be done. This comprehensive program plan covers the following elements:

- Summarize Current Data
- Simulation Models
- Identify, Conceptualize, Assess Uses
- System Studies

- Technology Needs Assessment and Development
- Ground Simulator Facilities
- Lunar Exploration Mission
- Lunar Extraction Mission
- Lunar Extraction Facility
- DDT&E for Lunar Uses
- DDT&E for Mars Uses
- DDT&E for Other Solar System Uses
- Education and Outreach
- NASA Program Management and Reports.

Figure 2 illustrates the overall plan architecture and the progression of the program plan via a road map from discovery/verification of lunar water ice or hydrogen through extraction to utilization of the resource. Each of major steps in the overall plan is briefly elaborated below.

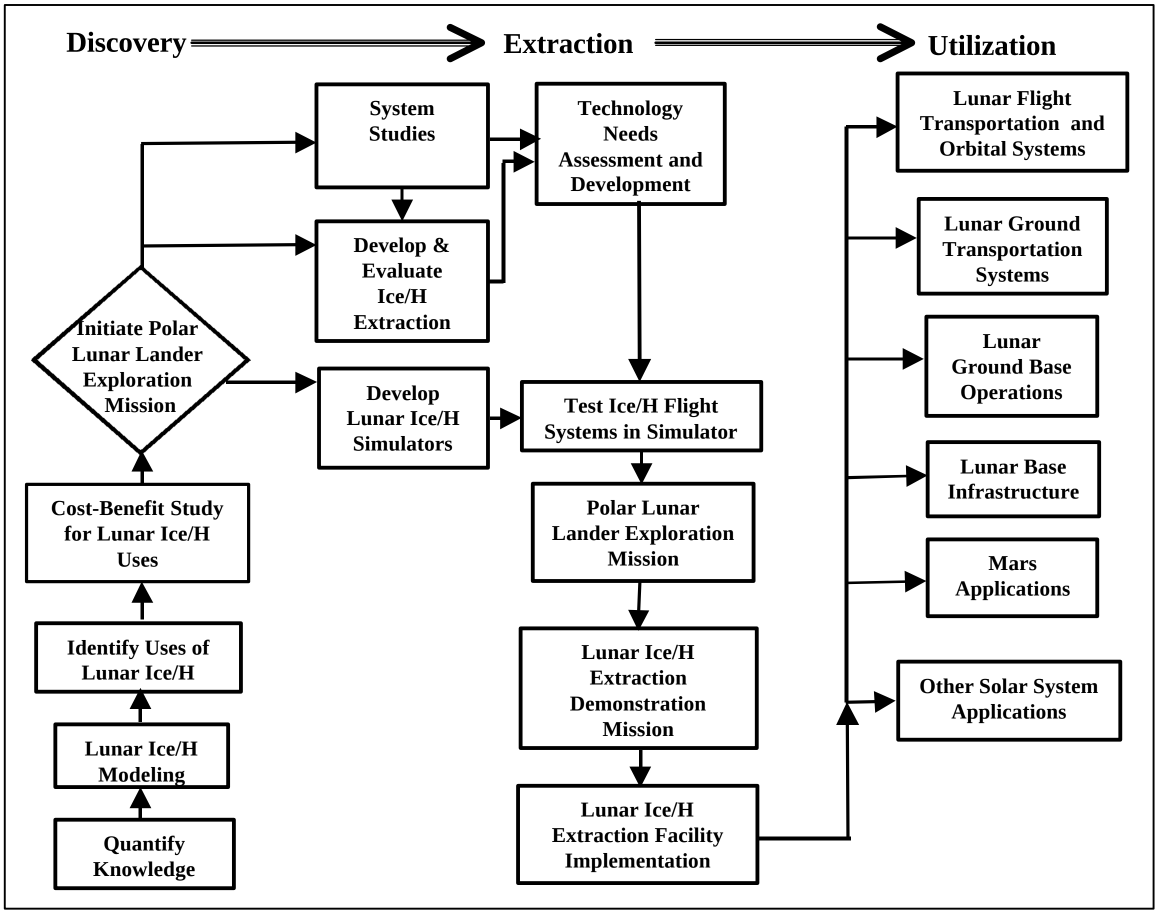

Figure 2. Lunar H_2/O Resource Use Program Road Map

Summarize Current Data – Summarize and document the scientific data available from Apollo, Luna, Clementine, Lunar Prospector, Earth-based telescopes and other sources into a coherent data base for the lunar H_2/O exploration effort.

Simulation Models – Develop simulation models of the possible physical/chemical processes and their contribution that may have resulted in polar lunar H_2O and/or H_2, and other volatiles being present in the cold traps.

Identify, Conceptualize, Assess Uses – Identify and evaluate all of the potential uses of lunar H_2/O. Some potential uses include lunar flight and orbit transportation systems, Mars flight transportation systems, other Solar System transports and explorers, lunar ground base operations, lunar ground-based transport vehicles and lunar base infrastructure. Once the various uses of the lunar water ice are identified and prioritized, a cost-benefit study would be performed to determine the most promising applications. The results of this cost-benefit assessment will help determine the best ways to utilize the valuable water ice resource on the Moon and give direction to the program.

System Studies – System studies would be performed for the major or critical components of systems that use H_2/O as well as ISRU systems that provide the H_2/O resource. One defined activity is to conduct system studies on cost-efficient space transportation systems. A second defined activity is to conduct system studies on cost-efficient approaches to conduct rover-based exploration of the polar regions. A third defined activity would be studies and evaluations of the most promising ice extraction techniques and logistics approaches. Studies and analysis also would be conducted in ground-based and lunar in-situ laboratory experiments. Other important study, analysis and design activities include: nuclear thermal device application assessment, development of a lunar H_2/O use and conservation plan, legal/political/treaty issue assessment, commercial development, a lunar environmental impact assessment, and cost modeling and analysis.

Technology Needs Assessment and Development – Once the lunar ice extraction and use approaches have been developed and evaluated, a more focused technology needs assessment can be performed. Any technology development required would occur during this latter stage. One of the greatest challenges in extracting the lunar ice or hydrogen will be operating machinery in the extreme conditions believed to be present near the deposits. With temperatures of ~70 K expected in the permanently-shadowed areas around the poles of the Moon, the operation of mechanical, electrical and fluid systems will require specific technology development. Some specific technology development may be required for solar and nuclear-based energy delivery systems, automated materials handling and processing, reduced gravity electrolysis systems, purification of water from the lunar regolith, water storage systems, energy storage and delivery, cryogenic hardening of electronic and mechanical systems, excavation technologies, rovers, ballistic flight vehicles, hydrogen peroxide production in 1/6 g, and alternate oxygen production of water, if not present.

Ground/Simulator Facilities – Lunar ice simulators would be developed to recreate the environmental conditions present in the permanently-shadowed regions of the Moon. Such simulators would serve multiple purposes. A large-scale lunar ice simulator would allow testing of various components of an ice extraction system or exploration missions. The ice deposition process could also be studied in smaller simulators. Layers of ice and regolith could be formed. Micrometeoroid stirring of the ice and regolith mixture could be approximated with mechanical stirring. Lunar stimulant with H_2 embedded would also be developed and used in the simulator.

Lunar Exploration Mission **–** A robotic rover would be developed to explore the regions near the north or south poles of the Moon where water ice and H_2 is believed to exist. An initial mission is defined to use a combination of solar and nuclear power. A multi-sample return mission is also integrated with this mission.

Lunar Extraction Demonstration Mission **–** A mission to the polar regions of the Moon would carry out the first ISRU pilot plant extraction demonstration experiments. One or more extraction approaches would be demonstrated under actual lunar conditions and would verify that the technology works.

Lunar Extraction Facility **–** As a result of the first lunar H_2/O pilot plant demonstration mission to the polar cold traps of the Moon, a great amount of information will be learned about the technology and operational approach of extraction. This information will drive the final design of the full-sized extraction facility on the Moon. The work of the program will feed into the definition of this mission.

DDT&E for Lunar Uses **–** Lunar systems are the primary targeted uses for the lunar ice resource. Since it appears that both fuel and oxidizer can be obtained locally, a reusable transportation system that can reach Moon-orbit space at low cost may be feasible. Ground-based transports could also be powered with propellants derived from lunar H_2/O. Water can easily be electrolyzed to produce hydrogen and oxygen, be liquefied and used as propellants. Other transportation systems, such as Moon-to-Earth or a lunar orbiting fueling station may also be feasible.

DDT&E for Mars Uses **–** This work would be conducted well after the program has been established and we have better data on the availability of Mars water in the Mars regolith. After a determination of feasibility, this effort would begin establishing a necessary DDT&E effort for systems for Mars mission support that would use H_2/O resources from the Moon.

DDT&E for other Solar System Uses **–** The use of lunar H_2/O for other solar system transport vehicles may have more significance than Mars transport vehicles. This task should be delayed until there is a mission that may be feasible by using lunar H_2/O resources.

Education and Outreach **-** Education and outreach to the general public/taxpayers has become an important part of NASA's mission. It would be a vital part of this program. The information generated by the overall program would be made available to the public.

NASA Program Management and Reports **–** This element of the program plan identifies the program management functions and program documentation that are believed necessary to manage and guide the ultimate goals of this program.

3.0 STUDY RESULTS AND FINDINGS

The results of the technical work conducted during the Phase I study is presented here. A bibliography is given in Appendix A. A data base printout that includes the papers and reports that were reviewed in the study are given in Appendix B. The Lunar H_2/O Resource Use Program Plan is given under an Appendix C fly sheet. The sections that follow describe the work that was done during the Phase I effort.

3.1 Summary of Lunar H_2/O Data

During the conduct of Task 1, we gathered most of the currently available data concerning ice or hydrogen deposits on the Moon. These data included new data from the Lunar Prospector mission, models of the lunar environment where the ice exists, ice accumulation and deflation models and all other information related to the discovery, extraction and/or utilization of water ice on the Moon. A bibliography (see Appendix A) and data base (see Appendix B) were generated. A document library was also created such that it could easily be used in the studies and analysis for Phase I and II.

A top-level discussion of what we know from the Apollo, Clementine and Lunar Prospector missions is presented below.

Apollo. The source of H_2 on the Moon comes from the collection of the solar wind over the past 4 billion years. Since the solar wind is 96% hydrogen and the ionized protons have a relatively low energy (~ a few keV), most of this "resource" is implanted in the surface of regolith particles. Gardening by frequent meteorite impacts has caused the near surface region to be turned over many times such that the impregnated, fine grained (~ 100 microns) regolith has been uniformly mixed to depths of several meters. The range of concentrations of several volatile elements in lunar regolith is given in Figure 3. Hydrogen shows the largest variation in concentration, from <1 wppm in highland materials to over 100 wppm in some glasses. Fegley and Swindle have predicted that the H_2 inventory of the first 3 m of the Moon is ~ 10 billion metric tonnes. The loosely bound hydrogen can be thermally evolved from the fine lunar regolith at temperatures of 300-700 C (see Figure 4). Other volatile elements are also evolved along with the H_2 include water vapor, CO_2, He, H_2, CH_4, CO or N_2 (the peaks are indistinguishable on a mass spectrometer), H_2S and SO_2. Also liberated were smaller quantities of the noble gases Ne, Ar, Kr and Xe. Careful study of Figure 4 reveals the original gas release pattern for the Apollo-11 Sample 10086.16, measured by a mass spectrometer as a function of temperature.

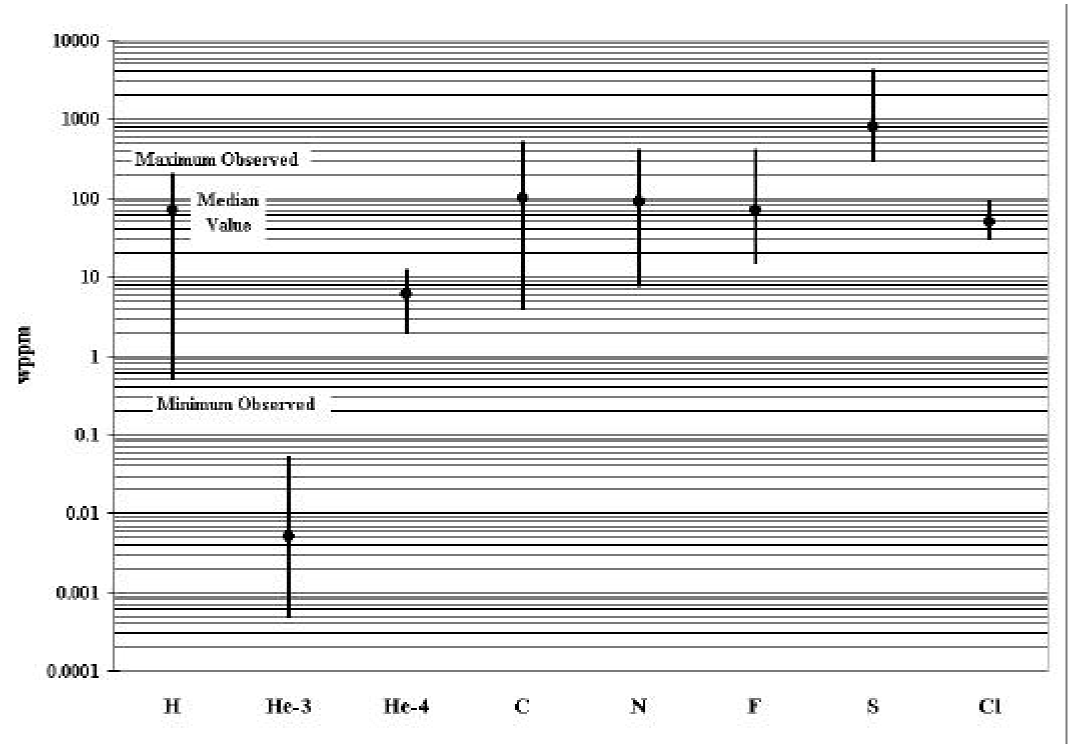

Figure 3. Concentration of Lunar Volatiles Measured in Apollo Samples Covers Wide Range of Values

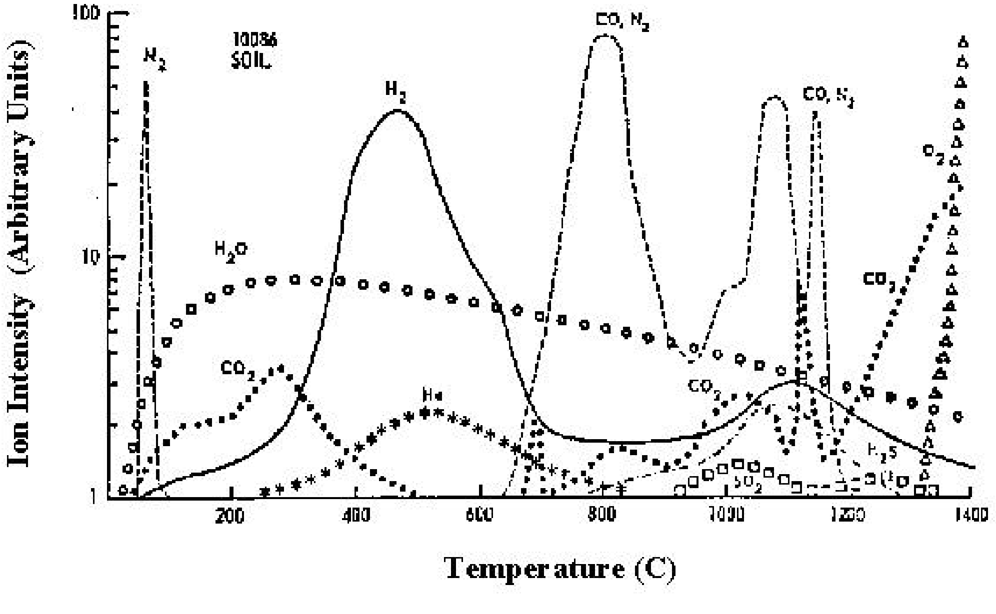

Figure 4. Original Gas Release Pattern for Apollo-11 Sample 10086 Was Very Complex

Another way of looking at these data (Figure 4) is as shown in Figure 5, a bar chart showing the range of temperatures over which the majority of the gases are evolved. Although H_2 is released over a very wide range of temperatures, the peak evolution ion intensity occurs at around 500 C and falls off to ~5% of that peak value at 700 C. In principle, a lunar hydrogen acquisition device would not need to exceed a temperature of 600 C to obtain >80% of the H_2 (see Figure 6). At the same time, some H_2O, CO_2, He, CH_4 and CO or N_2 will also be liberated. The sulfur containing volatiles H_2S and SO_2 will not be liberated until the temperature exceeds 800 C. This is fortunate, since the formation of sulfuric acid H_2SO_4 should be avoided because of its corrosive effect on the components of the processing system.

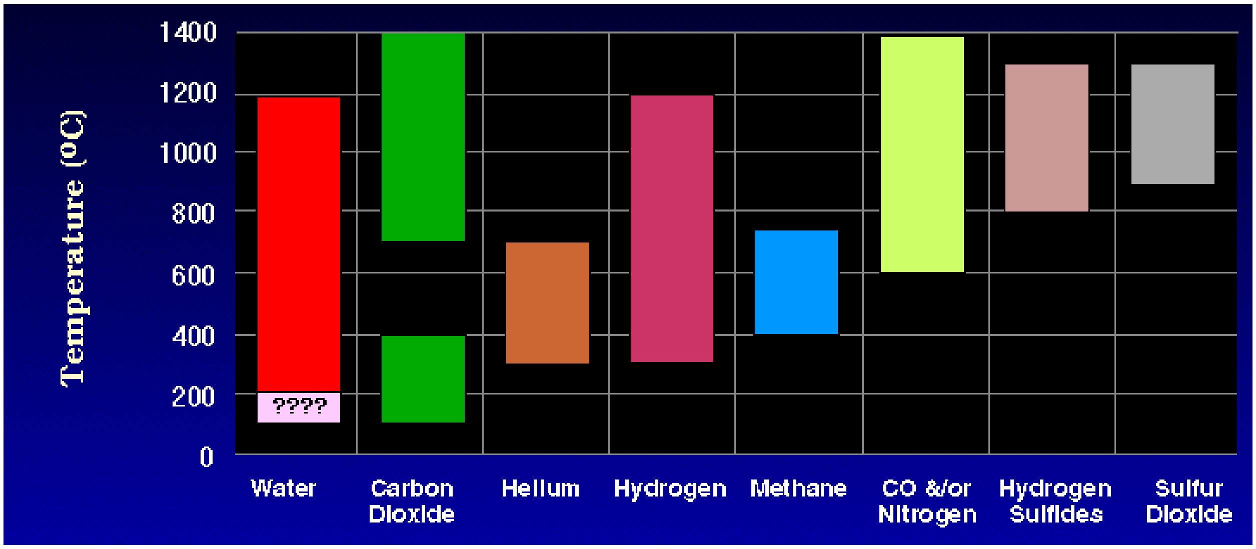

Figure 5. Release of Lunar Volatiles (i.e., >90%) Occurs over a Wide Range of Temperatures

The proton ion energy in the solar wind (from Pioneer 10, Data Set #1) ranges from ~0.5 keV to ~4 keV with two peaks occurring at the lower end of the spectrum (from Pioneer 10, Data Set #1). The depth of implantation depends on the ion energy, but is typically only 0.005 - 0.01 microns. This means that most of the H_2 is close to the surface of the regolith particles. Further, the average grain size of Lunar regolith samples from the Apollo missions range from 40-130 microns with some 80% of the volatiles contained in particles that are smaller than 60 microns. This asymmetry is attributed to the large surface to volume ratio of the smaller particles. Therefore, for reasons of conservation of energy and maximizing H_2 evolution, it is prudent to process only particles which fall in the size range of <60 microns.

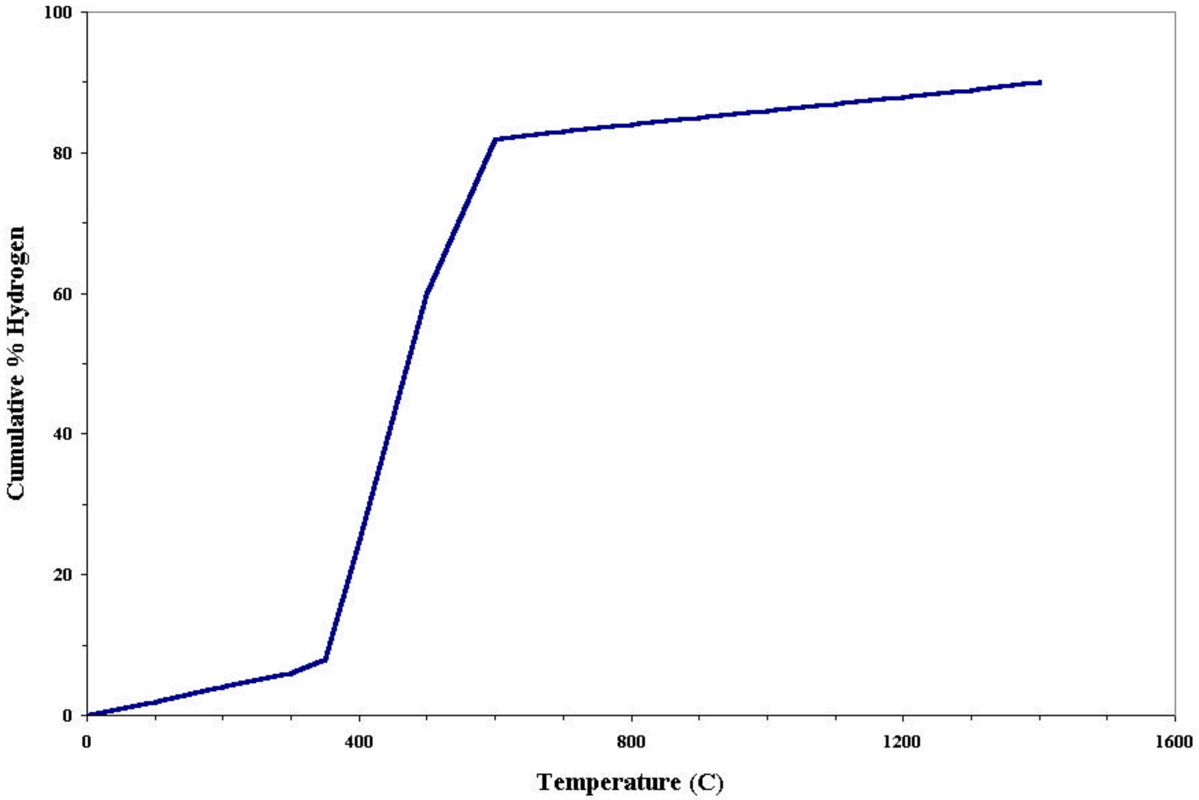

Figure 6. More than 80% of Solar Wind Implanted Hydrogen Can be Extracted from the Apollo 11 Sample 10086.16 by 600 C

Clementine. The Clementine mission indicated extensive areas of permanently shadowed terrain at the lunar poles, particularly around the south pole of the Moon. Clementine showed that an area of contiguous permanent shadow in the vicinity of the south pole extended over about 15,000 km^2 (Nozette et al., 1996). The shadow is continuous, because the lunar south pole lies within a large, ancient crater, the Aitken Basin, where the surface lies several kilometers below the mean sphere. This area of contiguous shadow is not the only portion of the lunar surface that is in permanent shadow. Considering statistical analysis and examination of polar terrain images, Watson et al., (1961) and Arnold (1979) estimated that about 0.5% of the Moon's surface (190,000 km^2) is in permanent shadow. They demonstrated that craters as much as 25 degrees from the pole could have their bottoms in permanent shadow. The permanent shadow, therefore, is a more widespread phenomenon and the contiguous shadowed area near the south pole is only a few percentages of the estimated total area that is in permanent shadow. The Clementine team also reported a bi-static radar signal received in one pass over the south pole, which was interpreted to indicate the presence of ice (Nozette et al., 1996).

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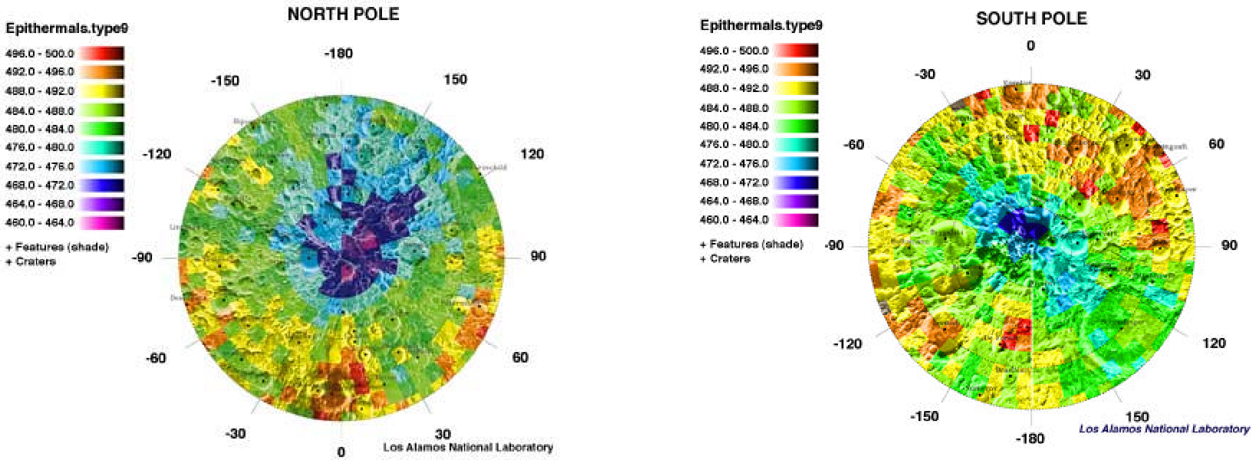

Figure 7. Lunar Prospector Neutron Spectrometer Data Showing the Concentrations of H_2/O

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A brief discussion of the sources of water and loss mechanisms is given below.

Sources of Lunar Water. The major sources of lunar water ice are believed to be micrometeoroids, solar wind hydrogen reduction of the lunar regolith, and comets (Arnold, 1979; Morgan and Shemansky, 1989). Micrometeoroids, studied directly through capture in the Earth's stratosphere, contain up to 10% water in crystalline form. When the micrometeoroids hit the Moon's surface, some of the material is vaporized and lost immediately. Any water molecules that remain will migrate across the surface and either be deposited in the cold trap, or photoionized and swept from the Moon by the solar wind. Water from this source will be deposited molecule by molecule in the cold trap.

The solar wind has uniformly struck the lunar surface throughout the eons, implanting protons into the outermost micron or so of any particle exposed at the surface. Due to stirring by micrometeoroid impact, small particles in the regolith have protons implanted over their entire surface, and are essentially saturated with hydrogen. When micrometeoroids impact the regolith, local heating allows the hydrogen to react with iron oxide in the soil, releasing water and producing metallic iron. There is a large body of data which relates the "maturity" of the lunar regolith to the amount of metallic iron contained in glassy agglutinates made (e.g., Morris, 1976). Water released in this manner can be transported to cold traps or lost from the Moon. This water also will be deposited on a molecule-by-molecule basis in the cold traps.

Comets must hit the Moon from time-to-time; however, the rate at which comets hit the Moon is quite uncertain. They are generally considered to be composed of about 50% water and other volatiles. Long-period comets (like Haley's Comet) have very high velocities with respect to the Earth-Moon system, and retention of their volatiles on impact is improbable. Short-period comets may strike the Moon with low enough velocity that significant proportions of their water is retained. Arnold (1979) concluded that the total water retained on the Moon from cometary impacts over the past two billion years may have been between 10^{16} and 10^{17} g, with an equal amount contributed by the impact of extinct comets. Water introduced by comet impact will also be accreted in the cold trap on a molecule-by-molecule basis; however, most of the ice will be from the impact of a few large comets, and it will be deposited rather quickly, possibly in distinct layers.

Loss Mechanisms from the Cold Traps. Several loss mechanisms have been proposed for ice that has been deposited in the cold traps including sublimation, sputtering, interstellar radiation and micrometeoroid vaporization. All of the removal mechanisms require the exposure of the ice at the surface; however, the incessant bombardment of the Moon by meteoroids will cover the surface with a deposition rate of approximately 1 mm/million years. In the case of a layer of ice deposited by a comet, any layer thicker than about 1 mm should be covered before it is destroyed completely.

3.2 Identified Uses of Lunar Water Ice/Hydrogen

Various uses of lunar polar water ice or hydrogen have been identified as a starting point for this study. Two major categories have been developed to help organize the various uses; they are: (1) Propellant Sources for Propulsion/Power Applications (Moon and Mars), and (2) Lunar Base Support Applications. Currently identified uses within each area are given in Tables 1 and 2. Solid or liquid hydrogen, oxygen and hydrogen peroxide are assumed to be possible resource combinations. Advanced cryogenic hybrid technology, being developed at ORBITEC for planetary surface ascent and descent engines, allow the use of the solid form. Additional synergy with other ISRU resources (Fe, Al, Mg, Ti, Na, K, C, N, He, O etc.) should be investigated. The use of methane for Mars applications as produced with lunar hydrogen should also be considered.

Once all the possible uses have been identified, they need to be assessed and analyzed to determine the cost-benefit of its use. The Program Plan (Appendix C) WBS Element 3.1 describes the approach that is suggested.

Table 1. Hydrogen/Oxygen Resource Propellant Uses for Propulsion/Power Applications

A. Lunar Flight Transportation and Orbital Support Systems
1. Lunar Surface-to-Lunar-Surface Transport Systems
2. Lunar Surface-to-Lunar-Orbit Transport Systems
3. Lunar Orbit-to-Libration-Point Station Transport Systems
4. Lunar Orbit-to-Earth-Orbit Transport Systems
5. Lunar Orbit-to-Earth-Reentry Transport Systems
6. Lunar Surface-to-Earth-Orbit Support Systems (SPS, Space Manufacturing, ISS, etc.)
7. Lunar Surface-to-Earth Reentry Transport Systems (exporting lunar resources back to Earth)
8. Lunar Orbit Communications and Remote Sensing Satellite Systems
9. Lunar Orbiting Service Station (LOSS) System
10. Earth Orbiting Service Station (EOSS) System
11. Lunar/Earth Libration Point Station System
B. Mars or Other Solar System Flight Transportation Systems
1. H/O Propellants for Main and Auxiliary Chemical Propulsion (including CH_4)
2. O_2 and H_2 for Solar Electric Propulsion for Mars
3. H_2O for Nuclear Steam Rocket
4. LH_2 for Nuclear or Solar Thermal Rocket
5. SH_2 with HEDM Additives for Chemical Propulsion
C. Lunar or Mars Ground-based Fuel Cell or Combustion-Driven Ground Transport Vehicles
1. Exploration-based (scientific and commercial) Robotic and Manned Rovers
2. Personnel Transporters
3. ISRU Material Transporters
4. Equipment Transporters
5. Regolith Bulldozers
6. Mining Equipment
7. Winged Aircraft and Powered Balloons (Mars only)
D. Non-Propulsion Mars Applications
1. Mars Crew Life Support Systems
2. Mars Crew Food Production Systems
3. Mars Crew Radiation Protection System
4. Mars Outpost Power Systems
5. Auxiliary or Emergency Power Systems
6. Mars Concrete Production

Table 2. Hydrogen /Oxygen Resource Propellant Uses for Lunar Base Support Applications

A. Crew Life Support Systems
1. Drinking Water
2. Atmospheric Oxygen
3. Atmospheric Humidity
4. Washing/Bathing
5. Waste Processing
6. Space Suit Life Support
B. Food Production Systems
1. Plant Growth
2. Food Processing
3. Plant Reprocessing and Resource Recovery
4. Animal-Based Food Production
C. Lunar Laboratory Research
1. Plant Research
2. Animal Research
3. Chemistry
4. Physics
5. Biology/Biotechnology
6. Mineralogy/Geology
7. ISRU Chemical Processing Research (zeolites, Na, K, concrete, etc.)
D. Lunar Base Infrastructure Needs
1. Lunar Oxygen Production with H Recovery
2. Lunar Concrete Production for Roads, Buildings, Shielding
3. Thermal Control Support Systems
4. Oxygen or Hydrogen as Inflating Gas for Inflatable Structures
5. Water Radiation Shielding for Habitats/Laboratories
6. Water for Lunar Base Manufacturing Need

3.3 Cost-Benefit Assessment for the Lunar H_2/O Applications

A preliminary cost-benefit assessment for the use of Lunar H_2/O to support just the main space transportation requirements for a 20-year Lunar Base development/operation as given in NASA/JSC (1986). The mission model is assumed to begin at the start of H_2/O availability on the Moon. The key measurand in this analysis is the Earth launch mass (ELM). A cost benefit for only the use of H_2/O for main space transportation will give the first key analytical evidence of the tremendous benefit from Lunar H_2/O resources at the poles.

Lunar surface propellant production requirements must be accounted in the measurement of efficiency of the main space transportation system. Only H/O chemical propellant/propulsion systems have been considered here. Chemical propulsion/vehicle design characteristics, and the associated performance of the total transportation infrastructure were reviewed, conceptual propulsion system designs and vehicle/basing concepts, and technology requirements were assessed in context of a lunar Surface Base (LSB) mission scenario defined by NASA/JSC in the 1986 Model.

3.3.1 Propulsion/Vehicle Systems

There are several propulsion and vehicle systems and technology alternatives that can be applied to the Earth-Moon transportation infrastructure when considering the availability of H_2/O. If water ice is present, then hydrogen and oxygen are available in the ratio of 1 to 8 (O/F ratio of 8). Under this scenario the extra oxygen would be used for life support, as the propulsion system is designed for an O/F of 5.5. If any hydrogen is available in the polar regions then the oxygen would be processed via the hydrogen or carbon reduction method to the quantity needed for an O/F of 5.5. An analysis was conducted to compare infrastructure based on Earth supplied H/O propellant with two options taking advantage of the availability of lunar H_2/O. To perform this analysis, propulsion and vehicle systems capable of supporting a lunar base operation must be identified and defined. "Families" of vehicles must be defined from propellant/vehicle alternatives that satisfy requirements. A "vehicle family" is a group of systems (e.g., an OTV and a lander) specifically designed for a given requirement. Propulsion systems were chosen based on the choice of a hydrogen/oxygen, pump-fed rocket engine as the baseline propulsion system. The baseline vehicle system follows Orbital Transfer Vehicle (OTV) configurations that have been studied in the past. Vehicle options include aerobrakes, propellant tankage, support system mass and landing gear mass.

Beyond the present study, characteristics of the baseline propulsion/vehicle designs could be varied to address sensitivities and tradeoffs. Figure 8 presents the parameters for which sensitivities could be examined. The parameters and their corresponding values at the ends of each line represent examples of data range excursions that might be considered in tradeoff studies. In considering these types of tradeoffs, it must be remembered that the individual parameters are rarely independent. In many cases, changing one parameter changes another. For example, a change in the mixture ratio results in a change of the specific impulse, thrust, and other engine parameters. These types of tradeoffs will be considered in Phase II study effort.

For the present study, engine and stage parameters, were estimated on standard JANNAF thermochemical analysis methods. Stage weight and performance estimates were used to size an aerobrake, propellant tankage, and landing gear vehicle systems to meet mission requirements. The analysis includes consideration of specific propellant supply nodes, basing nodes, and vehicle design parameters. A total vehicle mass and propellant capacity was determined for a specific reference design mission. These results then were fed to an analysis, which manifests mission payload requirements and propellant supply burdens to obtain total transportation requirements: the number of flights between each node and the propellant supply requirements of each supply node. From these results, total Earth Launch Mass (ELM) is calculated. The ELM is the total mass that must be launched from the surface of the Earth over the duration of a base operation scenario, or mission model. The ELM, in addition to the number of OTVs and associated support mass required, provides a relative measure of efficiency for a given vehicle family. Another measure associated with the ELM is mass payback ratio (Mass payback ratio is the total ELM divided by the delivered payload mass).

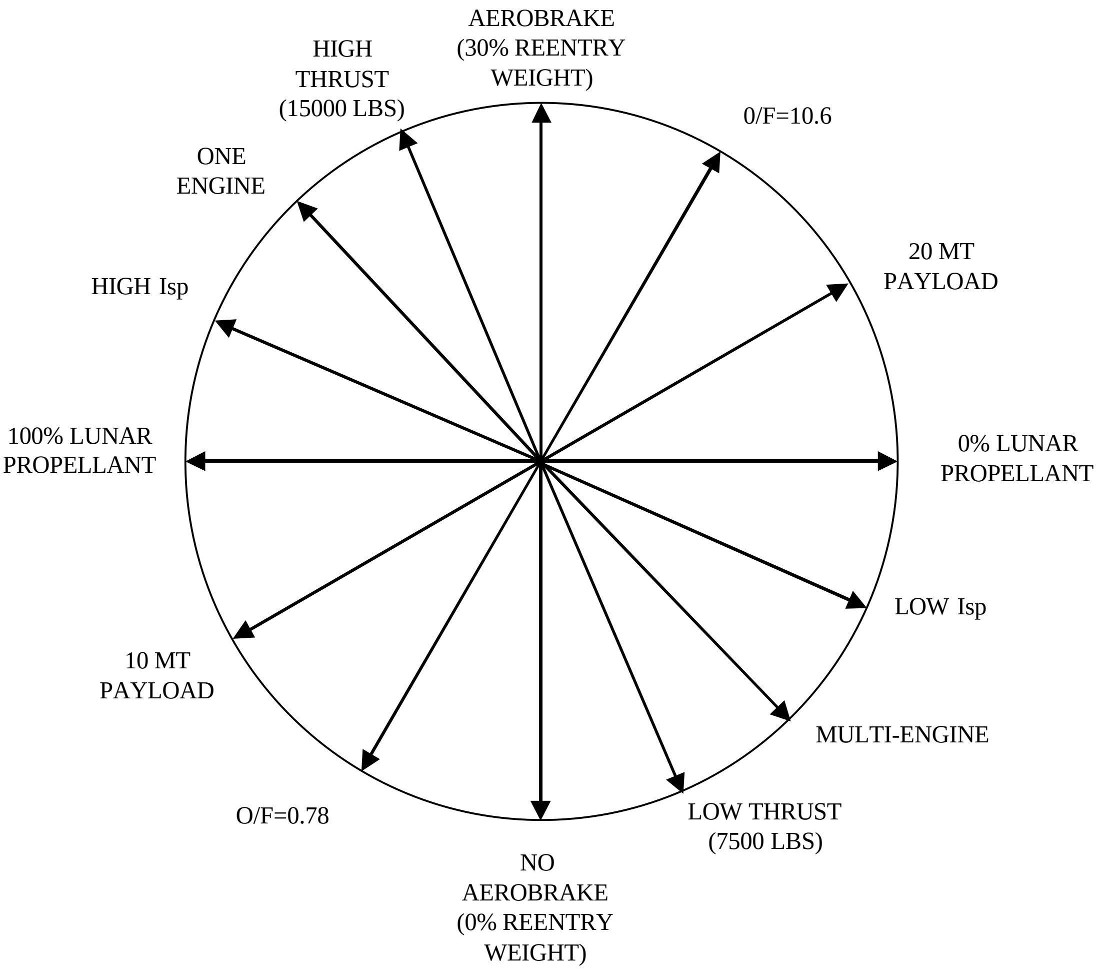


Figure 8. Applicable Tradeoffs and Sensitivities

3.3.2 Mission Requirements Definition

For the purposes of this Phase I study, ORBITEC adopted a Lunar Surface Base (LSB) Operation Scenario as defined by the updated NASA JSC Lunar Surface Base Mission Model circa 1986. The mission model is shown in Table 3. The nominal mission model covers 20 years and starts when lunar H_2/O is available. The mission model shows gaps with no flights in certain years and uneven flight rates over the 20-year mission period. However, this does not greatly impact transportation vehicle comparisons since the analysis is primarily based on total flights and mass over the 20-year mission period.

Table 3. JSC LSB Mission Model, January 1986

Year	Destination			No. of Payloads	Mass, MT (klbs)	Manned
	LO	LS	Return			
1	X			1	22.7 (50)	
2	X			1	22.7 (50)	
5		X		1	8.2 (18)	
9			X	1		X
10			X	1		X
11		X		2	2.3 (5)	X
		X		3	19.2 (42.4)	
12		X		1	19.2 (42.4)	
				3	2.3 (5)	X
13	X			1	22.7 (50)	
		X		3	2.3 (5)	X
		X		1	19.2 (42.4)	
15		X		9	2.3 (5)	X
		X		2	19.2 (42.4)	
		X		3	15.9 (35)	
16		X		4	15.9 (35)	
		X		3	10.4 (23)	X
		X		3	3.6 (8)	X
	X			1	22.7 (50)	
17		X		1	15.9 (35)	
		X		2	10.4 (23)	X
		X		4	3.6 (8)	X
19		X		5	15.9 (35)	
		X		4	10.4 (23)	X
		X		1	3.6 (8)	X
20		X		3	10.4 (23)	X
		X		3	3.6 (8)	X
21		X		1	3.6 (8)	X
		X		1	45.4 (100)	
		X		1	108.9 (240)	

The key factors that influence the vehicle design are the delta-v requirements between basing and propellant supply nodes. Nodes were chosen in the most obvious locations, LEO and Low Lunar Orbit (LLO). The resulting velocity increments are shown in Figure 9. With the nominal Moon-to-Earth trajectory selected, inclusion of an aerobrake would save over 3 km/sec. Other assumptions include typical payload and manned capsule mass. The manned capsule was assumed to have a mass of 6.9 metric tons (MT) (NASA/JSC, 1986). Payloads fall into six major sizes; 17 payloads at 2.3 MT, 4 at 3.6 MT, 12 at 10.4 MT, 9 at 15.9 MT, 7 at 19.2 MT, and 4 payloads at 22.7 MT. The 22.7 MT payloads are lunar orbiters. The 19.2 MT payloads include power stations, initial habitat/lab modules, and mobility/mining units. The 15.9 MT payloads are subsequent habitats, labs and scientific equipment. The 10.4 MT payloads are large payloads on a manned sortie mission while the 3.6 MT missions represent smaller payloads on a manned sortie and the 2.3 MT payloads are even smaller payloads accompanying manned sortie missions.

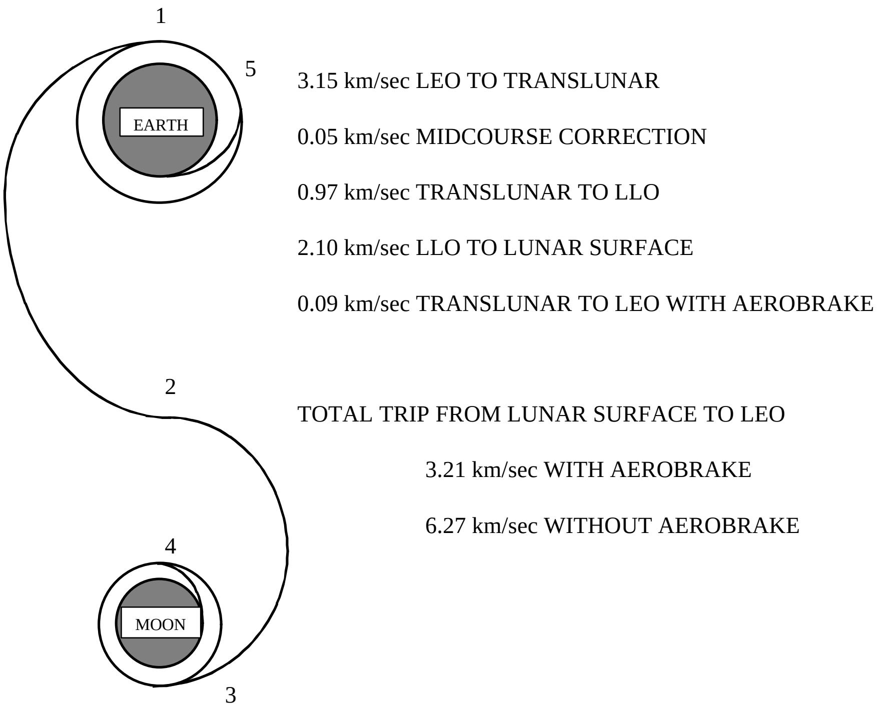


Figure 9. Assumed Earth-Moon Velocity Requirements (NASA/JSC, 1986)

3.3.3 Baseline Propulsion/Vehicle Concept

The baseline propulsion/vehicle concept was modeled after past NASA OTV studies. The propulsion system used liquid hydrogen/oxygen propellants that were pump-fed to a chamber pressure of 1380 N/cm^2 (2000 psi) and temperature of 3346 C at an O/F ratio of 5.5. The resulting specific impulse was estimated at 470 seconds. The basic propulsion system design was modeled after an Aerojet dual propellant expander engine cycle design. The total engine mass was estimated at 95 kg. Table 4 provides a summary mass statement for the assumed baseline propulsion system.

Table 4. Engine Data

EXPANDER CYCLE (FUEL SIDE)
CHAMBER IS REGEN. COOLED (MILLED SLOT CONSTRUCTION)
NOZZLE IS RADIATION COOLED
PROPELLANT COMBINATION IS LO_2/LH_2

ENGINE DIMENSIONS (INCHES)	
THROAT DIAMETER	1.55
CHAMBER DIAMETER	3.10
NOZZLE EXIT DIAMETER	26.86
NOZZLE EXTENSION ATTACH DIAMETER	6.93
CONVERGENT CHAMBER LENGTH	5.00
CYLINDRICAL CHAMBER LENGTH	7.60
CHAMBER STRUCTURAL THICKNESS	0.009
GAS SIDE WALL THICKNESS	0.033
NOZZLE EXTENSION THICKNESS	0.027
NOZZLE EXIT AREA RATIO	300.00
CHAMBER CONTRACTION RATIO	4.00
NOZZLE EXTENSION ATTACH AREA RATIO	20.00
NOZZLE LENGTH/ (MIN RAD LENGTH)	1.25
NOZZLE LENGTH	47.93
CHAMBER LENGTH	12.60
INJECTOR FACE FORWARD LENGTH	11.89
MOUNT LENGTH	2.00
ENGINE WEIGHTS (POUNDS)	
NOZZLE EXTENSION	23.01
CHAMBER	20.85
BIPROPELLANT VALVE	1.73
INJECTOR	4.53
TCA SUPPORT HARDWARE	3.42
TCA CONSTRUCTION	2.51
SINGLE THRUST CHAMBER ASSEMBLY	56.05
THRUST MOUNT	22.42
GIMAL SYSTEM	21.43
ENGINE BAY LINES	4.11
TOTAL NUMBER OF ENGINES	2
CLUSTER EXIT RADIUS	0.00
CLUSTER AREA RATIO	0.00
MODULE TILT ANGLE (DEG)	0.00
TOTAL ENGINE	112.10
TOTAL THRUST MOUNT	44.84
TOTAL GIMBAL SYSTEM	42.85
TOTAL ENGINE BAY LINES	8.22

PERFORMANCE	
DELIVERED ISP (VAC), SEC	469.61
IDEAL ISP (ODE), SEC	482.94
DELIVERED CSTAR, FT/SEC	7608
IDEAL CSTAR, FT/SEC	7647
CHAMBER PRESSURE, PSIA	2000
THRUST PER ENGINE (VAC), LBF	7500
TOTAL VAC THRUST, LBF	15000
BURN TIME, SEC	3587.93
OVERALL EFFICIENCY	0.972
ENERGY RELEASE EFFICIENCY	0.988
NOZZLE EFFICIENCY	0.984
KINETIC EFFICIENCY	1.000
VAPORIZATION EFFICIENCY	1.000
MIXING EFFICIENCY	0.997
MR DISTRIBUTION EFFICIENCY	0.991
BOUNDARY LAYER EFFICIENCY	0.989
DIVERNGENCE EFFICIENCY	0.995
TWO PHASE EFFICIENCY	1.000
FOR 2 ENGINES	
OXIDIZER FLOW RATE, LB/SEC	27.02
FUEL FLOWRATE, LB/SEC	4.92
TOTAL FLOWRATE, LB/SEC	31.94
CORE MIXTURE RATIO	6.00
CORE TEMPERATURE, DEG R	65.15
BARRIER MIXTURE RATIO	2.44
BARRIER TEMPERATURE, DEG R	3792
ENGINE MIXTURE RATIO	5.49
FUEL FILM COOLING FRACTION	0.09
INJ ELEMENT DENSITY, ELEM/IN**2	10.19
OX ORIFICE DIAMETER (IN)	0.059
FUEL ORIFICE DIAMETER (IN)	0.078

Table 5. Centaur D1-T Weight

UNMODELED COMPONENTS	MASS (kg)
STUB ADAPTER	114
EQUIPMENT	112
ACS	3
ULLAGE MOTORS	18
PROPELLANT	21
AUXILIARY PROPELLANT	67
GUIDANCE	77
AUTOPILOT SYSTEM	66
ELECTRICAL SYSTEM	65
RANGE SAFETY SYSTEM	24
TRACKING SYSTEM	5
TLM SYSTEM	128
ADAPTER	34
SEPARATION SYSTEM	24
HELIUM	4
ICE	5
UNMODELED COMP.	767

MODELED SUBCOMPONENTS	MASS (kg)
BASIC STRUCTURE	371
SECONDARY	124
MAIN ENGINE	274
FUEL SYSTEM	82
OX SYSTEM	52
PROPELLANT LOAD	8
HYDRAULIC SYSTEM	45
PRESSURIZATION	112
TOTAL	1068
UNMODELED COMP.	767
CENTAR DRY	1835
RESIDUAL	77
GASEOUS	115
AUXILIARY	59
CENTAUR WEIGHT	2086

Basic vehicle components were modeled after the Centaur D-1T. The Centaur D-1T masses are summarized in Table 5. The propellant tanks were assumed to be made from 301 CRES stainless steel at 0.36 mm minimum gauge size. The tanks were cylindrical with elliptical ends of ellipse ratio 1.38.

The baseline infrastructure included three basing/servicing nodes, reusable OTV, and a reusable lander. The nodes are at LEO, Low Lunar Orbit (LLO), and the Lunar Surface Base (LSB), all being nodes for servicing, propellant supply and payload changeout. The OTV has two engines and is designed for a fully loaded manned sortie of 15.9 MT payload to LLO from LEO and returning with only the manned capsule of 6.9 MT. The payloads larger than 15.9 MT are delivered in multiple trips and manifested to fill the vehicles. The baseline OTV includes an aerobrake with mass equal to 15% of the reentry mass for the reference design mission. The baseline lander is a reusable, two-engine vehicle with capability of delivering 15.9 MT (manned capsule plus payload) to the lunar surface from lunar orbit and returning to lunar orbit with 6.9 MT (the mass of the manned capsule alone). The masses for the baseline OTV and lander concepts are summarized in Table 6 below:

Table 6. OTV Lander Mass

OTV Mass, kg		Lander Mass, kg	
Dry (less AB & tanks)	1,030	Dry (less landing gear & tanks)	1,030
Aerobrake	3,411	Landing Gear	1,841
Oxygen Tank	367	Oxygen Tank	83
Fuel Tank	1,618	Fuel Tank	366
Propellant Capacity	83,892	Propellant Capacity	24,553
Payload	15,873	Payload	15,873
Mass Fraction:	0.93	Mass Fraction:	0.88

The high mass fraction of the OTV is largely due to the large velocity increments of the LEO-to-LLO trip and the associated large amount of propellant. Current vehicle technology exhibits mass fractions of upper stages to around 0.86. If tankage on current vehicles (e.g. Centaur) is increased to provide larger propellant capacities, the mass fraction will be driven higher; and this is the case here. The initial estimates for the dry mass for the OTVs and landers were both considered identical.

The design of the Baseline OTV also allows transport of 33,682 kg of propellant (from LEO to LLO) for the lander. No propellant is carried back from the Moon in the baseline case.

3.3.4 Vehicle Systems Characterization

The major vehicle systems (other than propulsion) analyzed in this study included aerobrakes, landing gear, propellant tankage and support system mass. The support system mass included avionics structural support, thermal protection, fuel tank pressure weights, fuel boil-off, residual fuels, interstage mass, and miscellaneous, masses, all based on Centaur data. The miscellaneous masses include tracking systems, range safety systems, auto-pilots, the electrical systems, the guidance systems, auxillary propellant systems, motors, altitude control systems, and any adapters needed for the propulsion system itself. These mass estimates were given in Table 5. The aerobrake, landing gear and tank masses (Table 6) were all calculated, for a given reference design mission.

Aerobrake masses were represented by a percentage of the reentry mass of the entire vehicle system. Typical Earth-produced aerobrakes range in masses from 15% to 50% of the reentry mass. The aerobrake mass must not exceed about 35% of the reentry mass to be of use for lunar base operations. The baseline aerobrake used in this study was 15% of the reentry mass. Another concept that may be quite valuable is that of a lunar-produced aerobrake. JSC estimated that a lunar-produced aerobrake mass would be approximately 18% of the reentry mass (Lunar Surface Return, 1984). Such an aerobrake would not have to be carried from LEO to Low Lunar Orbit and back again, but simply from LLO to LEO. Also, the lunar derived aerobrake would not be part of the ELM. The aerobrakes in the vehicle families were calculated based on the reentry mass of design reference missions. The mission included: (1) return of OTV with full payload only; (2) return of OTV with full payload and a small portion of oxygen; and (3) return of OTV with full payload and enough oxygen for the next outbound leg from LEO to LLO. The third reference mission required an aerobrake of mass about 13 MT. Such a large aerobrake may not be viable.

Landing gear mass for a lunar lander is a function of the landing mass of the lunar lander. Typical ratios of landing gear mass to total landing mass on the Moon are around 5%. Thus, a 5% lander mass was estimated for all lunar landers.

Propellant tankage is a major part of the total vehicle mass. However, advances in tankage have allowed projections of the specific mass of the tankage to be quite low, even for cryogenics. Tank estimates for vehicles developed here were derived from the Centaur data using CRES 301 stainless steel as the tank material, the tanks were configured in a cylindrical fashion with elliptical end using and elliptical ratio of 1.38. The thickness of the tank walls was estimated at 14 mils. Appropriate boil-off parameters were considered. Scaling of the tanks was done to accommodate specific reference design missions of the vehicle families and will be reported in the following section.

OTVs and lander masses were estimated with reusability in mind. No expendable vehicles were addressed. Expendable lunar lander systems will burden the OTV greatly as unproductive mass delivered to the lunar surface when compared to the reusable lunar lander. This additional mass delivery would increase the total Earth launch mass by an order of magnitude and should only be considered for a short period of time in the initial stages of the lunar base, if at all.

3.3.5 Propulsion/Vehicle System Family Descriptions

The propulsion and vehicle systems described in the last two sections were assembled in three vehicle families (groups of vehicles that can satisfy the mission) to assist in providing data points for analysis. The vehicle family systems were created utilizing specific design reference missions to size the various vehicle subsystems, especially tankage, landing gear, and aerobrakes. The vehicle family systems were developed with the common basing scenario. The basing scenario includes the Space Station in LEO to provide servicing, payload accommodation and propellant supply. A similar basing node located at LLO will be needed to operate as a propellant storage depot, a payload transfer from OTV to lander and for potential servicing of either the OTV or lander systems. The lunar surface base was seen as a propellant supply source from which oxygen and hydrogen could be supplied.

Table 7 summarizes the mass and mass fraction data developed for the three propulsion/vehicle family candidates. Each OTV in the table is identified by the letter “a”; each lander by the letter “b”. OTVs were single stage vehicles providing transportation between LEO and LLO. The lander provided transportation between LLO and the lunar surface.

Table 7. Vehicle Mass Summaries

VEHICLE		**MASS, MT**			**OTHER**		
		Engine	Propellant Tanks	A/B or Landing Gear	Dry	Total (less propellants)	Mass Fraction
1 BASELINE H/O	(a)	0.095	(1.99)*	(3.41)	0.84	(6.43)	(0.93)
	(b)	0.095	(0.45)	(1.84)	0.84	(3.32)	(0.88)
2 H/O with LLOX	(a)	0.095	1.33 (1.99)	2.89 (3.41)	0.84	5.25 (6.43)	0.89 (0.93)
	(b)	0.095	0.451 (0.45)	1.85 (1.84)	0.84	3.33 (3.32)	0.88 (0.88)
3 H/O with LLOX and LH2	(a)	0.095	0.545 (1.99)	2.80 (3.41)	0.84	4.37 (6.43)	0.87 (0.93)
	(b)	0.095	0.451 (0.45)	1.85 (1.84)	0.84	3.33 (3.32)	0.88 (0.88)

(a) OTV (b) Lander *Number in brackets corresponds to reference mission without Lunar propellant availability

Concepts with and without lunar propellants were addressed. When a propellant source was not available on the Moon, the OTV was designed to accommodate enough propellant for its entire round trip and the lander trips required. When propellant was available on the Moon, the OTV did not have to carry all lander propellant or all propellant for its own return. The lander was responsible to deliver all payloads and OTV propellant required from the lunar surface to LLO. However, the requirements for propellant delivery to LLO were not used to size the lander. The lander was sized based on the payload requirements. Multiple propellant delivery trips were provided where necessary. The parameters in parenthesis in Table 7 represent data for vehicle families designed without lunar propellant being available.

The first family is comprised of an OTV and lander with a Baseline H/O propulsion system without lunar propellants and with a nominal 15% mass aerobrake and 5% landing gear mass. The Baseline has only one reference mission: no lunar propellant available. The second family represents the Baseline with lunar oxygen being available and the third family represents the Baseline with both lunar oxygen and lunar hydrogen being available. Two reference missions exist for families two and three: (1) with lunar propellant available, and (2) no lunar propellant available. Note that the no lunar propellant reference mission represents the Baseline case. As more propellant becomes available, the propellant tank mass for the OTV decreases by about 1.5

MT; oxygen availability reduces tankage mass by about 0.7 MT while hydrogen availability saves an additional 0.8 MT. The oxygen availability also yields a 0.5 MT savings to the aerobrake mass with lunar hydrogen saving an additional 0.1 MT. The total propellant requirement for 15.9 MT payload delivery/return is reduced by over 50% with lunar oxygen and by over 65% with both lunar oxygen and hydrogen. The overall effect is a reduction of vehicle mass fraction requirements from 0.93 to 0.89 and 0.87 for lunar oxygen and lunar oxygen/hydrogen, respectively. Thus, availability of oxygen from the Moon reduces the overall technology of requirement of the single stage OTV to conduct a lunar mission.

This vehicle family data was used to produce data on a number of flights, propellant requirements, and total Earth launch mass for the entire mission model scenario given. Results are given below.

3.3.6 Lunar Surface Base Mission Propellant Supply and Cost-Benefit Analysis

The goal of this analysis was to examine the tradeoff between Earth to lunar surface transportation systems operating with propellant supplied solely from Earth to transportation systems relying significantly on propellants supplied from the Moon to determine cost-benefit. Propulsion and vehicle systems alternatives and vehicle families [a “family” is a selected combination of vehicles (e.g. a hydrogen/oxygen, H/O, Orbital Transfer Vehicle, OTV, and lunar lander) sized to satisfy all of the requirements of the mission model]. This analysis applies those vehicle family alternatives to a lunar base mission model to derive Earth launch mass requirements for the alternatives. Analyses were performed that determined which propulsion/vehicle systems are most efficient with respect to the Earth-Moon transportation system. The analysis flow is depicted in Figure 10. Transportation system total Earth Launch Mass (ELM) was used as the evaluation parameter. To develop the data with which to compare alternatives, the mission model was manifested out to vehicles within a family to produce a traffic model, which determines total propellant requirements at the various nodes. These propellant requirements then allowed estimation of propellant processing resource requirements required at the different nodes (Earth orbit, lunar orbit, lunar surface). The resource requirements then were integrated into the mission model as support requirements. The traffic model was updated as a result of additional propellant and propellant processing resource requirements. Iterations were performed to arrive at the total Earth Launch Mass (ELM) for the given mission model scenario.

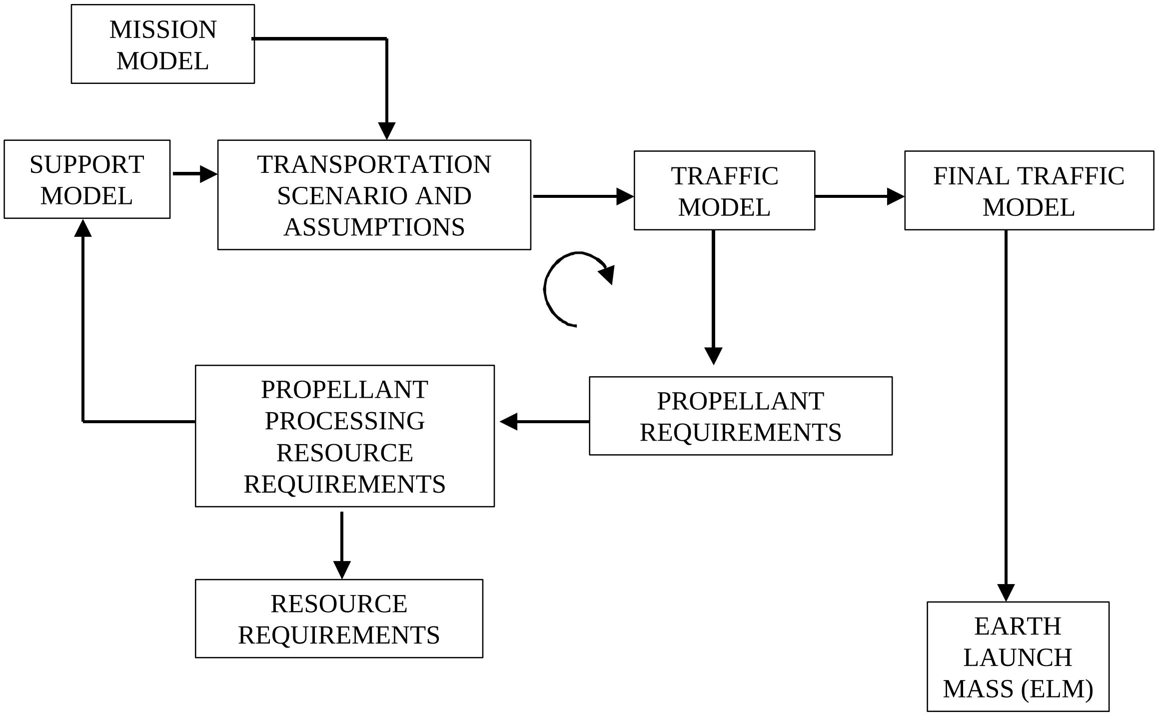
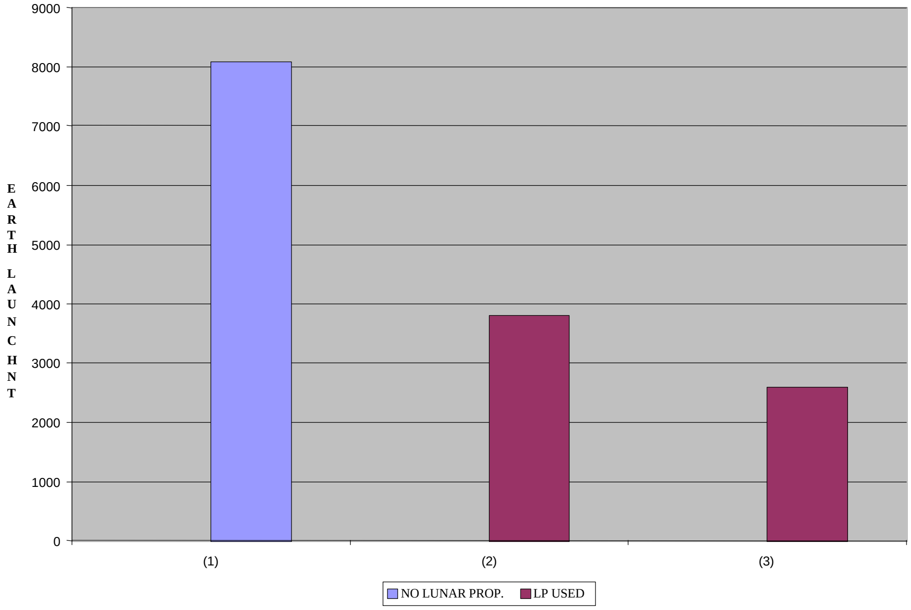


Figure 10. Family Study Flow

Figure 11 shows the total ELM for the various vehicle families with and without the use of lunar propellant. The legend defines vehicle families that are identified by code number is in the figure. The numbers on the horizontal axis of this bar chart relate to the Legend. Thus, the vehicle families included in this chart are Baseline hydrogen/oxygen family (1), the hydrogen/oxygen OTV and lander with lunar oxygen availability (2), and the hydrogen/oxygen OTV and lander concept with lunar oxygen and lunar hydrogen availability (3). A comparison of some of the three vehicle families for each year of the mission model is provided in Figure 12. One can see that the baseline hydrogen/oxygen propulsion/vehicle system with both oxygen and hydrogen available on the Moon requires the least amount of resources from the Earth.

The majority of ELM is propellant required to deliver both the payloads and the lunar propellant processing resources. Figure 13 provides the Earth, Moon, and total propellant requirements for the two vehicle families. The hydrogen/oxygen OTV and lander with both oxygen and hydrogen available from the Moon has by far the lowest Earth-derived propellant requirement. The relationship between the ELM and cost is simply the delivery cost per pound to low Earth orbit.

The total ELM estimates for any given vehicle family is comprised of the propellant requirements, the actual payloads that must be delivered to either low lunar orbit or to the lunar surface, and any support requirements including equipment and consumables for propellant processing. Of these three, the propellant for delivery of the payloads and support requirements are by far the largest portion of the total ELM.



(1) BASELINE, H/O OTV & LANDER (NO LUNAR PROPELLANT)
(2) H/O OTV & LANDER (LLOX AVAILABLE)
(3) H/O OTV & LANDER (LLOX & LH2 AVAILABLE)

Figure 11. Vehicle Family Results Summary

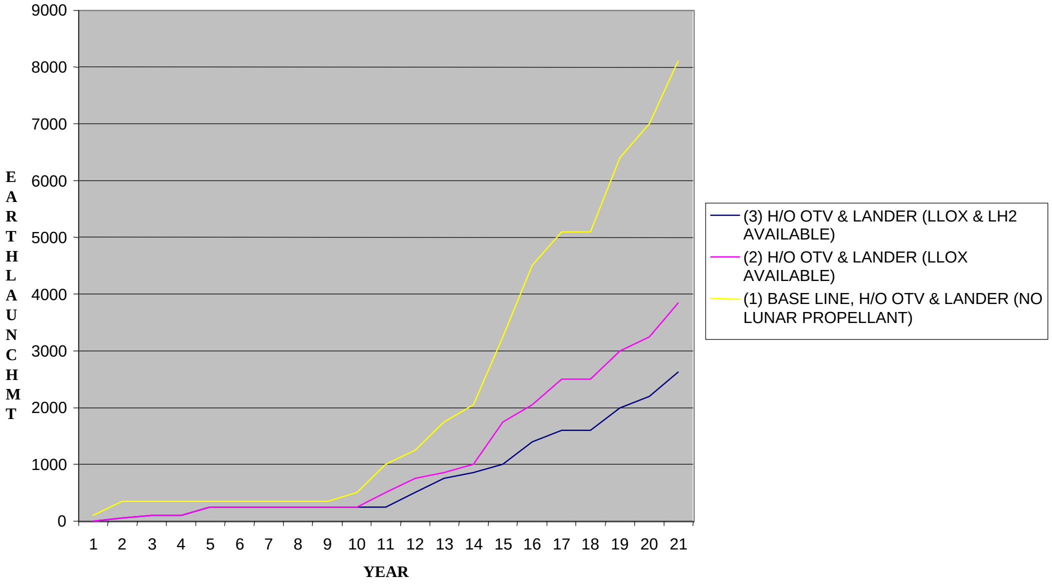
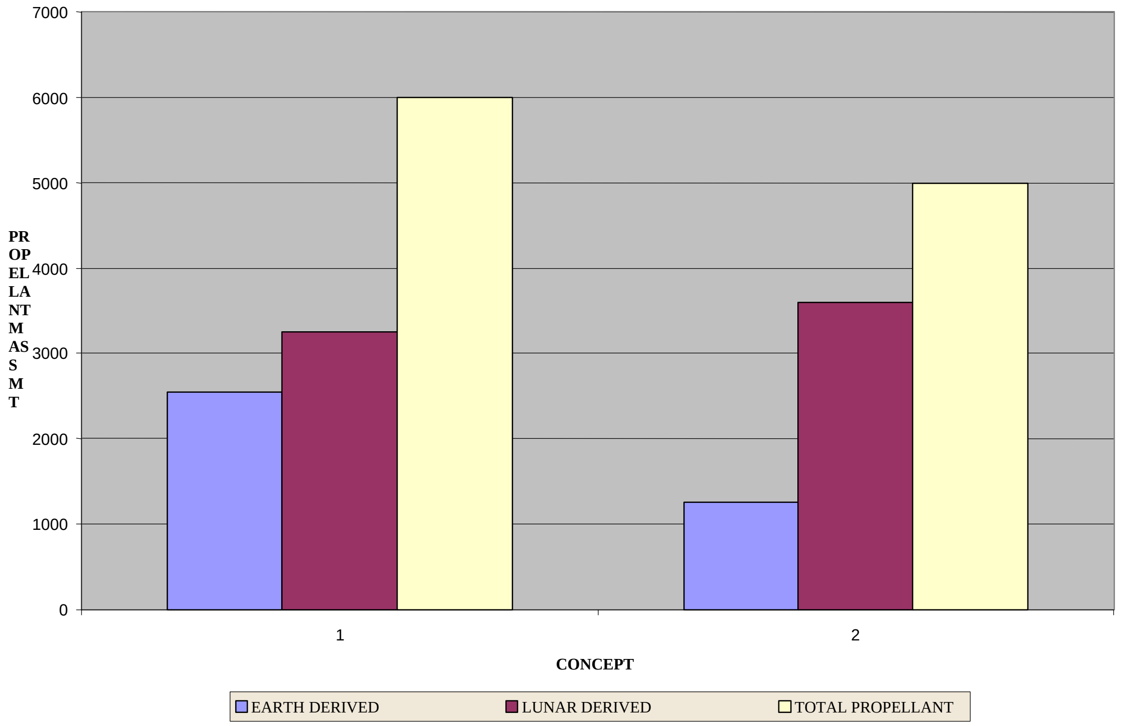


Figure 12. Concept Comparison – Lunar Propellant Available



(1) H/O OTV & LANDER (LLOX AVAILABLE)
(2) H/O OTV & LANDER (LLOX & LH2 AVAILABLE)

Figure 13. Propellant Requirement Summary with Lunar Propellant Available

Based on the above results, total mission model Earth launch costs were estimated (Table 8). These estimates were based on a range of three assumed values for the cost of launching a kilogram (kg) in to LEO. The assumed costs used were $10,000/kg, $1000/kg, and $400/kg. The cost savings due to the use of lunar propellant are substantial and evident. One key parameter related to ELM is a value known as the mass payback ratio. This ratio relates the mass required in LEO to the productive mass delivered to the lunar surface. To obtain this mass payback ratio we have divided the total ELM by the total mission model mass. Thus, there is a different mass payback ratio for each vehicle family and these are listed in Table 9. These mass payback ratios range from 2.3 to 6.1 and can be used to estimate the total ELM of any given mission to the Moon on a rough order of magnitude basis. These mass payback ratios calculated here include only the propellant and propellant processing support masses. They do not include the vehicle masses involved for the transportation system because these masses were not included in the ELM examined here. The mass of the transportation vehicles would change the mass payload ratios by about 0.5%.

Table 8. Total Earth to LEO Launch Costs

Vehicle Families	Unit Cost ($/kg)	Total Mass Launched (MT)	Total Cost ($B)
(1) Baseline OTV & Lander (No Lunar Propellant)	**10,000**	**8,000**	**80**
(2) Baseline OTV & Lander (Lunar Oxygen Available)	**10,000**	**3,900**	**39**
(3) Baseline OTV & Lander (Lunar Oxygen and Hydrogen Available)	**10,000**	**2,600**	**26**
(1) Baseline OTV & Lander (No Lunar Propellant)	**1,000**	**8,000**	**8.0**
(2) Baseline OTV & Lander (Lunar Oxygen Available)	**1,000**	**3,900**	**3.9**
(3) Baseline OTV & Lander (Lunar Oxygen and Hydrogen Available)	**1,000**	**2,600**	**2.6**
(1) Baseline OTV & Lander (No Lunar Propellant)	**400**	**8,000**	**3.2**
(2) Baseline OTV & Lander (Lunar Oxygen Available)	**400**	**3,900**	**1.6**
(3) Baseline OTV & Lander (Lunar Oxygen and Hydrogen Available)	**400**	**2,600**	**1.0**

Table 9. Mass Payback Ratios for Vehicle Families

	Vehicle FamilyMass	Payback Ratio
		Lunar Prop. –Year 1
(1)	Baseline OTV & Lander (No lunar propellant)	6.10
(2)	Baseline OTV & Lander (Lunar oxygen available)	3.36
(3)	Baseline OTV & Lander (Lunar oxygen and hydrogen available)	2.30

When addressing effects of lunar propellant processing on ELM one is actually measuring the value of the transportation system and associated lunar propellant processing system using ELM as the measurand. Generally, lunar propellant availability reduces the total mass, the mass fraction, and the ELM of the OTV. In addition, the earlier establishment of the lunar propellant supply within the mission scenario further lowers the ELM. Specifically, the effects of lunar oxygen on Baseline hydrogen/oxygen OTV and lander, and the effects of lunar oxygen and lunar hydrogen availability on the baseline systems on the hydrogen/oxygen OTV and lander systems were addressed.

The effects of the availability of lunar oxygen are shown in Figure 14 for no lunar propellant and lunar propellant available through the entire mission scenario. Lunar oxygen availability throughout the entire mission model will reduce the total ELM by 52.5% as compared to the Baseline where no lunar propellant is available.

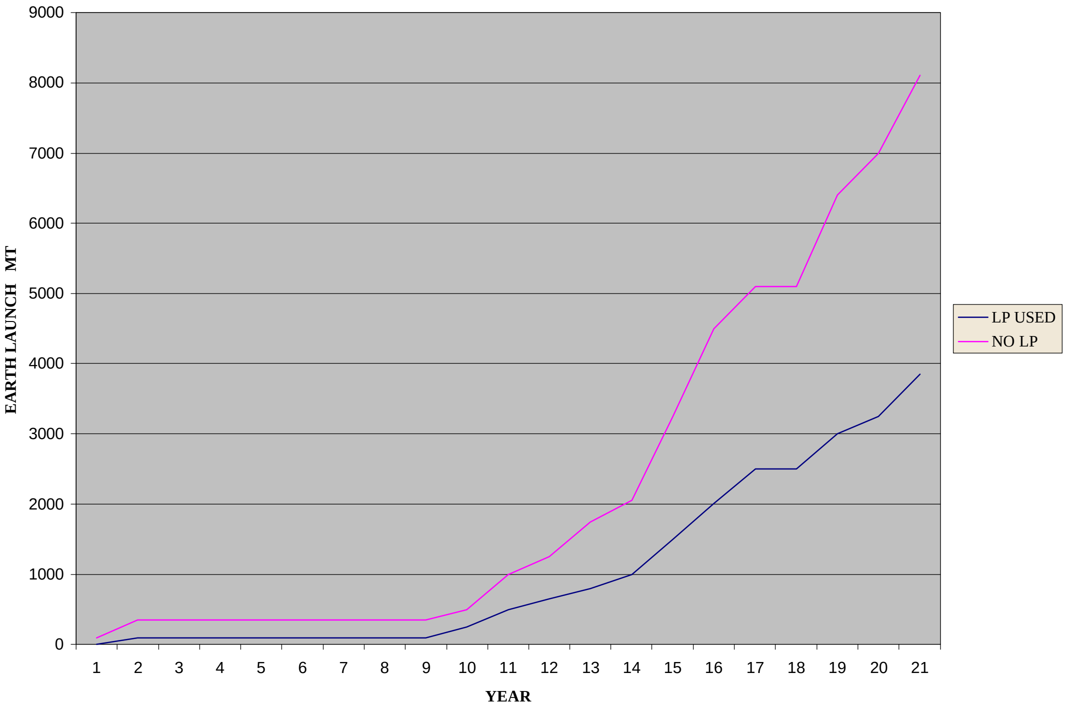


Figure 14. Lunar Propellant Effects Baseline H/O System with LLOX

Similar results are found in Figure 15 when considering the availability of both lunar oxygen and lunar hydrogen. Supplying lunar oxygen and hydrogen to the baseline system for the entire mission scenario, the ELM may be reduced by 67.5% over the Baseline.

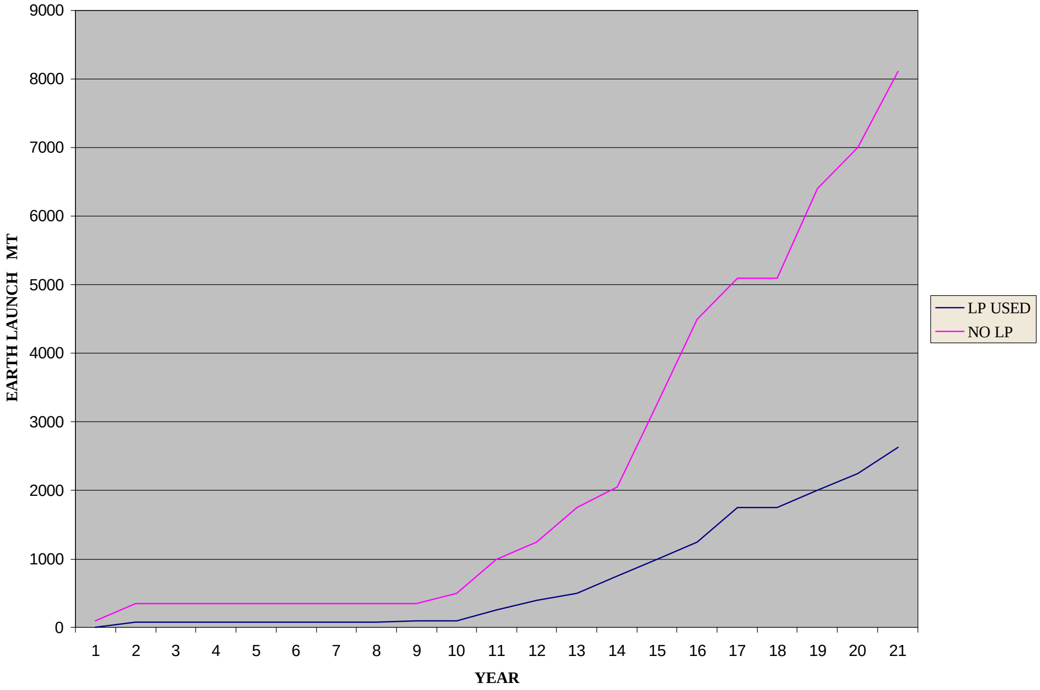


Figure 15. Effect of Lunar Propellant (LLOX LH_2) on H/O System

3.4 Preliminary System Requirements for a Polar Lunar Lander/Rover Mission

A robotic rover would be used to explore the regions near the north or south pole of the Moon where water ice and H_2 is believed to exist. Such a mission could provide valuable information on the location, concentration and physical properties of the water ice and H_2 deposits. This information could then be used to develop ice extraction processes and perfected ground-based lunar ice simulators or environmental chambers.

Preliminary system requirements for a low-cost, lunar-ice characterization mission, wherein several samples would be returned to Earth for detailed analysis are presented here. The baseline mission would use an ARPS power supply for the rover and a solar array for lander and launcher power (on a permanently sunlit crater rim). The lander would land on a permanently sunlit crater rim, the solar array would be deployed, and the ARPS-powered rover would be deployed on to the surface. The rover would then proceed into the cold trap and explore. A large suite of experiments could be included, such as:

- ***Wide-Angle Navigation Cameras*** with auxiliary lights to help the rover negotiate the Lunar terrain in the shadowed areas
- ***Panoramic Cameras*** with auxiliary lights for stereo, high-resolution visualization of the nearby terrain
- ***Microwave or Ultrasonic Sounder*** to determine the depth of ice deposits in the dry regolith
- ***Robotic Arm*** to collect and transfer surface regolith to rover instruments for analysis
- ***Sample Extraction System*** to obtain subsurface core samples for analysis on the rover

- ***Thermal Emission Spectrometer*** for analyzing the mineral composition of the regolith and volatiles
- ***Microscopic Imager*** to provide very detailed images of regolith and rocks
- ***Alpha-Proton-X-Ray Spectrometer*** to study the elemental chemistry of regolith and volatiles
- ***Cryogenic Temperature Sensors*** for determining surface and subsurface regolith temperatures
- ***Pyrolyzing Oven*** to vaporize and extract water-ice or hydrogen and other volatiles from the regolith for analysis by other instruments
- ***Hydrology Suite*** for analyzing the concentration and composition of water-ice in the regolith.

The instrumentation will be one of the driving forces in the rover design. The mission will also provide the opportunity to demonstrate ISRU technology in the cold traps. For example, various techniques may be employed to extract the H_2/O/regolith, including: drilling, scraping, scooping, cutting, rotary excavation, fluidizing, and etc.

Though many factors will play a role in the final mission design, an iterative process with respect to the experimental definition and power requirements should be followed to optimize the mission. The mass of the experimental equipment must be taken into consideration.

The sample return part of the mission would be accomplished by a Earth Return Vehicle (ERV) that would be launched from the lander. The rover would gather samples and place them in a sample container. At the end of the first phase of the mission, the rover will return to the lander site and give up its sample container to the ERV. The ERV would then be launched and the sample container would be recovered via reentry/parachute/aircraft capture over the Earth's ocean.

3.5 Lunar H_2/O Extraction Approaches

There are three basic approaches to extracting H_2/O that have been identified. The first involves the in-situ heating of H_2/O/regolith without excavation. The H_2/O/regolith is heated and (1) for water, vapor is collected at the surface by freezing, so that it can be transported mechanically out of the shadowed area, or liquid or gaseous water is transported by heated pipeline from the cold trap, or (2) hydrogen gas is driven from the regolith, collected at low pressure, pressurized, and then transported by pipeline from the cold trap. The second approach is to excavate the H_2/O/regolith mixture, but process it in a furnace situated in the cold trap, and (1) for water, transporting liquid or gaseous water from the cold trap to a collection site outside of the shadowed area, or (2) for hydrogen, transporting the gaseous product from the cold trap to a site outside the shadowed area. A third option is to excavate the H_2/O-rich regolith and transport it from the cold trap to a sunlit area for processing. Interesting complications may arise in the processing if other volatiles are significantly present (e.g. Hg, CH_4, Na, etc.).

Each of the H_2/O recovery approaches considered is composed of several elements:

- ***Regolith Preparation or Collection*** - This includes any conditioning of the H_2/O/regolith that is required before it can be processed. It also includes the collection of the H_2/O-rich regolith and placement in the reaction chamber, if required.

- ***Energy Source*** - This is the source of all the energy required in the extraction process. Energy requirements include the excavation equipment, reaction chamber, and transportation before and/or after processing.

- ***Energy Delivery to Shadowed Area*** - This is the method that energy is delivered to the excavation and extraction sites. This could include power cables, microwaves, reflectors, fuel cells, batteries, chemical reactors, pipes, etc.

- ***Extraction Process*** - This is the method that the H_2/O is being separated from the regolith. Some possible methods include distillation, mechanical separation, filtration, etc.

- ***Regolith or Resource Transportation*** - This is the method of transport of the processed resource or regolith out of the shadowed area.

Table 10 provides a preliminary set of processes for mining and extracting H_2/O in each of these areas.

Table 10. Preliminary Set of Processes for Mining and Extracting H_2/O

H_2/O/Regolith Preparation Or Collection	**Energy Source**	**Energy Delivery to Shadowed Area**	**H_2/O Extraction Process**	**H_2/O/Regolith Transport**
H_2/O/Regolith Preparation - Hammer & scoop - Air hammer - Auger - Block cutting - Explosive	Electrical - Nuclear reactor - GPHS-RTG -Chemical reactor - Fuel cell - Photovoltaics	Electrical energy - Wires, cables - Fuel cells - Batteries -Beamed power	Vaporization - Microwaves -Electrical furnace - Beamed heating - Chemical	Pipe out of shadow - Liquid water - Steam/vapor - H_2 gas Tanks on rovers
H_2/O/Regolith Collection - Scoop - Auger - Drag line bucket - Bulldozer	Direct Heating - Nuclear reactor - GPHS-RTG - Solar - Chemical - Laser	Thermal energy - Solar reflector -Insulated pipes - In-situ reactor - Beamed light - Chemical	Melting - Chemical - Solar - Nuclear - GPHS-RTG	Mechanical - Drag lines - Buckets - Gondolas - Conveyor belt - Dumbwaiter
		Mechanical energy - Cables - Belts	Condensation on cold plate	Ballistic - Rocket - Catapult

The most important environmental parameters for designing the extraction processes and systems are listed below:

a) ***Form of H_2/O/Regolith (implies physical properties of cohesion, strength)*** - This variable is most important in defining the excavation mechanisms that can be utilized. The following are the most likely configurations:

  - Finely granular - formed by gardening of lunar soil with introduction of ice grains
  - Ice chunks mixed in the regolith - formed by gardening of comet ice layers
  - Solid ice/regolith layer - formed by continuous accumulation of ice and diffusion of water.
  - Trapped H_2 gas from the solar wind.

b) ***Concentration of H_2/O*** - The concentration of H_2/O is important in determining whether processing should be done totally within or partially outside of the cold trap. If the concentration of H_2/O is low, it would be necessary to process a lot of regolith mixture to extract a small amount of water or hydrogen. Thus, processes that require less material movement would be favored. At the extreme, in-situ processing may be required for economic extraction at low resource concentrations. The concentrations currently reported by the Lunar Prospector mission are on the order of 1.6%. In this range, there would be significant tradeoffs between local extraction within the cold trap and excavation and transportation of regolith mixture to a processor outside of the cold trap. It is currently believed by the Lunar Prospector team that both H_2 and H_2O exist at the poles, with H_2O being predominant in the cold traps and H_2 being predominate in the polar non-permanently shadowed areas. It still may be possible that deposits of near-pure ice buried beneath a layer of dry regolith could be excavated. The final processing of the water ice could occur outside the cold trap where solar energy was readily available. An assessment of water contamination by other volatiles also needs to be made. The use of other volatile material also needs assessment.

c) ***Scale of Deposits*** - The scale of the deposit determines the distance between the cold trap and adjacent areas that have access to solar energy. This is important in designing transportation systems for energy and materials in and out of the cold trap. It also determines the time scale in which systems must operate in the cold trap before returning to a sunlit area. Finally, the scale of the deposit determines how much H_2/O can be extracted and, therefore, the degree that extraction apparatus needs to be relocated.

d) ***Terrain Accessibility*** - Small craters should not present any serious accessibility problems, but there may be boulders in the subsurface on the rims. Larger craters may pose severe access problems due to rugged crater walls, substantial relief, and the abundance of boulders. Access challenges in low relief terrain in permanent shadow should be minimal. Terrain accessibility would determine the style of access for surface mobility systems.

e) ***Availability of Solar Energy*** - The highest availability of solar energy would be for the small craters located outside the Aitken Basin. There may be areas of permanent sunlight on the rim of the larger south pole crater. Availability of solar energy close to the H_2/O deposits would influence the selection of energy provision and transmission approaches.

f) ***Temperature*** - Temperature in the cold trap is determined by the amount of scattered light that can be received and by the heat conduction through the surface. Any extraction system to be utilized within the cold trap must be capable of operating in temperatures ~70 K. It should be assumed that machinery would have to radiate heat to deep space.

Three extraction system scenarios were developed: (1) In-situ Ice Extraction via Microwave Heating; (2) Local Extraction of the Ice/Regolith Mixture with GPHS-RTG (General Purpose Heat Source - Radioisotope- fueled, Thermoelectric Generator) Thermal Processing and Steam Pipe Transport; (3) Local Drag Line Extraction of the Ice/Regolith Mixture with Solar Thermal Processing Outside the Permanent Shadow. These system approaches were developed to represent a number of different subsystems. They represent three combinations of the many possible subsystems that could compromise a complete extraction system. A brief system description for each of these extraction approaches follows; a detailed system study is needed to evaluate each concept and others. In Phase II, we plan on conducting a detailed evaluation of the most promising approaches.

System #1. In-situ Ice Extraction via Microwave Heating - (1) A photovoltaic array (see Figure 16) converts sunlight into electricity. The electricity is carried into the permanently shadowed area through a power cable. (2) The electricity powers a mobile microwave generator that is aimed at ice-containing regolith. No excavation is utilized. A dome covering is placed over the area that is being processed to contain water vapor. The microwave energy selectively heats and vaporizes the ice. The water vapor migrates from the regolith and is collected on cold plates located just above the surface. (3) The solid ice is removed from the cold plates and transported out of the shadow in a storage tank mounted on a H/O fuel cell-powered rover.

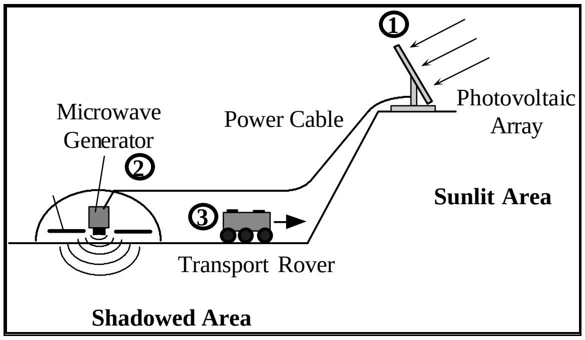


Figure 16. Schematic Diagram of Extraction System #1

System #2. Local Extraction of the Ice/Regolith Mixture with GPHS-RTG Thermal Processing and Steam Pipe Transport. (1) The ice/regolith mixture is excavated mechanically from the surface within the permanently shadowed area and carried by rover to a water extraction furnace (see Figure 17). The furnace is heated via nuclear GPHS modules, which stacked within the furnace wall. These GPHS modules are similar to the RTG modules used in the Cassini mission. The ice and regolith mixture is loaded into the processing chamber and sealed. The heat melts and vaporizes the ice. (2) The steam from this process is collected, heated further if necessary, and transported out of the permanent shadow in a sealed, highly insulated, steam pipe. A turbine-based electrical generator driven by the steam would provide electrical power for support equipment and heating the steam pipe, if required. The dry, processed regolith is removed from the processing chamber and new ice and regolith are added. (3) The steam passes through the pipe out of the shadowed area. A secondary generator turbine helps to recover some of the energy of the steam. The steam is condensed and collected for storage in a tank.

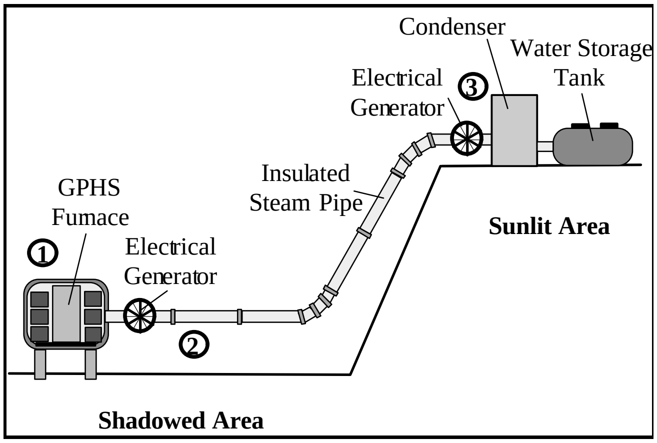


Figure 17. Schematic Diagram of Extraction System #2

System #3. Drag Line Removal of Ice/Regolith and Solar Thermal Processing Outside the Permanent Shadow. (1) Ice/regolith mixture is excavated and transported out of the shadow with a drag-line bucket (see Figure 18). If the ice/regolith mixture is hard, small explosions will be used to break the ice into smaller pieces that can be transported outside the permanent shadow for processing. If the ice/regolith mixture has a granular form, the surface preparation step is not required. (2) In a sunlit area, the ice/regolith mixture is placed into a solar furnace, a sealed, passive solar energy collector, which will melt the ice. The liquid water will be collected and filtered to remove particulate contaminants. The water may need distillation before use. (3) The water is stored as a liquid in storage tanks.

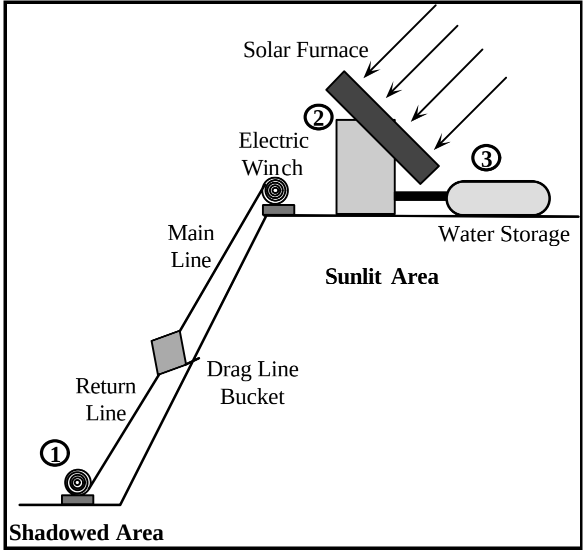


Figure 18. Schematic Diagram of System #3

3.6 Concepts for Resource Recovery

A valuable resource such as H_2/O on the Moon requires that use and conservation plans be developed such that this very valuable resource is not squandered or wasted, but is recovered if possible. The economically beneficial use of H_2/O needs to be well planned once the reserves have been reasonably determined by insitu and remote measurements. A key element in an use and conservation plan is the implementation and development of technologies that can support the water recovery from all possible applications, including rocket exhaust. Some recovery system examples include:

- Auxiliary Power Systems - water exhaust would be recovered in a recovery tank/heat exchanger. For fuel cell-based systems, water recovery is part of the system.
- Life Support Systems - Recovery and recycling is expected to be part of the system.
- Hatches - Air, water vapor need to be recovered internally, without gas escaping to the external environment. Air should be kept dry in hatches to prevent condensation and loss.
- Food Processing - Recovery and recycling is expected to be part of the system.
- Waste Processing - Recovery and recycling is expected to be part of the system.
- Manufacturing and Chemical Processing - Systems need to be designed to recover all chemicals and gasses.
- Concrete Processing - Technology should be developed that reduces the amount of water vapor in the processed lunar concrete. Pressurized manufacturing facilities would need to be designed to recover all gasses and water vapor.
- Rocket Engine Exhaust - Cold traps at the launch pad to catch and recover the close-in water exhaust; consider plume pointing during early ascent. Also consider water gas monitors and naturally cooled water recovery systems located in the polar cold traps.

3.7 Technology Development Requirements

During the Phase I study, areas of needed technology development were identified. One of the greatest challenges in extracting the lunar H_2/O will be operating machinery in the extreme conditions believed to be present near the H_2/O deposits. With temperatures of 70 K expected in the permanently-shadowed areas around the poles of the Moon, the operation of mechanical, electrical and fluid systems will require specific technology development. Some specific technology development may be required for: solar and nuclear-based energy delivery systems, automated materials handling and processing, reduced gravity electrolysis systems, purification of water from the lunar regolith, water storage systems, energy storage and delivery, cryogenic hardening of electronic and mechanical systems, excavation technologies, rovers, ballistic flight vehicles, and hydrogen peroxide production in 1/6 g, and alternate oxygen production, if needed. The technology needs that we identified are discussed below.

3.7.1 70 K-Cold Operations of Mechanical, Electrical and Fluid Systems

The anticipated extreme cold environment in the permanently shadowed cold traps of the Moon, will be a significant problem for robotic devices, mechanisms, scientific instruments, and other devices. Any device that operates in the cold traps of the Moon, will have great difficulty maintaining a working condition, unless its systems are properly designed for 70 K-type thermal conditions. Technology assessment of all possible subsystems and their operation in cold conditions is required. Granted, some systems could be kept warm through proper thermal management schemes, but others would not. Once an assessment has been achieved, the details of what items require cold testing and technology development should be made and implemented. Areas of possible technology development include: bearings and lubricants, electrical motors, electrical components, computers, chips, contacts, rotating joints, fluid lines, fluid valves, fluid regulators, etc.

3.7.2 Application of DOE’s ARPS, GPHS Brick, and Other Systems for this Application

The potential application of the radioisotope thermal power devices (RTPD's) for use in the cold traps appears to be well-justified based upon the logistics difficulties in the cold isolated environment during the applications of other approaches. The radioisotope systems that should be considered for early exploration and demonstration testing include a current RTG design (95% heat efficient or 5% electrical energy efficient; at 93 W_e/kg and 4.9 W_e/kg, respectively) and two advanced systems being developed by the DOE and NASA. One employs Alkali Metal Thermal-to-Electric Conversion (AMTEC) technology and is known as the Advanced Radioisotope Power System (ARPS) (20% electrical energy efficiency at 19.6 W_e/kg). The other uses thermodynamic electric power generation and is known as the Dynamic Isotope Power System (DIPS) (25% electrical energy efficiency at 24.5 W_e/kg). All three systems rely on the “General Purpose Heat Source (GPHS) using Plutonium oxide fuel pellets. The two very promising fusion systems should be reviewed for possible use. They are as defined by the University of Illinois and NPL Associates. One design is based on Inertial Electrostatic Confinement (IEC)-based fusion. The other is a low-energy nuclear reaction (LENR) fusion system. Very high value of specific power are predicted. The technology readiness is an issue. These power systems for lunar resource acquisition in the cold traps need to be assessed with respect to the other technologies that are proposed.

3.7.3 Small Nuclear Reactors

The long-term processing of lunar H_2/O will require larger, more efficient energy systems. Nuclear reactors are good candidates to satisfy this need, especially while operating in the cold traps. Recent studies of Mars exploration has also indicated that there will be a need for many small nuclear reactors to support the Mars exploration/colonization activity expected in the years that follow the initial exploration missions. While the Moon is likely to use significant solar power in the normally sunlit areas of manned activity, there is a need to investigate the feasibility of small nuclear reactor power systems for lunar ISRU processing in the permanently shadowed polar regions.

3.7.4 Microwave Energy Systems for In-situ Processing

The design, analysis and experimental testing of various microwave processing systems for H_2/O recovery is needed for open and closed H_2/O microwave processing approaches. "Open" concepts are those that do not have a totally enclosed processing chamber (continuous process);

"Closed" approaches are totally closed (batch process) and could process H_2 gas, water, and other volatiles. Selective frequency microwave systems need to be evaluated to provide the most efficient approaches. Prototypes would be built and tested in a lunar simulator with lunar simulant.

3.7.5 Cable Systems for Ground-based Automated Experimental and Large Automated H_2/O Acquisition and Processing Systems

One possible approach to providing energy to ground-based automated processing systems operating in the cold trap on the Moon is to use the permanently sunlit crater rim to generate electricity from solar energy and use a cable to transmit the power to the processing unit that is operating in the cold trap. Additionally, this cable/tube could be used to transfer H_2 or H_2O out of the cold trap to the sunlit region. This task would involve an assessment of how to design and operate such a cable. Design, analysis and experimental testing would be involved.

3.7.6 Technology for Materials Handling and Processing for Ground-based Automated Experimental and Large Automated H_2/O Acquisition and Processing Systems

This task would involve all of the technologies for materials (primarily regolith) handling as are needed for experimental and large processing systems. Included are drilling, sample coring, beneficiation, bulk transport, gas, liquid solid transport, gas, liquid, solid storage, etc.

3.7.7 Electrolysis Systems and Fuel Cells in Zero and Partial g Environments

Technology assessment and demonstrations are needed for water electrolysis and H_2/O_2 fuel cell technology as applied to the ISRU processing mission and applications that operate both at close to zero-g or at 1/6th g. These systems are important for nearly all of the applications identified that use H_2/O resources. The size of these units must be assessed so that the properly size prototypes can be developed. Their potential use in the cold traps needs to be assessed for technology development.

3.7.8 Water Rocket Technologies for Orbit Transfer and Orbital Auxiliary Propulsion

Technologies are needed to use water as a H_2/O_2 propellant storage method for orbit transfer and orbital auxiliary propulsion. Water is easily transported or stored in un-insulated, light-weight tanks. Water can be stored in these tanks without the boil off loss of propellant, as in the case of liquid hydrogen or liquid oxygen. Electrolysis systems operating in zero-g, as are to be evaluated in Section 3.7.7, would be used when propellant is needed. For OTV use, high capacity orbiting service station systems would be necessary. For orbital auxiliary propulsion, smaller on-board electrolysis units are required. For OTV applications, large efficient liquifers and cryogenic storage tanks would be needed would be required. Zero-loss cryogenic fluid transfer systems would be required. The use of highly-efficient magnetic refrigeration systems should be investigated.

3.7.9 Solar Energy Beaming into the Cold Region

This task would design, assess, and experiment with the collection and beaming of solar light energy from one position (crater edge) to another (cold trap) at specified distances to match those that would be expected on the Moon. An experimental unit of reasonable size would be built and demonstrated. The system should be sized to match at least a first experimental unit size for lunar applications. Options include: direct optical solar beaming and solar pumped lasers.

3.7.10 Microwave Energy Beaming into the Cold Region

This task involves the design, analysis, and demonstration testing of microwave energy transmission from an antenna to a collector in the cold trap. The size of the prototype unit to be tested will be a reasonable size to simulate actual solar energy conversion to microwave energy and beaming into the cold trap. Previous studies would be used for initial scoping.

3.7.11 Water Recovery Systems Near Lunar Launch and landing Sites

This task involves the development of water recovery technologies that would be operated at the launch sites. The requirements of this technology include the collection of the H_2O-based exhaust from operational launches and landings. Cold trap freezers in the area appear to be the first option. Previous studies would be used for initial scoping.

3.7.12 Water Recovery Systems for All Water Use Applications

Technology demonstrations of various water recovery systems would be achieved under this task. Previous water conservation planning studies would be used for initial scoping.

3.7.13 Lunar Sample Return Mission Technology Using Processed Water Ice for Propellants

This task would design, analyze, and develop bread-board technology demonstration devices that will allow for a Lunar sample return, using processed water ice in the cold trap. This mission would utilize much of the other work already underway. Radioisotope thermal generator devices would likely be used, but others should be assessed.

3.7.14 Ballistic-based Flight Transporters

Technology development work needs to be done for small and large ballistic flight vehicles that are used to transport material from one location on the Moon’s surface to another. Previous studies would be used for initial scoping. New propulsion technologies that use hydrogen and oxygen are needed to provide lower weight, and higher performance.

3.7.15 Rovers and Ground-based Transporters

Technology development work needs to be done for small rovers and ground-based vehicles that are used to transport material from one location on the Moon’s surface to another. Previous studies would be used for initial scoping. New power conversion technologies that use liquid hydrogen and liquid oxygen as propellants are needed to provide for lower weight and higher performance.

3.7.16 Assess H_2O_2 Use in Propulsion Systems and H_2O_2 Production for Lunar Transport Applications

The return of H_2O_2 in the USAF and NASA bi-propellant propulsion programs, coupled with lunar resource availability, will likely create interest in looking at H_2O_2 for Mars applications. The reduction in tank insulation mass and the potential for hypergolic ignition makes this an attractive option. Previous studies would be used for initial scoping.

3.7.17 Determine the Best Approach for Processing Oxygen from the Regolith if Water is Not Present

There are a wide variety of oxygen-producing approaches that can be used on the Moon if water is not present. The major candidates are (1) carbon-based reduction of lunar oxides, (2) hydrogen-based reduction of iron oxide, (3) silicate electrolysis, (4) vapor phase reduction, and etc. These and other concepts need to be analyzed and the best approaches developed and demonstrated as a back up for oxygen production should water not be present.

3.8 Preliminary Architecture and Overall Program Plan

The purpose of this proposed/Program plan is to energize NASA to put in place a management organization, budget resources, and technical direction to take full advantage of lunar water or hydrogen ISRU resource that has been discovered at the lunar poles to support a much lower-cost human exploration program.

This effort has as its overall objective to develop an initial Program Plan Document for NASA that outlines the process for development of a valid, well-analyzed approach to a complete and reasonable architecture that allows economical uses of lunar H_2/O in achieving maximum potential support for the exploration of space.

ORBITEC has defined the overall architecture elements for the discovery, extraction and utilization of H_2/O found near the north and south poles of the Moon. The architecture elements are embedded in an initial overall program plan document that defines what is to be done. Elements of a potential architecture then define a plan to further examine these elements. The major result of this Phase I NIAC effort is this proposed comprehensive program plan for the discovery, acquisition, and use of lunar water ice/hydrogen. This comprehensive program plan covers the following major Work Breakdown Structure (WBS) elements:

- Summarize Current Data (1.0)
- Simulation Models (2.0)
- Identify, Conceptualize, Assess Uses (3.0)
- System Studies (4.0)
- Technology Needs Assessment and Development (5.0)
- Ground Simulator Facilities (6.0)
- Lunar Exploration Mission (7.0)
- Lunar Extraction Mission (8.0)
- Lunar Extraction Facility (9.0)
- DDT&E for Lunar Uses (10.0)
- DDT&E for Mars Uses (11.0)
- DDT&E for Other Solar System Uses (12.0)
- Education and Outreach (13.0)
- NASA Program Management and Reports (14.0).

Figure 19 illustrates the progression of the program plan via a road map from discovery/verification of lunar water ice or hydrogen through extraction to utilization of the resource. Each of the major steps in the overall plan is briefly elaborated below by WBS number.

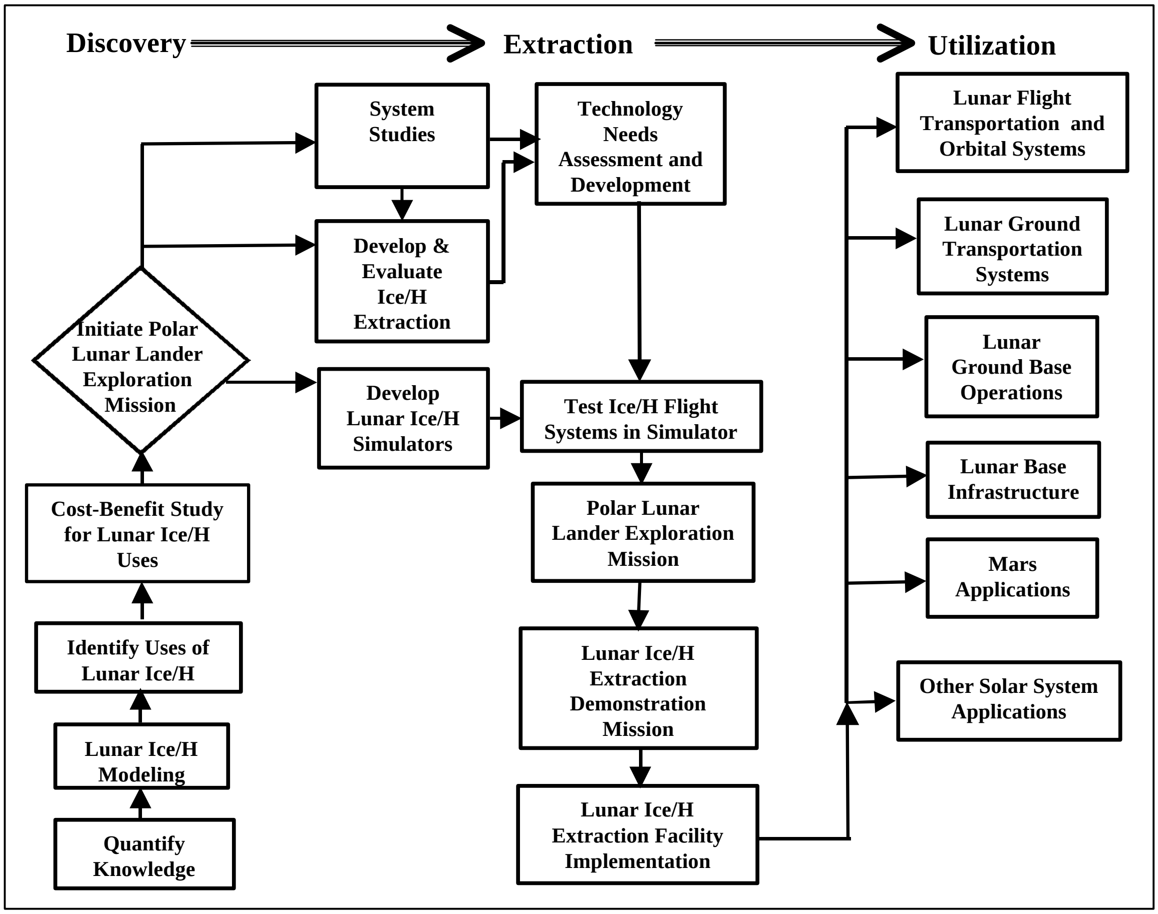


Figure 19. Lunar H_2/O Resource Use Program Road Map

Summarize Current Data (1.0) – Summarize and document the scientific data available from Apollo, Luna, Clementine, Lunar Prospector, Earth-based telescopes and other sources into a coherent data base for the lunar H_2/O exploration effort.

Simulation Models (2.0) – Develop simulation models of the possible physical/chemical processes and their contribution that may have resulted in polar lunar H_2O and/or H_2, and other volatiles being present in the cold traps.

Identify, Conceptualize, Assess Uses (3.0) – Identify and evaluate all of the potential uses of lunar H_2/O. Some potential uses include lunar flight and orbit transportation systems, Mars flight transportation systems, other Solar System transports and explorers, lunar ground base operations, lunar ground-based transport vehicles and lunar base infrastructure. Once the various uses of the lunar water ice are identified and prioritized, a cost-benefit study would be performed to determine the most promising applications. The results of this cost-benefit assessment will help determine the best ways to utilize the valuable water ice resource on the Moon and give direction to the program.

System Studies (4.0) – System studies would be performed for the major or critical components of systems that use H_2/O as well as ISRU systems that provide the H_2/O resource. Early activities under this WBS element are broad-scoped; later efforts will be much more detailed, focusing on specific mission implementation plans. One defined activity is to conduct system studies on cost-efficient space transportation systems. A second defined activity is to conduct system studies on cost-efficient approaches to conduct rover-based exploration of the polar regions. A third defined activity would be studies and evaluations of the most promising ice extraction techniques and logistics approaches, based on the H_2/O data from Lunar Prospector. Studies and analysis also would be conducted in ground-based and lunar in-situ laboratory experiments. Other important study, analysis and design activities include: nuclear thermal device application assessment, development of a lunar H_2/O use and conservation plan, legal/political/treaty issue assessment, commercial development, a lunar environmental impact assessment, and cost modeling and analysis.

Technology Needs Assessment and Development (5.0) **–** Once the lunar ice extraction and use approaches have been developed and evaluated, a more focused technology needs assessment can be performed. Any technology development required would occur during this latter stage. One of the greatest challenges in extracting the lunar ice or hydrogen will be operating machinery in the extreme conditions believed to be present near the deposits. With temperatures of ~70 K expected in the permanently-shadowed areas around the poles of the Moon, the operation of mechanical, electrical and fluid systems will require specific technology development. Some specific technology development may be required for solar and nuclear-based energy delivery systems, automated materials handling and processing, reduced gravity electrolysis systems, purification of water from the lunar regolith, water storage systems, energy storage and delivery, cryogenic hardening of electronic and mechanical systems, excavation technologies, rovers, ballistic flight vehicles, and hydrogen peroxide production in 1/6 g, and alternate oxygen production approaches, if needed.

Ground/Simulator Facilities (6.0) **–** Lunar ice simulators would be developed to recreate the environmental conditions present in the permanently-shadowed regions of the Moon. Such a simulator would serve multiple purposes. A large-scale lunar ice simulator would allow testing of various components of an ice extraction system or exploration missions. The ice deposition process could also be studied in such a simulator. Layers of ice and regolith could be formed. Micrometeoroid stirring of the ice and regolith mixture could be approximated with mechanical stirring. Lunar stimulant with H_2 embedded would also be developed.

Lunar Exploration Mission (7.0) **–** A robotic rover would be used to explore the regions near the north or south poles of the Moon where water ice and H_2 is believed to exist. An initial mission is defined to use a combination of solar and nuclear power. A multi-sample return mission is also integrated with this mission.

Lunar Extraction Demonstration Mission (8.0) **–** A mission to the polar regions of the Moon would carry out the first insitu scientific experiments as well as the first pilot plant extraction demonstration experiments. One or more extraction approaches would be demonstrated under actual lunar conditions and would verify that the technology works.

Lunar Extraction Facility (9.0) **–** As a result of the first lunar H_2/O pilot plant demonstration mission to the polar cold traps of the Moon, a great amount of information will be learned about the technology and operational approach of extraction. This information will drive the final design of the full-sized extraction facility on the Moon. The work of the program will feed into the definition of this mission. Details will be developed as this program plan evolves.

DDT&E for Lunar Uses (10.0) – Lunar systems are the primary targeted uses for the lunar ice resource. Since it appears that both fuel and oxidizer can be obtained locally, a reusable transportation system that can reach Moon-orbit space at low cost may be feasible. Ground-based transports could also be powered with propellants derived from lunar water. Water can easily be electrolyzed to produce hydrogen and oxygen, be liquefied and used as propellants. Other transportation systems, such as Moon-to-Earth or a lunar orbiting fueling station may also be feasible.

DDT&E for Mars Uses (11.0) – This WBS task element will be conducted well after the program has been established and we have better data on the availability of Mars water in the Mars regolith. After a determination of feasibility, this effort would begin establishing a necessary DDT&E effort for systems for Mars mission support that would use H_2/O resources from the Moon.

DDT&E for other Solar System Uses (12.0) – The use of lunar H_2/O for other solar system transport vehicles may have more significance than Mars transport vehicles. This task should be delayed until there is a mission that may be feasible by using lunar H_2/O resources.

Education and Outreach (13.0) - Education and outreach to the general public/taxpayers has become an important part of NASA’s mission. It would be a vital part of this program. In this task, the information generated by the overall program would be made available to the public.

NASA Program Management and Reports (14.0) – This element of the program plan identifies the program management functions and program documentation that are believed necessary to manage and guide the ultimate goals of this program.

Overall Schedule and Budget

The overall schedule and budget for the H_2/O plan is provided below by WBS area (in Figures 20 and 21). The schedule and budget is only shown for the first 10 years of activity. Cost estimates are in current (2000 YR) year K dollars. We expect that changes in the plan will occur after the program is initiated. As knowledge is gained, it may motivate changes in the plan. NASA is expected to modify the plan to fit annual budget resources and program constraints, which have not been considered in the development of the plan. Some additional schedule and budget detail is provided in the detailed plan write up. A bibliography of related works is provided at the end of the document.

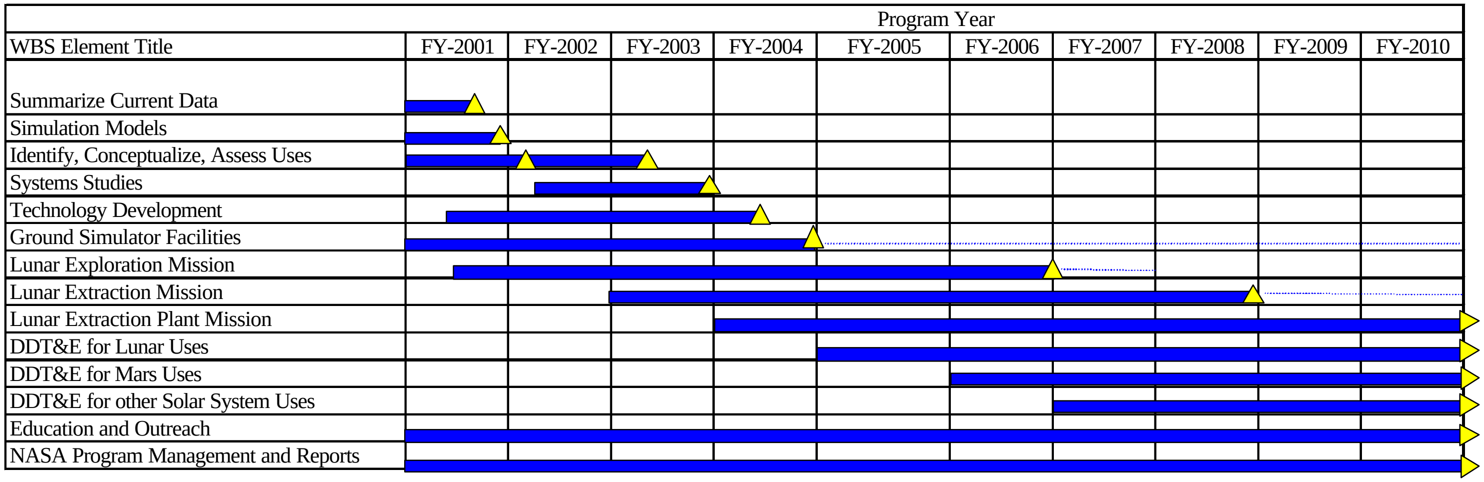


Figure 20. Overall Program Schedule

					FY-2000 Dollars					
WBS Element #	WBS Element Title	FY-2001	FY-2002	FY-2003	FY-2004	FY-2005	FY-2006	FY-2007	FY-2008	FY-2009	FY-2010
1.0	Summarize Current Data	100									
2.0	Simulation Models	300									
3.0	Identify, Conceptualize, Assess Uses	1,000	1,000	500							
4.0	Detailed Systems Studies		1,500	2,500							
5.0	Technology Development	4,000	8,000	8,000	4,000						
6.0	Ground Simulator Facilities	200	1,000	2,000	8,000	1,000	1,000	1,000	1,000	1,000	1,000
7.0	Lunar Exploration Flight Mission	1,000	9,000	20,000	50,000	60,000	30,000	2,000			
8.0	Lunar Extraction Mission			1,000	2,000	12,000	30,000	70,000	70,000	20,000	2,000
9.0	Lunar Extraction Plant Mission				1,000	1,000	8,000	10,000	20,000	60,000	70,000
10.0	DDT&E for Lunar Uses					1,000	5,000	10,000	10,000	30,000	40,000
11.0	DDT&E for Mars Uses						500	1,000	5,000	5,000	5,000
12.0	DDT&E for other Solar System Uses							500	500	500	500
13.0	Education and Outreach	30	40	50	80	100	100	100	100	50	50
14.0	NASA Program Management and Reports	500	1,000	1,000	1,500	1,500	2,000	2,000	2,000	2,000	1,000
	Program Totals	7,130	21,540	35,050	66,580	76,600	76,600	96,600	108,600	118,550	119,550

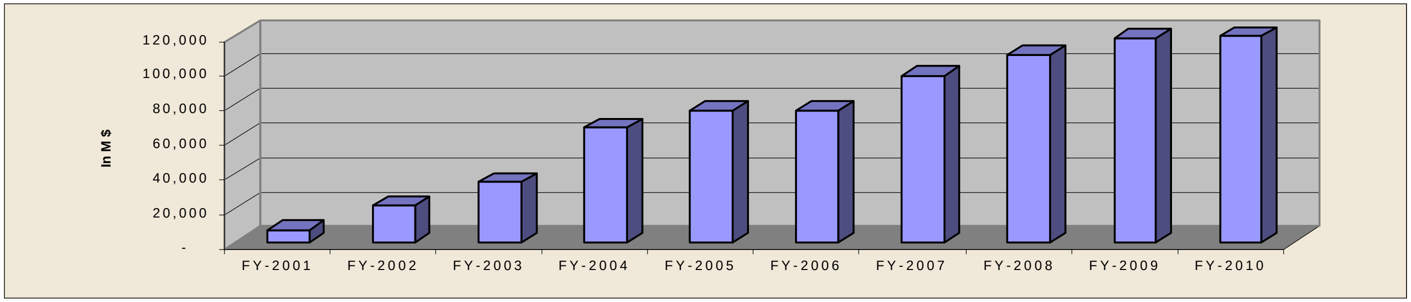


Figure 21. Overall Program Budget

4.0 CONCLUSIONS

The conclusions that have made as a result of this Phase I NIAC study are as follows:

- Hydrogen (from H_2O or H_2) is available on the Moon in useful abundance at the poles (~260 MMT, if water)
- 260 MMT of water ice at the lunar poles is about equivalent to 370,000 Space Shuttle launches if compared to the H/O available in the Space Shuttle External Tank
- A 68% cost-reduction in Earth launch mass is the calculated result from H_2/O use over a 10-year period of lunar base activity
- Assuming a $10,000/kg Earth launch cost and using Lunar H_2/O over a 10 year period to support a nominal lunar surface base, ISRU <u>saves</u> an estimated $54B when compared to the non-ISRU case ($80B)
- Lunar base development will be heavily dependent on this resource, as a water-based economy/system will develop
- If hydrogen is the primary form, then oxygen processing from the regolith will be necessary -- technology for this is readily available (hydrogen or carbon reduction, etc.)
- Early manned Mars exploration and developments could well be enhanced by using lunar water/hydrogen
- Chemical or nuclear-based Earth-Mars transports may be economically enhanced for some time
- Later Mars surface activities would likely use Mars-based resources H_2O and CO_2
- The ten-year Program Plan developed under this project appears to be doable within the magnitude of the expected NASA budget
- Interest in the Moon as the next logical step has been gaining ground since the recent failures of the Mars spacecraft
- International cooperation could reduce the U.S. contribution; commercial interests could also contribute and reduce the government's funding.

5.0 RECOMMENDATIONS

This section presents ORBITEC's study recommendations that have been based on the Phase I work. Our recommendations are:

1. NIAC fund ORBITEC's proposed Phase II effort
2. Expand and define the system architecture and revise and improve the Program Plan
3. Perform additional cost-benefit assessments for the lunar ice/hydrogen applications
4. Study and analyze promising extraction techniques/logistics approaches
5. Gain participation of key NASA staff in the development of the Program Plan
6. Gain participation of Dr. Robert Cassanova, NIAC Director, in the development of the Program Plan as if it were a pilot approach that could be used for the development of other advanced concepts
7. Develop an Executive Briefing package on the Program Plan to be presented at the NIAC Fellows Meeting in November 2002 and then later to NASA upper level management, either by NIAC or ORBITEC or a NIAC/ORBITEC team
8. Adopt the Program Plan and implement it by: (1) an integrated plan as presented, or (2) a partially integrated into other programs.

APPENDIX A

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BIBLIOGRAPHY

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APPENDIX B

LUNAR INFORMATION DATA BASE

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APPENDIX C

LUNAR H_2/O RECOVERY AND USE PROGRAM PLAN

THE LUNAR H_2/O RESOURCE USE PROGRAM PLAN

Developed under:

DEVELOPMENT OF LUNAR ICE/HYDROGEN RECOVERY SYSTEM ARCHITECTURE NIAC-PHASE I CONTRACT

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FOREWORD

The significant presence of hydrogen in the form of water ice or bound hydrogen in permanently shadowed depressions near the lunar poles will influence both the near and long-term prospects for lunar and Mars exploration and development. In this document the two forms of hydrogen (H_2O and H_2) shall be represented by H_2/O. Since the most recent data from Lunar Prospector indicate that water ice or hydrogen is present in the polar regolith in significant quantities (up to 260 million metric tons), it is important to characterize it and how to extract it for beneficial use. This proposed program plan has been developed to provide NASA an overall initial approach for lunar ice discovery, extraction and utilization.

Man's space activity will soon focus on the Moon as the next logical step for human exploration. We must find ways to keep the cost of exploration as low as possible. The Moon is an attractive low-cost source of resources for the development of near-Earth/Moon space and beyond because the Moon is close to Earth, it has a small gravity field and most of the chemical elements important in the development of space capabilities (e.g., oxygen, metals) can be readily found on the surface. Previously, the most significant problem with lunar development has been the scarcity of fuel for spacecraft and transport vehicles. Although oxygen is present in abundance in the minerals of the lunar regolith, no concentrated source of hydrogen was known with certainty to exist, prior to the Clementine and recent Lunar Prospector mission. If rocket fuel must be imported to the Moon to launch payloads from the Moon, it is very difficult to devise a low-cost Moon-to-space transportation system. However, if both fuel and oxidizer can be obtained locally and relatively easily, a reusable transportation system that can reach Moon-orbit space at low cost would be very attractive. This is the promise of lunar water or hydrogen. Water can easily be electrolyzed to produce hydrogen and oxygen, be liquefied and used as propellants. If hydrogen is abundant in the polar regolith, it too can be easily recovered and processed. If developed as a supply of propellant, a myriad of other beneficial uses for lunar water or hydrogen can be developed, ranging from life support to construction materials.

Two general classes of resource extraction processes can be considered for removal of ice or hydrogen. In the first class of processes, energy (solar-beamed, nuclear, etc.) is transported into the shadowed regions, hydrogen or water is extracted in-situ, and transported out of the cold trap. Alternatively, a hydrogen/water-containing regolith can be mined in the cold trap, transported outside the cold trap, and the hydrogen/water extracted in a location with abundant solar energy.

The existence of water ice or hydrogen deposits in the cold traps at the poles on the Moon represents an extremely valuable resource future lunar exploration and development. The plan that is presented here is considered a starting point for a NASA-funded program. It represents what we believe, a well-thought out initial plan that will require continuous updates as work is conducted and new knowledge becomes available.

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EXECUTIVE SUMMARY

Introduction

The existence of large quantities of water-ice or hydrogen (H_2/O) on the Moon will have a profound effect on human exploration and colonization of the Solar System. Current quantity estimates (if ice) are equivalent to the hydrogen and oxygen used in 370,000 Space Shuttle launches. Lunar H_2/O could be used to produce rocket propellant and to support human operations on the Moon and at other locations in the Solar System. Using propellants indigenous to the Moon would circumvent the costly operation of transporting propellants from Earth. Also, spacecraft launched from the Moon's weaker gravity well require less propellant to achieve lunar orbit. The Moon is a very desirable point of departure for trips to Mars. Without indigenous resources, huge masses must be launched from Earth to attain exploration goals, translating into high costs and infrastructure. The identification and characterization of lunar H_2/O represents an enormously important step in humankind becoming a truly space-faring species.

Plan Summary

The purpose of this proposed/Program plan is to energize NASA to put in place a management organization, budget resources, and technical direction to take full advantage of lunar water or hydrogen ISRU resource that has been discovered at the lunar poles to support a much lower-cost human exploration program.

This effort has as its overall objective to develop an initial Program Plan Document for NASA that outlines the process for development of a valid, well-analyzed approach to a complete and reasonable architecture that allows economical uses of lunar H_2/O in achieving maximum potential support for the exploration of space.

ORBITEC has defined the overall architecture elements for the discovery, extraction and utilization of H_2/O found near the north and south poles of the Moon. The architecture elements are embedded in an initial overall program plan document that defines what work is to be done. Elements of a potential architecture then define a plan to further examine these elements. The major result of this Phase I NIAC effort is this proposed comprehensive program plan for the discovery, acquisition, and use of lunar water ice/hydrogen. This comprehensive program plan covers the following major Work Breakdown Structure (WBS) elements:

- Summarize Current Data (1.0)
- Simulation Models (2.0)
- Identify, Conceptualize, Assess Uses (3.0)
- System Studies (4.0)
- Technology Needs Assessment and Development (5.0)
- Ground Simulator Facilities (6.0)
- Lunar Exploration Mission (7.0)
- Lunar Extraction Mission (8.0)
- Lunar Extraction Facility (9.0)
- DDT&E for Lunar Uses (10.0)
- DDT&E for Mars Uses (11.0).

- DDT&E for Other Solar System Uses (12.0)
- Education and Outreach (13.0)
- NASA Program Management and Reports (14.0).

Figure 1 illustrates the progression of the program plan via a road map from discovery/verification of lunar water ice or hydrogen through extraction to utilization of the resource. Each of major steps in the overall plan is briefly elaborated below by WBS number.

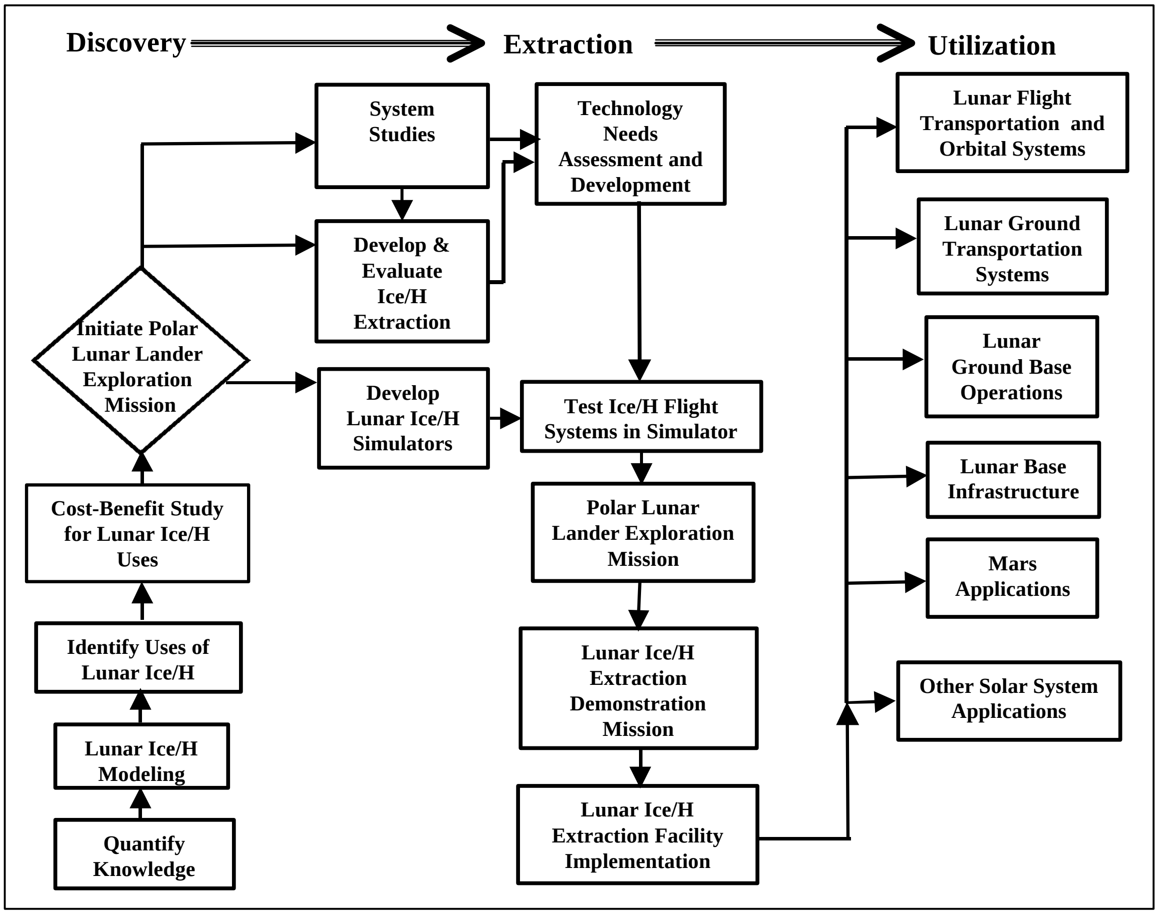

Figure 1. Lunar H_2/O Resource Use Program Road Map

Summarize Current Data (1.0) – Summarize and document the scientific data available from Apollo, Luna, Clementine, Lunar Prospector, Earth-based telescopes and other sources into a coherent data base for the lunar H_2/O exploration effort.

Simulation Models (2.0) – Develop simulation models of the possible physical/chemical processes and their contribution that may have resulted in polar lunar H_2O and/or H_2, and other volatiles being present in the cold traps.

Identify, Conceptualize, Assess Uses (3.0) – Identify and evaluate all of the potential uses of lunar H_2/O. Some potential uses include lunar flight and orbit transportation systems, Mars flight transportation systems, other Solar System transports and explorers, lunar ground base operations, lunar ground-based transport vehicles and lunar base infrastructure. Once the various uses of the lunar water ice are identified and prioritized, a cost-benefit study would be performed to determine the most promising applications. The results of this cost-benefit assessment will help determine the best ways to utilize the valuable water ice resource on the Moon and give direction to the program.

System Studies (4.0) – System studies would be performed for the major or critical components of systems that use H_2/O as well as ISRU systems that provide the H_2/O resource. Early activities under this WBS element are broad-scoped; later efforts will be much more detailed, focusing on specific mission implementation plans. One defined activity is to conduct system studies on cost-efficient space transportation systems. A second defined activity is to conduct system studies on cost-efficient approaches to conduct rover-based exploration of the polar regions. A third defined activity would be studies and evaluations of the most promising ice extraction techniques and logistics approaches, based on the H_2/O data from Lunar Prospector. Studies and analysis also would be conducted in ground-based and lunar in-situ laboratory experiments. Other important study, analysis and design activities include: nuclear thermal device application assessment, development of a lunar H_2/O use and conservation plan, legal/political/treaty issue assessment, commercial development, a lunar environmental impact assessment, and cost modeling and analysis.

Technology Needs Assessment and Development (5.0) – Once the lunar ice extraction and use approaches have been developed and evaluated, a more focused technology needs assessment can be performed. Any technology development required would occur during this latter stage. One of the greatest challenges in extracting the lunar ice or hydrogen will be operating machinery in the extreme conditions believed to be present near the deposits. With temperatures of ~70 K expected in the permanently-shadowed areas around the poles of the Moon, the operation of mechanical, electrical and fluid systems will require specific technology development. Some specific technology development may be required for solar and nuclear-based energy delivery systems, automated materials handling and processing, reduced gravity electrolysis systems, purification of water from the lunar regolith, water storage systems, energy storage and delivery, cryogenic hardening of electronic and mechanical systems, excavation technologies, rovers, ballistic flight vehicles, and hydrogen peroxide production in 1/6 g, and alternate oxygen production approaches, if needed.

Ground/Simulator Facilities (6.0) – Lunar ice simulators would be developed to recreate the environmental conditions present in the permanently-shadowed regions of the Moon. Such a simulator would serve multiple purposes. A large-scale lunar ice simulator would allow testing of various components of an ice extraction system or exploration missions. The ice deposition process could also be studied in such a simulator. Layers of ice and regolith could be formed. Micrometeoroid stirring of the ice and regolith mixture could be approximated with mechanical stirring. Lunar stimulant with H_2 embedded would also be developed.

***Lunar Exploration Mission (7.0)* –** A robotic rover would be used to explore the regions near the north or south poles of the Moon where water ice and H_2 is believed to exist. An initial mission is defined to use a combination of solar and nuclear power. A multi-sample return mission is also integrated with this mission.

***Lunar Extraction Demonstration Mission (8.0)* –** A mission to the polar regions of the Moon would carry out the first insitu pilot plant extraction demonstration experiments. One or more extraction approaches would be demonstrated under actual lunar conditions and would verify that the technology works.

***Lunar Extraction Facility (9.0)* –** As a result of the first lunar H_2/O pilot plant demonstration mission to the polar cold traps of the Moon, a great amount of information will be learned about the technology and operational approach of extraction. This information will drive the final design of the full-sized extraction facility on the Moon. The work of the program will feed into the definition of this mission. Details will be developed as this program plan evolves.

***DDT&E for Lunar Uses (10.0)* –** Lunar systems are the primary targeted uses for the lunar ice resource. Since it appears that both fuel and oxidizer can be obtained locally, a reusable transportation system that can reach Moon-orbit space at low cost may be feasible. Ground-based transports could also be powered with propellants derived from lunar water. Water can easily be electrolyzed to produce hydrogen and oxygen, be liquefied and used as propellants. Other transportation systems, such as Moon-to-Earth or a lunar orbiting fueling station may also be feasible.

***DDT&E for Mars Uses (11.0)* –** This WBS task element will be conducted well after the program has been established and we have better data on the availability of Mars water in the Mars regolith. After a determination of feasibility, this effort would begin establishing a necessary DDT&E effort for systems for Mars mission support that would use H_2/O resources from the Moon.

***DDT&E for other Solar System Uses (12.0)* –** The use of lunar H_2/O for other solar system transport vehicles may have more significance than Mars transport vehicles. This task should be delayed until there is a mission that may be feasible by using lunar H_2/O resources.

Education and Outreach (13.0) - Education and outreach to the general public/taxpayers has become an important part of NASA's mission. It would be a vital part of this program. In this task, the information generated by the overall program would be made available to the public.

***NASA Program management and Reports (14.0)* –** This element of the program plan identifies the program management functions and program documentation that are believed necessary to manage and guide the ultimate goals of this program.

Overall Schedule and Budget

The overall schedule and budget for the H_2/O plan is provided below by WBS area (in Figures 2 and 3). The schedule and budget is only shown for the first 10 years of activity. Cost estimates are in current (2000 YR) years dollars. We expect that changes in the plan will occur after the program is initiated. As knowledge is gained, it may motivate changes in the plan. NASA is expected to modify the plan to fit annual budget resources and program constraints, which have not been considered in the development of the plan. Some additional schedule and budget detail is provided in the detailed plan write up. A bibliography of related works is provided at the end of the document.

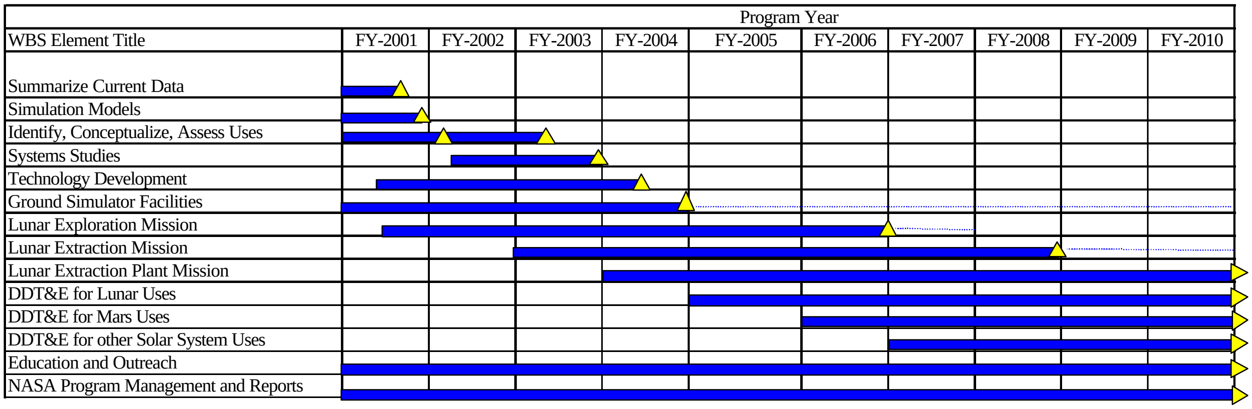

Figure 2. Overall Program Schedule

						FY-2000 K Dollars					
WBS Element #	**WBS Element Title**	**FY-2001**	**FY-2002**	**FY-2003**	**FY-2004**	**FY-2005**	**FY-2006**	**FY-2007**	**FY-2008**	**FY-2009**	**FY-2010**
1.0	Summarize Current Data	100									
2.0	Simulation Models	300									
3.0	Identify, Conceptualize, Assess Uses	1,000	1,000	500							
4.0	Systems Studies		1,500	2,500							
5.0	Technology Development	4,000	8,000	8,000	4,000						
6.0	Ground Simulator Facilities	200	1,000	2,000	8,000	1,000	1,000	1,000	1,000	1,000	1,000
7.0	Lunar Exploration Flight Mission	1,000	9,000	20,000	50,000	60,000	30,000	2,000			
8.0	Lunar Extraction Mission			1,000	2,000	12,000	30,000	70,000	70,000	20,000	2,000
9.0	Lunar Extraction Plant Mission				1,000	1,000	8,000	10,000	20,000	60,000	70,000
10.0	DDT&E for Lunar Uses					1,000	5,000	10,000	10,000	30,000	40,000
11.0	DDT&E for Mars Uses						500	1,000	5,000	5,000	5,000
12.0	DDT&E for other Solar System Uses							500	500	500	500
13.0	Education and Outreach	30	40	50	80	100	100	100	100	50	50
14.0	NASA Program Management and Reports	500	1,000	1,000	1,500	1,500	2,000	2,000	2,000	2,000	1,000
	Program Totals	7,130	21,540	35,050	66,580	76,600	76,600	96,600	108,600	118,550	119,550

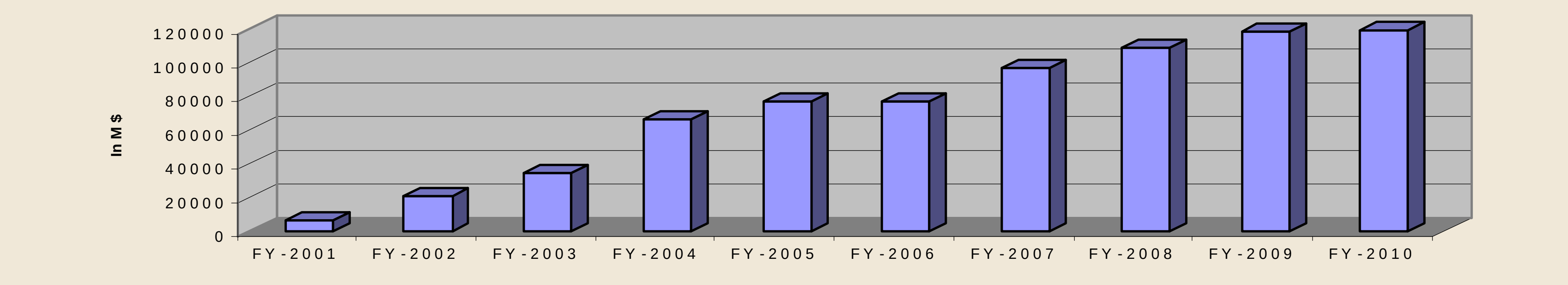

Figure 3. Overall Program Budget

DETAILED PROGRAM PLAN AND WBS

In this section, the detailed program plan and WBS recommended to NASA is presented. For each major WBS section, a background discussion is provided, followed by a brief work statement, schedule, and estimated funding resources. WBS elements that depend upon the work early in the program have not been detailed at this time because more data are required for their realistic definition.

1.0 Summarize and Quantify all the Scientific Data Available

The purpose of this WBS Element is to summarize and document the scientific data available into a coherent data base for the lunar H_2/O exploration effort from Apollo, Luna 16, Clementine, Lunar Prospector, Earth-based telescopes and other sources into a coherent database for the lunar H_2/O exploration effort. This would include the opinions of the leading scientists regarding the interpretations of any measurements. A top-level discussion of what we know from Apollo, Clementine and Lunar Prospector is presented below.

Apollo. The source of H_2 on the Moon comes from the collection of the solar wind over the past 4 billion years. Since the solar wind is 96% hydrogen and the ionized protons have a relatively low energy (~ a few keV), most of this "resource" is implanted in the surface of regolith particles. Gardening by frequent meteorite impacts has caused the near surface region to be turned over many times such that the impregnated, fine grained (~ 100 microns) regolith has been uniformly mixed to depths of several meters. The range of concentrations of several volatile elements in lunar regolith is given in Figure 4. Hydrogen shows the largest variation in concentration, from <1 wppm in highland materials to over 100 wppm in some glasses. Fegley and Swindle have predicted that the H_2 inventory of the first 3 m of the Moon is ~ 10 billion metric tonnes. The loosely bound hydrogen can be thermally evolved from the fine lunar regolith at temperatures of 300-700 C (see Figure 5). Other volatile elements are also evolved along with the H_2 include water vapor, CO_2, He, H_2, CH_4, CO or N_2 (the peaks are indistinguishable on a mass spectrometer), H_2S and SO_2. Also liberated were smaller quantities of the noble gases Ne, Ar, Kr and Xe. Careful study of Figure 5 reveals the original gas release pattern for the Apollo-11 Sample 10086.16, measured by a mass spectrometer as a function of temperature.

Another way of looking at these data (Figure 5) is as shown in Figure 6, a bar chart showing the range of temperatures over which the majority of the gases are evolved. Although H_2 is released over a very wide range of temperatures, the peak evolution ion intensity occurs at around 500 C and falls off to ~5% of that peak value at 700 C. In principle, a lunar hydrogen acquisition device would not need to exceed a temperature of 600 C to obtain >80% of the H_2 (see Figure 7). At the same time, some H_2O, CO_2, He, CH_4 and CO or N_2 will also be liberated. The sulfur containing volatiles H_2S and SO_2 will not be liberated until the temperature exceeds 800 C. This is fortunate, since the formation of sulfuric acid H_2SO_4 should be avoided because of its corrosive effect on the components of the processing system.

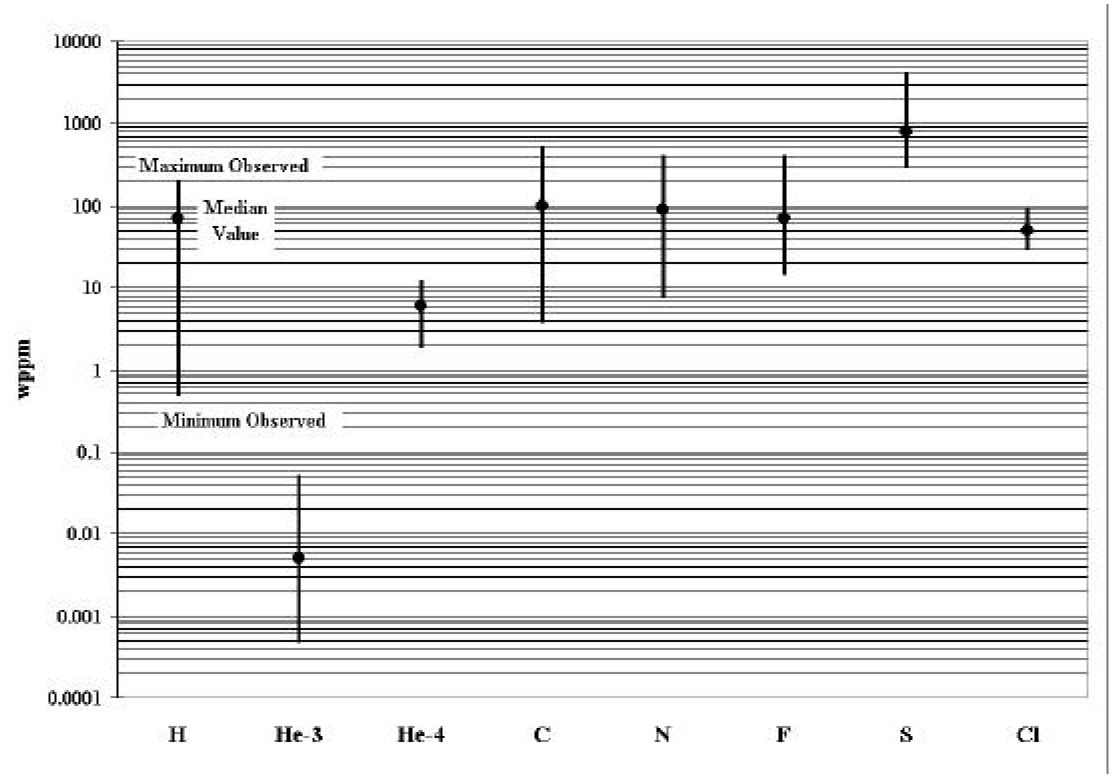

Figure 4. Concentration of Lunar Volatiles Measured in Apollo Samples Covers Wide Range of Values

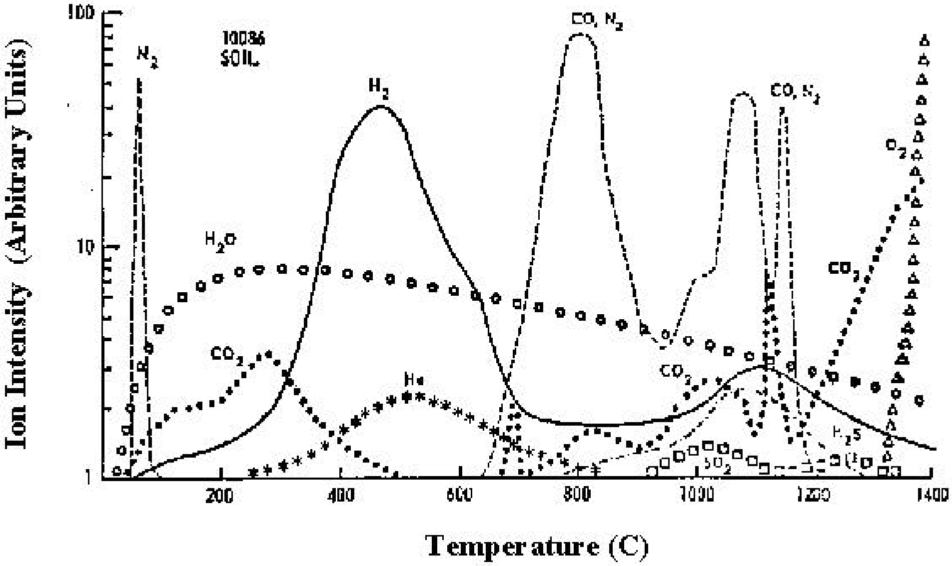

Figure 5. Original Gas Release Pattern for Apollo-11 Sample 10086 Was Very Complex

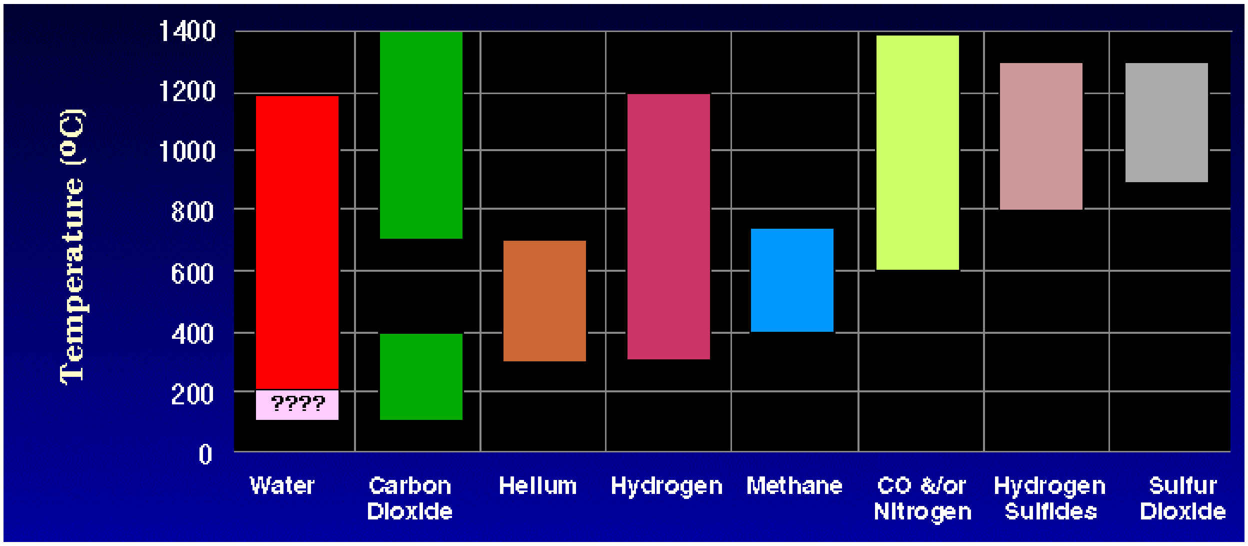

Figure 6. Release of Lunar Volatiles (i.e., >90%) Occurs over a Wide Range of Temperatures

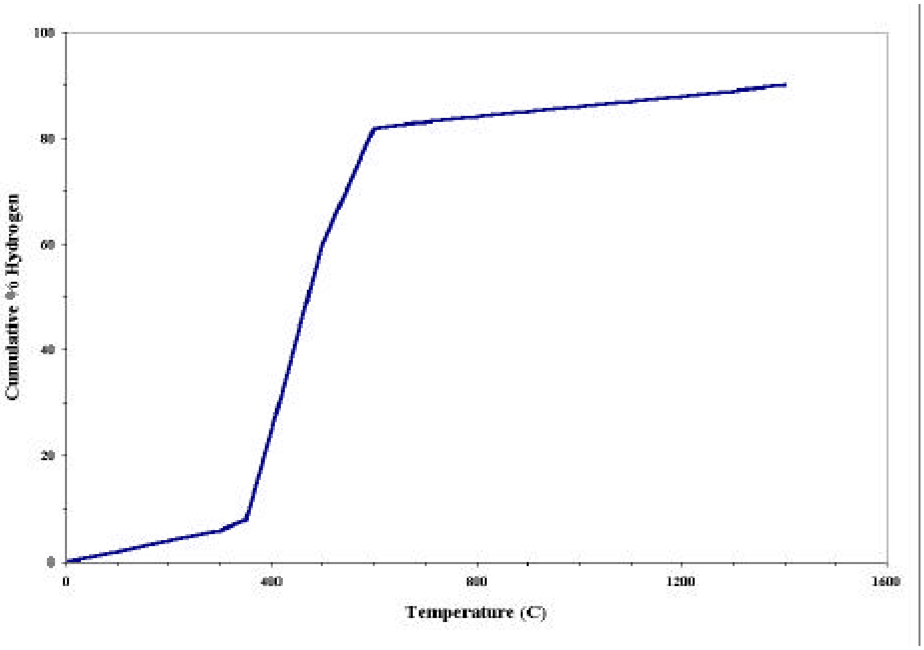

Figure 7. More than 80% of Solar Wind Implanted Hydrogen Can Be Extracted from the Apollo 11 Sample 10086.16 by 600 C

The proton ion energy in the solar wind (from Pioneer 10, Data Set #1) ranges from ~0.5 keV to ~4 keV with two peaks occurring at the lower end of the spectrum (from Pioneer 10, Data Set #1). The depth of implantation depends on the ion energy, but is typically only 0.005 - 0.01 microns. This means that most of the H_2 is close to the surface of the regolith particles. Further, the average grain size of Lunar regolith samples from the Apollo missions range from 40-130 microns with some 80% of the volatiles contained in particles that are smaller than 60 microns. This asymmetry is attributed to the large surface to volume ratio of the smaller particles. Therefore, for reasons of conservation of energy and maximizing H_2 evolution, it is prudent to process only particles which fall in the size range of <60 microns.

Clementine. The Clementine mission indicated extensive areas of permanently shadowed terrain at the lunar poles, particularly around the south pole of the Moon. Clementine showed that an area of contiguous permanent shadow in the vicinity of the south pole extended over about 15,000 km^2 (Nozette et al., 1996). The shadow is continuous, because the lunar south pole lies within a large, ancient crater, the Aitken Basin, where the surface lies several kilometers below the mean sphere. This area of contiguous shadow is not the only portion of the lunar surface that is in permanent shadow. Considering statistical analysis and examination of polar terrain images, Watson et al., (1961) and Arnold (1979) estimated that about 0.5% of the Moon's surface (190,000 km^2) is in permanent shadow. They demonstrated that craters as much as 25 degrees from the pole could have their bottoms in permanent shadow. The permanent shadow, therefore, is a more widespread phenomenon and the contiguous shadowed area near the south pole is only a few percentages of the estimated total area that is in permanent shadow. The Clementine team also reported a bi-static radar signal received in one pass over the south pole, which was interpreted to indicate the presence of ice (Nozette et al., 1996).

Lunar Prospector. The Lunar Prospector, launched on January 6, 1998, carried an experiment called the Neutron Spectrometer. This experiment was designed to detect the presence of hydrogen, which is believed to indicate the presence of water ice. The Neutron Spectrometer is designed to detect minute levels of water ice at concentrations of less than 0.01%. The instrument focused on areas near the lunar poles where ice was thought to exist. The original analysis of the data returned from Lunar Prospector indicated water ice mixed in with the lunar regolith at relatively low concentrations. These ice concentrations were conservatively estimated at 0.3 to 1 percent by mass at the Moon's poles, or up to 300 million metric tons (Feldman et al., 1998). Figure 8 shows Lunar Prospector Neutron Spectrometer data showing the concentration of H_2/O for the Moon's north and south poles.

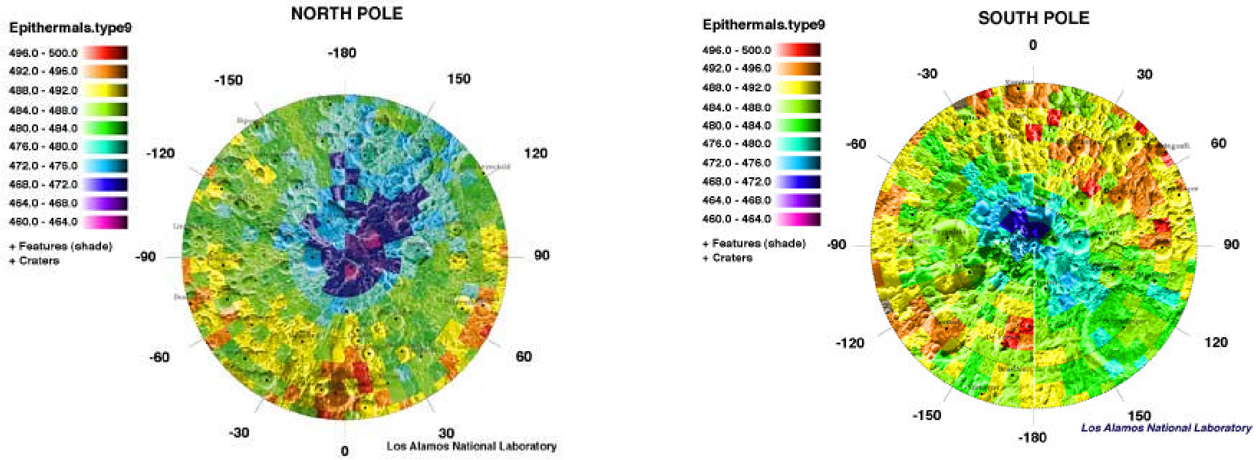

Figure 8. Lunar Prospector Neutron Spectrometer Data Showing the Concentrations of H_2/O

Current data (per Al Binder) indicate up to 260 million metric tons (MMT) of water ice have been predicted to within the first 2 meters of lunar regolith by the science team (July 1999). The current confidence level in this number is not very high, but it is likely the best estimate available until we measure insitu in the cold traps. Estimates indicate 200 MMT at the south pole and 60 MMT at the north pole. Ice is likely in deposits of pure water ice buried beneath ~5 cm of dry regolith in ~1.5% (or 1700 ppm if water ice) concentrations in the permanently shadowed areas. Concentrations appear higher at the North Pole**.** Kulcinski, Schmidt and others have suggested that the neutron spectrometer data are due to increased hydrogen concentration in the regolith, not water. Therefore, this plan considers this possibility. Al Binder and Bill Feldman will be constructing a total hydrogen concentration map of the Moon to within an accuracy of 1% that is expected to be complete in 2001. Binder now believes that both hydrogen and water exist in the polar regions. The data and interpretations indicate that both H_2 and H_2O may exist in the permanently shadowed areas and that higher than usual H_2 concentration (by a factor of 2) exist in the colder regolith just outside the cold traps. In approximately 2 years from this report date, the entire Moon's surface hydrogen concentration should be mapped.

1.1 Work Statement

The work to be performed under this 1.0 WBS Element is to summarize and document all of the reasonable data and scientific interpretations of the leading scientists that have looked at the relevant issues of water ice or hydrogen present in the cold traps of the lunar poles. Data available from Apollo, Luna, Clementine, and Lunar Prospector shall be included. The most recent analysis of Lunar Prospector Science Team shall be included. Any other relevant science data from US or foreign sources or other instruments shall be included.

1.2 Schedule

This WBS Element shall be conducted in FY-2001 over a 9-month period.

1.3 Estimated Funding Resources

The estimated budget for this 1.0 WBS Element is $100 K.

2.0 Develop Simulation Models of the Possible Physical/Chemical Processes

The purpose of this 2.0 WBS Element is to develop simulation models of the possible physical/chemical processes and their contributions that may have resulted in polar Lunar H_2O and/or polar Lunar H. Models for the existence of ice in permanently shadowed polar cold traps have been discussed since the work of Watson et al., (1961). The plausible sources of water on the Moon are micrometeoroids, the reaction of solar wind protons with the lunar surface and comet impacts. Existing lunar ice models consider the rates of accretion of water to the Moon, losses during ballistic migration of water molecules across the lunar surface to the cold traps and losses from the cold traps. None of the published models have explicitly included the gardening of the lunar surface by meteoroids, which can both protect ice by covering it and destroy ice by vaporizing it.

2.1 Work Statement

This 2.0 WBS Element involves the development of analytical models that describe the deposition of water, methane, hydrogen, or other species in the lunar polar cold traps. The models developed shall be made user-friendly such that they can be easily used by others later for simulations that predict concentrations of various species when ground truth in certain locations is known. Modeling shall include the following: (1) solar wind impact on the Moon's surface; (2) micro-meteor and meteor impacts on the surface; (3) comet impacts.

2.2 Schedule

This WBS Element shall be conducted in FY-2001 over an 11-month period.

2.3 Estimated Funding Resources

The estimated budget for this 2.0 WBS Element is $300 K.

3.0 Identify, Conceptualize, and Assess Uses of Lunar Polar H_2/O

The purpose of this 3.0 WBS Element is to identify, conceptualize, and assess uses of lunar polar water ice or hydrogen. This is a very important task early in this program that will: (1) identify all of the potential uses of lunar water ice or hydrogen; (2) conceptualize advanced concepts that are needed to process and use the resources; and (3) and assess the cost benefit of using the resource.

Various uses of lunar polar water ice or hydrogen have been identified as a starting point for this activity. Two major categories have been developed to help organize the various uses; they are: (1) Propellant Sources for Propulsion/Power Applications (Moon and Mars), and (2) Lunar Base Support Applications. Currently identified uses within each area are given in Tables 1 and 2. Solid, liquid or gaseous hydrogen, oxygen and hydrogen peroxide are assumed to be possible resource combinations. Additional synergy with other ISRU resources (Fe, Al, Mg, Ti, Na, K, C, N, He, O etc.) should be investigated. The use of methane for Mars applications as produced with lunar hydrogen should also be considered.

3.1 Work Statement

The work statement for this 3.0 WBS Element is defined here. The key aspects of the task are given below as defined subtasks. Figure 9 provides an overview of this WBS element. Subtask elements are briefly described below.

3.1.1 Identify Propellant Resources for Propulsion/Power Applications (WBS 3.1)

This subtask task is to completely identify, conceptualize, and describe all possible uses of the lunar H_2/O resources that make sense in a lunar or Mars infrastructure. The starting point for the effort is the information given in Table 1. Each use shall be described in a system concept.

3.1.2 Identify Lunar Base Support Applications (WBS 3.2)

This subtask task is to completely identify, conceptualize, and describe all possible uses of the lunar H_2/O resources that make sense in a lunar base support applications. The starting point for the effort is the information given in Table 2. Each use shall be described in a system concept.

3.1.3 Preliminary Quantification and Prioritization of Needs (WBS 3.3)

The purpose of this subtask is to: (1) provide preliminary quantification of the potential use of the resource, and (2) assign the uses at different logical confidence levels so that systems can be scoped properly. The period of time for consideration and ISRU use should be recommended by the study contractor and approved by the government study COTR.

Table 1. Hydrogen/Oxygen Resource Propellant Uses for Propulsion/Power Applications

A. Lunar Flight Transportation and Orbital Support Systems
1. Lunar Surface-to-Lunar-Surface Transport Systems
2. Lunar Surface-to-Lunar-Orbit Transport Systems
3. Lunar Orbit-to-Libration-Point Station Transport Systems
4. Lunar Orbit-to-Earth-Orbit Transport Systems
5. Lunar Orbit-to-Earth-Reentry Transport Systems
6. Lunar Surface-to-Earth-Orbit Support Systems (SPS, Space Manufacturing, ISS, etc.)
7. Lunar Surface-to-Earth Reentry Transport Systems (exporting lunar resources back to Earth)
8. Lunar Orbit Communications and Remote Sensing Satellite Systems
9. Lunar Orbiting Service Station (LOSS) System
10. Earth Orbiting Service Station (EOSS) System
11. Lunar/Earth Libration Point Station System
B. Mars or Other Solar System Flight Transportation Systems
1. H/O Propellants for Main and Auxiliary Chemical Propulsion (including CH_4)
2. O_2 or H_2 for Solar Electric Propulsion for Mars
3. H_2O for Nuclear Steam Rocket
4. LH_2 for Nuclear or Solar Thermal Rocket
5. SH_2 with HEDM Additives for Chemical Propulsion
C. Lunar or Mars Ground-based Fuel Cell or Combustion-Driven Ground Transport Vehicles
1. Exploration-based (scientific and commercial) Robotic and Manned Rovers
2. Personnel Transporters
3. ISRU Material Transporters
4. Equipment Transporters
5. Regolith Bulldozers
6. Mining Equipment
7. Winged Aircraft and Powered Balloons (Mars only)
D. Non-Propulsion Mars Applications
1. Mars Crew Life Support Systems
2. Mars Crew Food Production Systems
3. Mars Crew Radiation Protection System
4. Mars Outpost Power Systems
5. Auxiliary or Emergency Power Systems
6. Mars Concrete Production

Table 2. Hydrogen/Oxygen Resource Propellant Uses for Lunar Base Support Applications

A. Crew Life Support Systems
1. Drinking Water
2. Atmospheric Oxygen
3. Atmospheric Humidity
4. Washing/Bathing
5. Waste Processing
6. Space Suit Life Support
B. Food Production Systems
1. Plant Growth
2. Food Processing
3. Plant Reprocessing and Resource Recovery
4. Animal-Based Food Production
C. Lunar Laboratory Research
1. Plant Research
2. Animal Research
3. Chemistry
4. Physics
5. Biology/Biotechnology
6. Mineralogy/Geology
7. ISRU Chemical Processing Research (zeolites, Na, K, concrete, etc.)
D. Lunar Base Infrastructure Needs
1. Lunar Oxygen Production with H Recovery
2. Lunar Concrete Production for Roads, Buildings, Shielding
3. Thermal Control Support Systems
4. Oxygen or Hydrogen as Inflating Gas for Inflatable Structures
5. Water Radiation Shielding for Habitats/Laboratories
6. Water for Lunar Base Manufacturing Need

3.1.4 Develop Concept Definitions for System/Subsystems for Use Systems, Required Support Infrastructure, and the ISRU Systems (WBS 3.4)

The systems and subsystems that use the resources must be defined in enough detail such that the resource quantity need assessment is reasonable and feasible. Data from Subtasks in Sections 3.1.1, 3.1.2 and 3.1.3 are to be input for this subtask. The analysis later on in this WBS task shall also consider all H_2/O resources to be supplied from Earth. The ISRU processing systems/subsystems and related infrastructure support systems need to be defined in enough detail so that reasonable estimates are made. The concepts defined in 3.1.1 and 3.1.2, and others that are developed in the study, as well as the conceptual designs for ISRU support systems, require mass estimates and re-supply estimates.

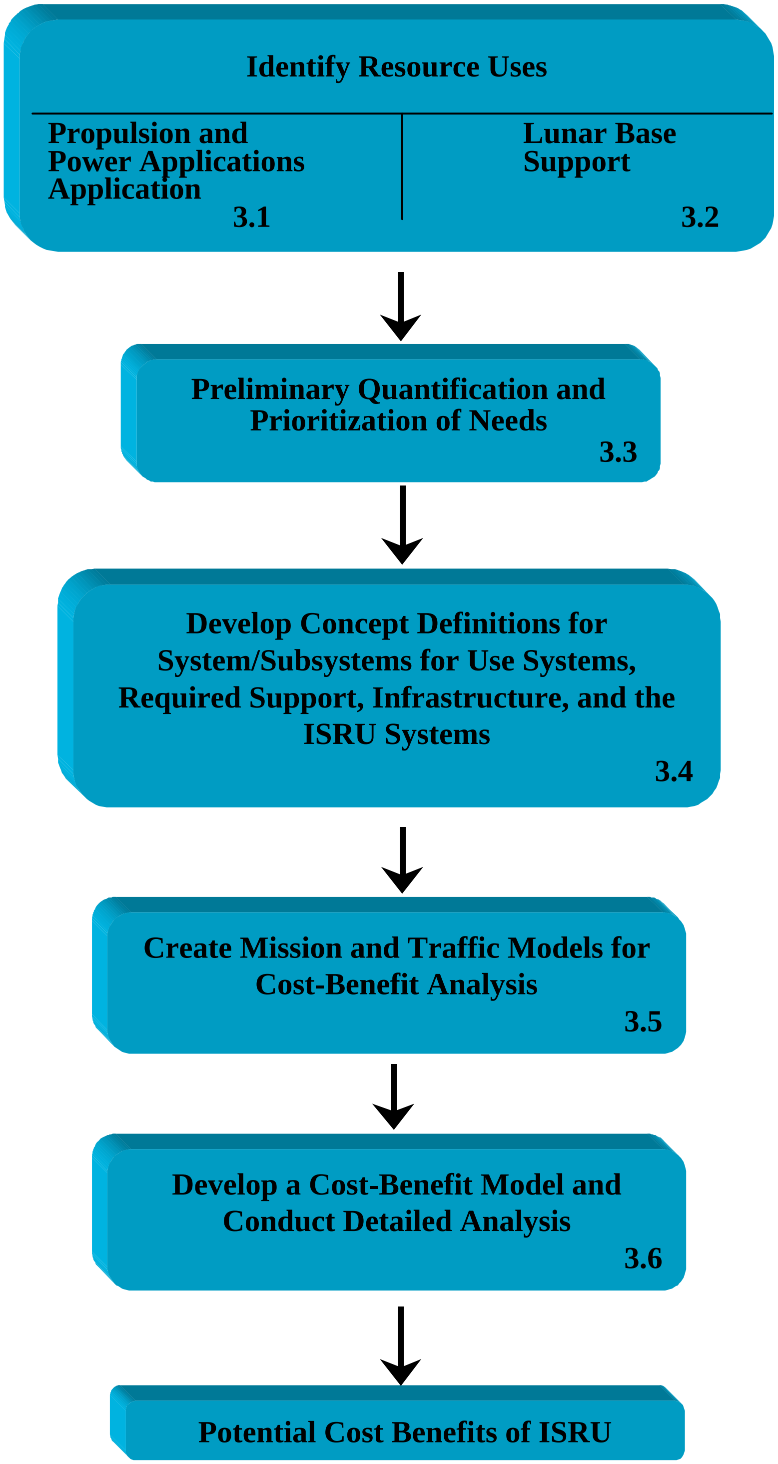

Figure 9. Overview of 3.0 WBS Element to Identify, Conceptualize, and Assess Uses of Lunar Polar Water Ice or Hydrogen

3.1.5 Create Mission and Traffic Models for Cost-Benefit Analysis (WBS 3.5)

Based upon the work of the previous subtasks in WBS 3.0, this subtask is to create mission and traffic models that can be used in the cost-benefit analysis. Past lunar NASA and other traffic models and lunar base definitions should be reviewed, modified, updated, and used in the analysis process. High, medium and low overall mission/traffic models should be used to bracket the potential cost benefit.

3.1.6 Develop a Cost-Benefit Model and Conduct Detailed Analysis (WBS 3.6)

A cost-benefit model shall be developed based upon previous subtasks. The cost analysis shall include a comparison of no ISRU vs. major ISRU activities on the Moon using H_2/O and other ISRU-derived materials. Available CER's should be used. High, medium, and low mission/traffic models should be developed. The analysis should also include parametric Earth launch mass costs of $10,000/kg, $1000/kg, and $400/kg. Cost-benefit for specific mission areas and uses, as well as the entire program architecture should be determined as a function of defined and undefined sensitivities.

3.2 Schedule

This WBS Element shall be conducted in Years 1, 2, and 3 (FY 2001-2003) of the program over a 28-month period. The expected 3.0 WBS Task level schedule (Figure 10) is given below.

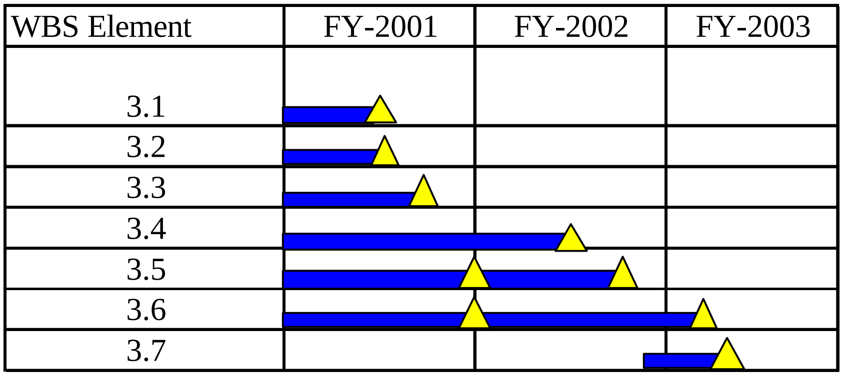

Figure 10. Subtask Schedule for WBS 3.0

3.3 Estimated Funding Resources

The total estimated budget for this 3.0 WBS Element is $2,500 K.

4.0 System Studies

This WBS Element involves system studies of key areas. System studies would be performed for the major or critical components of systems that use H_2/O as well as ISRU systems that provide the H_2/O resource. Early activities under this WBS element are broad-scoped, later efforts will be much more detailed, focusing on specific mission implementation plans. One defined activity is to conduct system studies on cost-efficient space transportation systems. A second defined activity is to conduct system studies on cost-efficient approaches to conduct rover-based exploration of the polar regions. A third defined activity would be studies and evaluations of the most promising ice extraction techniques and logistics approaches, based on the H_2/O data from Lunar Prospector. Studies and analysis would also be conducted in ground-based and lunar in-situ laboratory experiments. Other important study, analysis and design activities include: nuclear thermal device application assessment, development of a lunar H_2/O use and conservation plan, legal/political/treaty issue assessment, commercial development, a lunar environmental impact assessment, and cost modeling and analysis.

4.1 Work Statement

The work statement for this 4.0 WBS Element is defined here. The key aspects of the task are given below as defined subtasks.

4.1.1 Study Cost-Efficient Space Transportation Systems (WBS 4.1)

This subtask involves the study of cost-efficient space transportation systems that can support a manned and robotic lunar base activity, lunar outposts, lunar surface exploration, lunar ISRU exploitation, lunar orbiting service stations, a Earth-Moon libration station, and etc. over a reasonable time frame and take full advantage of H_2/O ISRU resources. The study should review all the possible space transportation elements and possible technologies that can use H_2/O either supplied from Earth or from the Moon. The transportation elements that have already been implied in Table 1 should be included. All lunar surface and orbital infrastructure need to be included in the analysis. Only space transportation technologies that use hydrogen, oxygen, or propellants derived from these basic resources shall be considered. Chemical propulsion (liquid or gas, premix bi-propellant, cryogenic solid hybrid, or HEDM-based cryogenic solid hybrid), nuclear thermal, nuclear electric, solar thermal, and solar electric should be included as candidates. Systems need to be defined in enough detail that accurate mass statements, performance, reliability, cost (non-recurring and recurring) can be characterized. Mission and traffic model input from WBS 3.0 shall initially be used to drive the detailed analysis.

4.1.2 Study Cost-Efficient Approaches to Conducting Rover-based Exploration (WBS 4.2)

This subtask studies the most cost-efficient approaches to conducting rover-based exploration. By the time this program plan is implemented, many innovative Discovery proposals from American industry will have been written and submitted to NASA. Many of these proposals, likely to go unfunded, could be a valuable resource of information. It is suggested that these contractors be included in this study task as subcontractors so that the best ideas will come forth and be used. Considerations that should be included for rover power are:

- Use a solar energy collector perched up on a crater rim that microwave or laser beams the energy to the rover operating in the cold trap.
- Use a solar energy collector in the permanent sunlight to charge the rover batteries after each battery- powered sortie into the permanent shadows of the cold trap.
- Use radioactive thermal generators of high efficiency to power the rover as it operates in the cold trap.
- Use a hydrogen/oxygen fuel cell to generate enough energy for one good roving sortie.

4.1.3 Study Promising Extraction Techniques/Logistics Approaches (WBS 4.3)

This subtask would study the most promising H_2/O extraction techniques/logistics approaches. There are three basic approaches to extracting H_2/O that have been identified. The first involves the in-situ heating of H_2/O/regolith without excavation. The H_2/O/regolith is heated and (1) for water, vapor is collected at the surface by freezing, so that it can be transported mechanically out of the shadowed area, or liquid or gaseous water is transported by heated pipeline from the cold trap, or (2) hydrogen gas is driven from the regolith, collected at low pressure, pressurized, and then transported by pipeline from the cold trap. The second approach is to excavate the H_2/O/regolith mixture, but process it in a furnace situated in the cold trap, and (1) for water, transporting liquid or gaseous water from the cold trap to a collection site outside of the shadowed area, or (2) for hydrogen, transporting the gaseous product from the cold trap to a site outside the shadowed area. A third option is to excavate the H_2/O-rich regolith and transport it from the cold trap to a sunlit area for processing.

Each of the H_2/O recovery approaches considered is composed of several elements:

- ***Regolith Preparation or Collection*** - This includes any conditioning of the H_2/O/regolith that is required before it can be processed. It also includes the collection of the H_2/O-rich regolith and placement in the reaction chamber, if required.

- ***Energy Source*** - This is the source of all the energy required in the extraction process. Energy requirements include the excavation equipment, reaction chamber, and transportation before and/or after processing.

- ***Energy Delivery to Shadowed Area*** - This is the method that energy is delivered to the excavation and extraction sites. This could include power cables, microwaves, reflectors, fuel cells, batteries, chemical reactors, pipes, etc.

- ***Extraction Process*** - This is the method that the H_2/O is being separated from the regolith. Some possible methods include distillation, mechanical separation, filtration, etc.

- ***Regolith or Resource Transportation*** - This is the method of transport of the processed resource or regolith out of the shadowed area.

Table 3 provides a preliminary set of processes for mining and extracting H_2/O in each of these areas.

Table 3. Preliminary Set of Processes for Mining and Extracting H_2/O

H_2/O/Regolith Preparation Or Collection	Energy Source	Energy Delivery to Shadowed Area	H_2/O Extraction Process	H_2/O/Regolith Transport
H_2/O/Regolith Preparation - Hammer & scoop - Air hammer - Auger - Block cutting - Explosive	Electrical - Nuclear reactor - GPHS-RTG - Chemical reactor - Fuel cell - Photovoltaics	Electrical energy - Wires, cables - Fuel cells - Batteries - Beamed power	Vaporization - Microwaves - Electrical furnace - Beamed heating - Chemical	Pipe out of shadow - Liquid water - Steam/vapor - H_2 gas Tanks on rovers
H_2/O/Regolith Collection - Scoop - Auger - Drag line bucket - Bulldozer	Direct Heating - Nuclear reactor - GPHS-RTG - Solar - Chemical - Laser	Thermal energy - Solar reflector - Insulated pipes - In-situ reactor - Beamed light - Chemical	Melting - Chemical - Solar - Nuclear - GPHS-RTG	Mechanical - Drag lines - Buckets - Gondolas - Conveyor belt - Dumbwaiter
		Mechanical energy - Cables - Belts	Condensation on cold plate	Ballistic - Rocket - Catapult

The most important environmental parameters for designing the extraction processes and systems are listed below:

a) ***Form of H_2/O/Regolith (implies physical properties of cohesion, strength)*** - This variable is most important in defining the excavation mechanisms that can be utilized. The following are the most likely configurations:

- Finely granular - formed by gardening of lunar soil with introduction of ice grains
- Ice chunks mixed in the regolith - formed by gardening of comet ice layers
- Solid ice/regolith layer - formed by continuous accumulation of ice and diffusion of water.
- Trapped H_2 gas from the solar wind.

b) ***Concentration of H_2/O*** - The concentration of H_2/O is important in determining whether processing should be done totally within or partially outside of the cold trap. If the concentration of H_2/O is low, it would be necessary to process a lot of regolith mixture to extract a small amount of water or hydrogen. Thus, processes that require less material movement would be favored. At the extreme, in-situ processing may be required for economic extraction at low resource concentrations. The concentrations currently reported by the Lunar Prospector mission are on the order of 1.6%. In this range, there would be significant tradeoffs between local extraction within the cold trap and excavation and transportation of regolith mixture to a processor outside of the cold trap. It is currently believed by the lunar prospector team that both H_2 and H_2O exist at the poles, with H_2O being predominant in the cold traps and H_2 being predominate in the polar non-permanently shadowed areas. It still may be possible that deposits of near-pure ice buried beneath a layer of dry regolith could be excavated. The final processing of the water ice could occur outside the cold trap where solar energy was readily available. An assessment of water contamination by other volatiles also needs to be made. The use of other thin volatile material also needs assessment.

c) ***Scale of Deposits*** - The scale of the deposit determines the distance between the cold trap and adjacent areas that have access to solar energy. This is important in designing transportation systems for energy and materials in and out of the cold trap. It also determines the time scale in which systems must operate in the cold trap before returning to a sunlit area. Finally, the scale of the deposit determines how much H_2/O can be extracted and, therefore, the degree that extraction apparatus needs to be relocated.

d) ***Terrain Accessibility*** - Small craters should not present any serious accessibility problems, but there may be boulders in the subsurface on the rims. Larger craters may pose severe access problems due to rugged crater walls, substantial relief, and the abundance of boulders. Access challenges in low relief terrain in permanent shadow should be minimal. Terrain accessibility would determine the style of access for surface mobility systems.

e) ***Availability of Solar Energy*** - The highest availability of solar energy would be for the small craters located outside the Aitken Basin. There may be areas of permanent sunlight on the rim of the larger south pole crater. Availability of solar energy close to the H_2/O deposits would influence the selection of energy provision and transmission approaches.

f) ***Temperature*** - Temperature in the cold trap is determined by the amount of scattered light that can be received and by the heat conduction through the surface. Any extraction system to be utilized within the cold trap must be capable of operating in temperatures ~70 K. It should be assumed that machinery would have to radiate heat to deep space.

In the process of selecting the best approach for extraction, the following evaluation criteria are suggested:

- Minimum Cost
- Maximum Performance
- Minimum Complexity
- High Reliability, High Life Expectancy, and High Safety Margin
- Low Technical Risk
- Minimal Maintenance and Crew Time Requirements
- System Versatility/Flexibility
- Minimal Lunar Environmental Impact.

4.1.4 Conduct Ground-Based and Lunar In-situ Laboratory Studies/Experiments/ Scientific Research (WBS 4.4)

This subtask would involve the initial development of ground-based and Lunar in-situ laboratory studies and experiments and scientific research. Before the research can be done, ground-based facilities must be built (see WBS 6.0). The overall goal of the simulators would be to: (1) assess the water ice deposition process and ice/regolith characteristics under simulated lunar environmental conditions (temperature, pressure, and thermal radiation) environment; and (2) assess the hydrogen deposition process under simulated lunar environmental conditions. Simulators to be used for this task would be made available through WBS 6.0.

4.1.4.1 Lunar Water Ice (WBS 4.4.1)

For lunar ice, the expected capabilities would include the following:

- Allow scientists to study the ice deposition process and measure the physical properties of ice and regolith mixtures under conditions similar to those found in the cold traps near the lunar poles
- A regolith-stirring device is used to simulate micrometeoroid gardening of the ice/regolith mixture
- Simulate the lunar environmental conditions including temperature, pressure and thermal radiation
- Form ice/regolith indurated mixtures
- Form ice/regolith fine-granular mixtures
- Form ice/regolith breccias (coarse aggregates of ice and regolith)
- Deposit ice on a cold regolith surface
- Deposit ice on a cold ice surface
- Allow physical manipulation of ice or ice/regolith mixtures
- Measurement of temperature of ice or ice/regolith surface.

The following is a list of possible experiments that could be performed in a fully-developed Lunar Ice Simulation (LIS) system. Although this list may not be comprehensive, it is representative of the type of experiments that could be performed and the questions that could be answered with a developed LIS system.

- Deposit ice directly from water vapor under simulated lunar cold trap conditions on to a cold plate, an existing layer of ice, a layer of ice/regolith mixture or on a layer of dry regolith.
- Measure the thermo-physical properties of the ice or ice/regolith mixture under the simulated lunar cold trap conditions including: hardness, shear strength, impact strength, density, compressive strength (tamping), heat capacity, thermal conductivity, porosity, and permeability.
- Observe the surface and subsurface structure of the ice or ice/regolith mixture during ice deposition and preparation activities via a high-resolution video camera at various ice/regolith ratios.
- Test and observe ice extraction technologies (subsystems and complete systems) under simulated lunar cold trap conditions, including: drilling, scraping, scooping, cutting, rotary

excavation, grinding, mechanical separation, fluidizing, sand blasting, impacting, steam jet, microwave interaction/penetration and laser beam interaction.

- Deposit ice with varying deuterium/hydrogen (D/H) ratios such that a flight mass spectrometer can test its operation so we can determine the ice source on the Moon (comet, solar wind and meteorites have different D/H distributions). Also, assess the He^3/He^4 ratio, the O^{16}/O^{17} ratio, and the O^{18}/O^{17} ratio to help determine the source of oxygen (lunar, solar wind, cometary, etc.). Determine the concentrations of the following: S, CO, CO_2, N_2, Na, and K.
- Deposit ice under different regolith depths – consider testing a microwave sounder, x-ray, and ultrasound for a simulated flight experiment.
- Conduct neutron emission measurements at the surface.

4.1.4.2 Lunar Hydrogen (WBS 4.4.2)

For lunar hydrogen, different simulators would need to be designed. A lunar hydrogen acquisition demonstration experiment would validate the technology needed for extracting hydrogen from lunar regolith. A mission concept could include a small rover or mini-miner in the 200 kg class that can demonstrate key technologies, including collection of the regolith, benefitiation of the regolith, heating and heat recovery of the lunar regolith, use of direct solar heating, measurement of the processed gases via a light-weight mass spectrometer, and separation of the gases for temporary storage and quantification before release to the lunar atmosphere. Significant savings are available if ISRU produced hydrogen and other volatiles for propulsion and life support use from the Moon can become a reality. A small-scale technology flight experiment for recovery of lunar volatiles and in particular, H_2, He^3, He etc. could also become a vital part of man's next steps in our return to Moon.

This task should consider the use of standard, ion-implantation equipment to design an experiment for implanting H^+ into lunar simulant material. An experiment could then be designed using lunar regolith simulant, which has been implanted with protons, to determine the most efficient processes for H_2 extraction. In particular, methods for steady state extraction could be compared to batch extraction from the standpoint of optimizing evolution and minimizing energy consumption. This could be followed with small-scale laboratory experiments to test beneficiation and heating methods, which are appropriate for lunar applications. Such heating methods may use electric resistance, laser heaters, and microwaves.

4.1.5 Nuclear Thermal Device Application and Design Assessment (WBS 4.5)

This subtask will assess the application of nuclear thermal devices for H_2/O resource missions. It has become apparent that operations in the permanently shadowed cold traps can be greatly simplified by using radioactive thermal power devices (RTPD's). These power devices are expected to have significant advantages over other more operationally complex (solar-microwave, solar direct beam, solar pumped laser, chemical power conversion (this would be good after resource flow has been established). Studies of Mars exploration has also indicated a significant utility for RTPD's. This task will assess the different applications of these devices in the exploration program and provide realistic systems designs for these applications, with the primary application the recovery of lunar H_2/O from the cold traps of the Moon.

4.1.6 Resource Use and Conservation Plan (WBS 4.6)

This subtask shall develop a resource use and conservation plan. A valuable resource such as H_2/O on the Moon requires that use and conservation plans be developed such that this very valuable resource is not squandered or wasted. The economically beneficial use of H_2/O needs to be well planned once the reserves have been reasonably determined by insitu and remote measurements. A key element in the use and conservation plan is the implementation and development of technologies that can support the water recovery from all possible applications, including rocket exhaust. Starting with the list of possible applications, different types of recovery systems would be analyzed for feasibility and then defined. Some recovery system examples include:

- Auxiliary Power Systems - water exhaust would be recovered in a recovery tank/heat exchanger. For fuel cell-based systems, water recovery is part of the system.
- Life Support Systems - Recovery and recycling is expected to be part of the system.
- Hatches - Air, water vapor need to be recovered internally, without gas escaping to the external environment. Air should be kept dry in hatches to prevent condensation and loss.
- Food Processing - Recovery and recycling is expected to be part of the system.
- Waste Processing - Recovery and recycling is expected to be part of the system.
- Manufacturing and Chemical Processing - Systems need to be designed to recover all chemicals and gasses.
- Concrete Processing - Technology should be developed that reduces the amount of water vapor in the processed lunar concrete. Pressurized manufacturing facilities would need to be designed to recover all gasses.
- Rocket Engine Exhaust - Cold traps at the launch pad to catch and recover the close-in water exhaust; consider plume pointing during early ascent. Also consider water gas monitors and naturally cooled water recovery systems located in the polar cold traps. Migration should be assessed by the models developed under WBS 2.0.

4.1.7 Legal/Political/Treaty Issue Assessment (WBS 4.7)

With exploitation of a lunar resource for national, international or commercial use, legal and political issues will develop. An assessment of these issues is recommended so that they can be treated properly and ensure that no “program stoppers” exist.

4.1.8 Commercial Development and Commercial/Government Partnership Potential Assessments (WBS 4.8)

There has been a lot of discussion about the government/industrial partnerships that are possible to support the development of a lunar base activity. The purpose of this task would be to evaluate the possible interactions and benefits to both. International participation should also be included. Any limits to commercial exploitation should be identified and evaluated.

4.1.9 Lunar Environmental Impact Assessment (WBS 4.9)

This subtask will perform an EIA for the Moon using NEPA guidelines. With the development of a major lunar base and activity, it is likely that an official Environmental Impact Assessment will be necessary. The impact of human activities on the Moon will need to be studied to be sure that we do not damage the Moon or change the Moon in an unwanted way. The use of a valuable resource such as H_2/O, and other resources such as: helium-3, other volitiles, etc. needs to be assessed. Because of the nature of the lifeless Moon, the impact to the Moon's atmosphere and its albedo appear to be the other issues that need assessment. Dr. Gerald Kulcinski, of the University of Wisconsin, prepared the first environmental assessment of lunar operations for helium-3 mining (Kulcinski, et.al., 1992).

4.1.10 Cost Modeling and Analysis (WBS 4.10)

As part of this analysis task, detailed cost models need to be developed and applied to make informed decisions about the program. While a certain level of cost modeling will have been completed in previous work under this program (WBS 3.5/3.6), a more detailed and comprehensive approach is needed. This cost model would include all aspects of the mission to the Moon and other uses. The model would be exercised to conduct total system cost analysis to evaluate the cost-benefit of H_2/O from the Moon.

4.2 Schedule

This WBS Element shall be conducted in Years 2 and 3 (FY-2002 and FY-2003) of the program over a 21-month period. The expected WBS Task level schedule is given below in Figure 11.

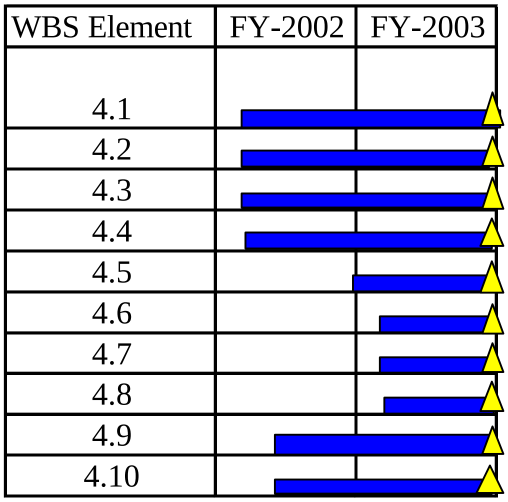

Figure 11. Subtask Schedule for WBS 4.0

4.3 Estimated Funding Resources

The total estimated budget for this WBS Element 4.0 is $4,000 K. The estimated breakout by sub-element is given in Table 4 below.

Table 4. WBS 4.0 Budget Estimates

WBS Element	**Estimated Budget ($K)**
4.1 Study Cost-Efficient Space Transportation Systems	1000
4.2 Study Cost-Efficient Approaches to Conducting Rover-based Exploration	600
4.3 Study Promising Extraction Techniques/Logistics Approaches	500
4.4 Conduct Ground-Based and Lunar In-Situ Laboratory Experiments/Scientific Research	1000
4.5 Nuclear Thermal Device Application Assessment	200
4.6 Resource Use and Conservation Plan	100
4.7 Legal/Political/Treaty Issue Assessment	50
4.8 Commercial Development and Commercial/Government Partnership Potential Assessments	50
4.9 Lunar Environmental Impact Assessment	200
4.10 Cost Modeling and Analysis	300
TOTAL	**4000**

5.0 Technology Needs Assessment and Development

Once the lunar ice extraction process and use approaches have been defined and evaluated, a more focused technology needs assessment can be performed. Any technology development required would occur during this latter stage. One of the greatest challenges in extracting the lunar H_2/O will be operating machinery in the extreme conditions believed to be present near the H_2/O deposits. With temperatures of 60-100 K expected in the permanently-shadowed areas around the poles of the Moon, the operation of mechanical, electrical and fluid systems will require specific technology development. Some specific technology development may be required for: solar and nuclear-based energy delivery systems, automated materials handling and processing, reduced gravity electrolysis systems, purification of water from the lunar regolith, water storage systems, energy storage and delivery, cryogenic hardening of electronic and mechanical systems, excavation technologies, rovers, ballistic flight vehicles, hydrogen peroxide production in 1/6 g, and alternate oxygen production, if needed. The purpose of this WBS Element (5.0) is to identify technology that is needed and develop those technologies if not available. Many areas that are currently believed to require a technology need assessment have been identified; they are presented here.

5.1 Work Statement

This 5.0 WBS Element is broken down into the areas that have been initially identified for technology assessment and further development. The initial work areas are given below.

5.1.1 Overall Technology Needs Assessment (WBS 5.1)

The purpose of this element of WBS 5.0 is to review the work done on the program to date and assess, review, and re-define the technology needs and development tasks that have been initially defined below. It is expected that this initial list will change as the more promising concepts are defined and analyzed.

5.1.2 70 K-Cold Operations of Mechanical, Electrical and Fluid Systems (WBS 5.2)

The anticipated extreme cold environment in the permanently shadowed cold traps of the Moon, will be a significant problem for robotic devices, mechanisms, scientific instruments, and other devices. Any device that operates in the cold traps of the Moon, will have great difficulty maintaining a working condition, unless its systems are properly designed for 70K-type thermal conditions. Technology assessment of all possible subsystems and their operation in cold conditions is needed. Granted, some systems could be kept warm through proper thermal management schemes, but others would not. Once an assessment has been achieved, the details of what items require cold testing and technology development should be made and implemented. Areas of possible technology development include: bearings and lubricants, electrical motors, electrical components, computers, chips, contacts, rotating joints, fluid lines, fluid valves, fluid regulators, etc.

5.1.3 Application of DOE's ARPS, GPHS Brick, and other Systems for this Application (WBS 5.3)

The potential application of the radioisotope thermal power devices (RTPD's) for use in the cold traps appears to be well-justified based upon the logistics difficulties in the cold isolated environment during the applications of other approaches. The radioisotope systems that should be considered for early exploration and demonstration testing include a current RTG design (95% heat efficient or 5% electrical energy efficient; at 93 W_e/kg and 4.9 W_e/kg, respectively) and two advanced systems being developed by the DOE and NASA. One employs Alkali Metal Thermal-to-Electric Conversion (AMTEC) technology and is known as the Advanced Radioisotope Power System (ARPS) (20% electrical energy efficiency at 19.6 W_e/kg). The other uses thermodynamic electric power generation and is known as the Dynamic Isotope Power System (DIPS) (25% electrical energy efficiency at 24.5 W_e/kg). All three systems rely on the "General Purpose Heat Source (GPHS) using Plutonium oxide fuel pellets. The two very promising fusion systems should be reviewed for possible use. They are as defined by the University of Illinois and NPL Associates. One design is based on Inertial Electrostatic Confinement (IEC)-based fusion. The other is a low-energy nuclear reaction (LENR) fusion system. Very high value of specific power are predicted. The technology readiness is an issue. These power systems for lunar resource acquisition in the cold traps need to be assessed with respect to the other technologies that are proposed.

5.1.4 Small Nuclear Reactors (WBS 5.4)

The long-term processing of lunar H_2/O will require larger, more efficient energy systems. Nuclear reactors are good candidates to satisfy this need, especially while operating in the cold traps. Recent studies of Mars exploration has also indicated that there will be a need for many small nuclear reactors to support the Mars exploration/colonization activity expected in the years that follow the initial exploration missions. While the Moon is likely to use significant solar power in the normally sunlit areas of manned activity, this task would investigate the feasibility of nuclear reactor power systems for lunar ISRU processing in the permanently shadowed polar regions. This task will assess the need for "small" nuclear reactors by conducting design studies. Required power levels will be determined by other previous studies that will have been conducted.

5.1.5 Microwave Energy Systems for In-situ Processing (WBS 5.5)

This task would involve the design, analysis and experimental testing of various microwave processing systems for H_2/O recovery. This task would investigate open and closed H_2/O microwave processing approaches. "Open" concepts are those that do not have a totally enclosed processing chamber (continuous process); "Closed" approaches are totally closed (batch process) and could process H_2 gas, water, and other volatiles. Selective frequency microwave systems need to be evaluated to provide the most efficient approaches. Prototypes would be built and tested in a lunar simulator with lunar simulant.

A brief description of one concept follows: A photovoltaic array converts sunlight into electricity and then the electricity is carried into the permanently shadowed area through a power cable. The electricity powers a mobile microwave generator that is aimed at ice-containing regolith; no excavation is utilized. The microwave energy selectively heats and/or vaporizes the ice or hydrogen. A dome covers the area that is being processed to contain the water vapor or hydrogen produced. For water vapor, H_2O migrates from the regolith and is collected on cold plates located just above the surface. The solid ice is removed from the cold plates and transported out of the shadow in a storage tank mounted on a fuel cell-powered rover. For H_2 present, most of the gas would be collected and then separated.

5.1.6 Cable Systems for Ground-based Automated Experimental and Large Automated H_2/O Acquisition and Processing Systems (WBS 5.6)

One possible approach to providing energy to ground-based automated processing systems operating in the cold trap on the Moon is to use the permanently sunlit crater rim to generate electricity from solar energy and use a cable to transmit the power to the processing unit that is operating in the cold trap. Additionally, this cable/tube could be used to transfer H_2 or H_2O out of the cold trap to the sunlit region. This task would involve an assessment of how to design and operate such a cable. Design, analysis and experimental testing would be involved.

5.1.7 Technology for Materials Handling and Processing for Ground-based Automated Experimental and Large Automated H_2/O Acquisition and Processing Systems (WBS 5.7)

This task would involve all of the technologies for materials (primarily regolith) handling as are needed for experimental and large processing systems. Included are: drilling; sample coring; beneficiation; bulk transport; gas, liquid solid transport; gas, liquid, solid storage; etc.

5.1.8 Electrolysis Systems and Fuel Cells in Zero and Partial g Environments (WBS 5.8)

This task would involve the technology assessment and demonstrations of water electrolysis and H_2/O_2 fuel cell technology as applied to the ISRU processing mission and applications that operate both at close to zero-g or at 1/6th g. These systems are important for nearly all of the applications identified that use H_2/O resources. The size of these units must be assessed so that the properly size prototypes can be developed. Their potential use in the cold traps needs to be assessed for technology development.

5.1.9 Water Rocket Technologies for Orbit Transfer and Orbital Auxiliary Propulsion (WBS 5.9)

This work in this task would develop the technologies that are needed to use water as a H_2/O_2 propellant storage method for orbit transfer and orbital auxiliary propulsion. Water is easily transported or stored in un-insulated, light-weight tanks. Water can be stored in these tanks without the boil off loss of propellant, as in the case of liquid hydrogen or liquid oxygen. Electrolysis systems operating in zero-g, as are to be evaluated in Section 5.1.8, would be used when propellant is needed. For OTV use, high capacity orbiting service station systems would be necessary. For orbital auxiliary propulsion, smaller on-board electrolysis units are required. For OTV applications, large efficient liquifers and cryogenic storage tanks would be needed would be required. Zero-loss cryogenic fluid transfer systems would be required. The use of highly-efficient magnetic refrigeration systems should be investigated.

5.1.10 Solar Energy Beaming into the Cold Region (WBS 5.10)

This task will design, assess, and experiment with the collection and beaming of solar light energy from one position (crater edge) to another (cold trap) at specified distances to match those that would be expected on the Moon. An experimental unit of reasonable size would be built and demonstrated. The system should be sized to match at least a first experimental unit size for lunar applications. Options include: direct optical solar beaming and solar pumped lasers.

5.1.11 Microwave Energy Beaming into the Cold Region (WBS 5.11)

This task involves the design, analysis, and demonstration testing of microwave energy transmission from an antenna to a collector in the cold trap. The size of the prototype unit to be tested will be a reasonable size to simulate actual solar energy conversion to microwave energy and beaming into the cold trap. Previous studies would be used for initial scoping.

5.1.12 Water Recovery Systems Near Lunar Launch and landing Sites (WBS 5.12)

This task involves the development of water recovery technologies that would be operated at the launch sites. The requirements of this technology include the collection of the H_2O-based exhaust from operational launches and landings. Cold trap freezers in the area appear to be the first option. Previous studies would be used for initial scoping.

5.1.13 Water Recovery Systems for All Water Use Applications (WBS 5.13)

Technology demonstrations of various water recovery systems would be achieved under this task. Previous water conservation planning studies would be used for initial scoping.

5.1.14 Lunar Sample Return Mission Technology Using Processed Water Ice for Propellants (WBS 5.14)

This task would design, analyze, and develop bread-board technology demonstration devices that will allow for a Lunar sample return, using processed water ice in the cold trap. This mission would utilize much of the other work already underway. Radioisotope thermal generator devices would likely be used, but others should be assessed.

5.1.15 Ballistic-based Flight Transporters (WBS 5.15)

Technology development work needs to be done for small and large ballistic flight vehicles that are used to transport material from one location on the Moon's surface to another. Previous studies would be used for initial scoping. New propulsion technologies that use hydrogen and oxygen are needed to provide lower weight, and higher performance.

5.1.16 Rovers and Ground-based Transporters (WBS 5.16)

Technology development work needs to be done for small rovers and ground-based vehicles that are used to transport material from one location on the Moon's surface to another. Previous studies would be used for initial scoping. New power conversion technologies that use liquid hydrogen and liquid oxygen as propellants are needed to provide for lower weight and higher performance.

5.1.17 Assess H_2O_2 Use in Propulsion Systems and H_2O_2 Production for Lunar Transport Applications (WBS 5.17)

The return of H_2O_2 in the USAF and NASA bi-propellant propulsion programs, coupled with lunar resource availability, will likely create interest in looking at H_2O_2 for Mars applications. The reduction in tank insulation mass and the potential for hypergolic ignition makes this an attractive option. Previous studies would be used for initial scoping.

5.1.18 Determine the Best Approach for Processing Oxygen from the Regolith if Water is Not Present (WBS 5.18)

There are a wide variety of oxygen-producing approaches that can be used on the Moon if water is not present. The Major candidates are (1) Carbon-based reduction of lunar oxides, (2) hydrogen-based reduction of iron oxide, (3) silicate electrolysis, (4) vapor phase reduction and, etc. These and other concepts need to be analyzed and the best approaches developed and demonstrated as a back up for oxygen production should water not be present.

5.2 Schedule

The work of this WBS element would be conducted over 37 months from FY-2001 through FY-2004. Each subtask would be conducted over the entire period, except 5.17 would be done in the second full year.

5.3 Estimated Funding Resources

The estimated funding resources ($24,000 K) are given in Table 5 below:

Table 5. WBS 5.0 Budget Estimates

WBS Element	Estimated Budget ($K)
5.1 Overall Technology Needs Assessment	500
5.2 70 K-Cold Operations of Mechanical, Electrical and Fluid Systems	2000
5.3 Application of DOE's ARPS, GPHS Brick, and other Systems for this Application	4000
5.4 Small Nuclear Reactors	2000
5.5 Microwave Energy Systems for In-situ Processing	1000
5.6 Tether Systems for Ground-based Automated Experimental and Large Automated H_2/O Acquisition and Processing Systems	1000
5.7 Technology for Materials Handling and Processing for Ground-based Automated Experimental and Large Automated H_2/O Acquisition and Processing Systems	1000
5.1.8 Electrolysis Systems and Fuel Cells in Zero and Partial g Environments	1000
5.9 Water Rocket Technologies for Orbit Transfer and Orbital Auxiliary Propulsion	800
5.10 Solar Energy Beaming into the Cold Region	1000
5.11 Microwave Energy Beaming into the Cold Region	700
5.12 Water Recovery Systems Near Lunar Launch and landing Sites	800
5.13 Water Recovery Systems for All Water Use Applications	400
5.14 Lunar Sample Return Mission Technology Using Processed Water Ice for Propellants	800
5.15 Ballistic-based Flight Transporters	2400
5.16 Rovers and Ground-based Transporters	1400
5.17 Assess H_2O_2 Use in Propulsion Systems and H_2O_2 Production for Lunar Transport Applications	200
5.18 Electrolysis Systems and Fuel Cells in Zero and Partial g Environments	3000
TOTAL	**24,000**

6.0 Ground-Based Prototype Facility Development

Lunar ice or hydrogen simulators would be developed to recreate on Earth the environmental conditions present in the permanently-shadowed regions of the Moon. The pressure and temperature environment would be recreated and small amount of water vapor would be introduced or hydrogen would be implanted. Such simulators would serve multiple purposes. A large-scale, lunar ice or hydrogen simulator would allow testing of various components of an ice extraction system for exploration missions. The ice deposition process could also be studied in a large ice simulator. Layers of ice and regolith could be formed. Micrometeoroid stirring of the ice and regolith mixture could be approximated with mechanical stirring.

If the H_2/O turns out to be H_2, then more emphasis would be appropriate to develop simulators that simulate regolith with embedded H_2 gas. These simulators can be developed via ion-implantation (see Section 4.1.4.2).

The objective of this task is to develop systems that can simulate the physical structure of the lunar H_2/O/dust mixtures to test and demonstrate mechanisms for the mining and processing of lunar H_2/O deposits. The simulators, with increasing size and complexity, would be used to perform scientific research and engineering experiments to help determine the characteristics of the lunar H_2/O deposits and the feasibility of acquisition devices for flight. This includes measuring fundamental properties such as the form of the H_2/O deposited. Simulators would be utilized to support studies of ice extraction from the lunar regolith in permanently-shadowed areas. The preliminary requirements for simulator systems large enough to accommodate full-scale testing of a lunar robotic lander or H_2/O recovery systems would also be determined in this task.

6.1 Work Statement

The purpose of this task would be to develop a set of lunar H_2/O simulators of various sizes that can be used to assess the deposition process and H_2/O/regolith characteristics under simulated lunar environmental conditions (temperature, pressure, and thermal radiation) environment. See Section 4.1.4 for more related information.

6.2 Schedule

The work of this WBS Element would be conducted from FY-2001 through to the end of the program.

6.3 Estimated Funding Resources

The estimated funding resources are $17,200 K up to FY-2010.

7.0 DDT&E and Flight Deployment of Space Flight Mission to Lunar Poles with Sample Return

A robotic rover would be used to explore the regions near the north or south pole of the Moon where water ice and H_2 is believed to exist. Such a mission could provide valuable information on the location, concentration and physical properties of the water ice and H_2 deposits. This information could then be used to develop ice extraction processes and perfected ground-based lunar ice simulators or environmental chambers.

This task proposes to carry out a, low-cost, lunar-ice characterization mission, wherein insitu measurements would be made and several samples would be returned to Earth for detailed analysis. The baseline mission would use an ARPS power supply for the rover and a solar array for lander and launcher power (on a permanently sunlit crater rim). The lander would land on a permanently sunlit crater rim, the solar array would be deployed, and the ARPS-powered rover would be deployed on to the ground. The rover would then proceed into the cold trap and explore and take data and samples. A large suite of scientific experiments could be included, such as:

- ***Wide-Angle Navigation Cameras*** with auxiliary lights to help the rover negotiate the Lunar terrain in the shadowed areas
- ***Panoramic Cameras*** with auxiliary lights for stereo, high-resolution visualization of the nearby terrain
- ***Microwave or Ultrasonic Sounder*** to determine the depth of ice deposits in the dry regolith
- ***Robotic Arm*** to collect and transfer surface regolith to rover instruments for analysis
- ***Sample Extraction System*** to obtain subsurface core samples for analysis on the rover
- ***Thermal Emission Spectrometer*** for analyzing the mineral composition of the regolith
- ***Microscopic Imager*** to provide very detailed images of regolith and rocks
- ***Alpha-Proton-X-Ray Spectrometer*** to study the elemental chemistry of regolith
- ***Cryogenic Temperature Sensors*** for determining surface and subsurface regolith temperatures
- ***Pyrolyzing Oven*** to vaporize and extract water-ice from the regolith for analysis by other instruments
- ***Hydrology Suite*** for analyzing the concentration and composition of water-ice in the regolith.

The instrumentation will be one of the driving forces in the rover design. The mission will also provide the opportunity to demonstrate ISRU technology in the cold traps. For example, various techniques may be employed to extract the H_2/O/regolith, including: drilling, scraping, scooping, cutting, rotary excavation, fluidizing, and etc.

Though many factors will play a role in the final mission design, an iterative process with respect to the experimental definition and power requirements should be followed to optimize the mission. The mass of the experimental equipment must be taken into consideration.

The sample return part of the mission would be accomplished by a Earth Return Vehicle (ERV) that would be launched from the lander. The rover would gather samples and place them in a sample container. At the end of the first phase of the mission, the rover will return to the lander site and give up its sample container to the ERV. The ERV would then be launched and the sample container would be recovered via reentry/parachute/aircraft capture over the Earth's ocean.

7.1 Work Statement

This task is a major development flight program, the planning for which is beyond the scope of this effort. The details of the design would be the responsibility of the first four sub-task elements. A detailed work plan should be developed once this program is well under way. The expected elements of the WBS involving a logical approach for this flight experiment include the following:

- System Requirements and Experiment/Measurement Definition
- Engineering and Analysis
- Component Development and Testing
- Detailed Design
- Hardware Development and Checkout
- Operations Testing and Performance Evaluation in Ground-based Simulators
- Flight System LV Integration
- Mission Flight/Sample Return
- Mission Operations, Data Analysis and Outreach.

7.2 Schedule

The work of this WBS Element would be conducted over 6.5 years from FY-2001 through FY-2007.

7.3 Estimated Funding Resources

The estimated funding resources are $172,000 K.

8.0 Lunar H_2/O Extraction Mission

As a result of the first Lunar mission to the polar cold traps of the Moon, a great amount of information will be obtained and knowledge gained. This information, assumed to be of positive value, will drive the need to demonstrate the first reasonably sized pilot lunar H_2/O extraction plant on the Moon. The work of the program will feed into the definition of this mission. Details will be developed as this program plan evolves.

8.1 Work Statement

Again, this task is a major development flight program and its complete work plan is beyond the scope of this effort. The details of the design would be the responsibility of the first four sub-task elements. A detailed work plan should be developed once this program is well under way. The expected elements of the WBS involving a logical approach for this flight experiment include the following:

- System Requirements and Production Definition
- Engineering and Analysis
- Component Development and Testing
- Detailed Design
- Hardware Development and Checkout
- Operations Testing and Performance Evaluation in Ground-based Simulators
- Flight System LV Integration
- Mission Flight
- Mission Operations, Data Analysis, and Outreach.

8.2 Schedule

The work of this WBS Element would be conducted over 8 years from FY-2003 through FY-2010.

8.3 Estimated Funding Resources

The estimated funding resources are $207,000 K.

9.0 Lunar Water Ice/H Extraction Facility

As a result of the first Lunar H_2O pilot plant mission to the polar cold traps of the Moon, a great amount of information will be obtained and knowledge gained about the technology and operational approach of extraction. This information will drive the final design of the full-sized extraction facility on the Moon. The work of the program will feed into the definition of this mission. Details will be developed as this program plan evolves.

9.1 Work Statement

Again, this task is a major development flight program and its complete work plan is beyond the scope of this effort. The details of the design would be the responsibility of the first four sub-task elements. A detailed work plan should be developed once this program is well under way. The expected elements of the WBS involving a logical approach for this flight experiment include the following:

- System Requirements and Production Definition
- Engineering and Analysis
- Component Development and Testing
- Detailed Design
- Hardware Development and Checkout
- Operations Testing and Performance Evaluation in Ground-based Simulators
- Flight System LV Integration
- Mission Flight
- Mission Operations, Data Analysis, and Outreach.

9.2 Schedule

The work of this WBS Element would be conducted over 9 years from FY-2004 through FY-2012.

9.3 Estimated Funding Resources

The estimated funding resources are \$170,000 K (through FY-2010) and \$192,000 K (through FY-2012).

10.0 Utilization DDT&E For Lunar Systems That Use Polar Lunar H_2/O

Lunar systems are the primary targeted uses for the lunar ice resource. Since it appears that both fuel and oxidizer can be obtained locally, a reusable transportation system that can reach Moon-orbit space at low cost may be feasible. Ground-based transports could also be powered with propellant derived from lunar water. Water can easily be electrolyzed to produce hydrogen and oxygen, be liquefied and used as propellants. Other transportation systems, such as Moon-to-Earth or a lunar orbiting fueling station may also be feasible.

10.1 Work Statement

This 10.0 WBS Task Element will be conducted after the program has been well established. The purpose of this effort is to perform Design, Development, Test and Evaluation (DDT & E) of systems that will use the H_2/O resource from the Moon. There are three classifications of Lunar systems in the WBS:

(1) Lunar flight and orbital support systems
(2) Lunar ground-based fuel cell or combustion-driven ground transport vehicles
(3) Other lunar base applications using lunar water-ice or hydrogen.

Examples for each of these three categories are listed in Tables 1 and 2 and won't be repeated here. Selection and definition of what systems will be included here should wait until the program has been implemented and the best, cost-effective systems and sub-system approaches have been selected.

10.2 Schedule

The work of this WBS Element would be conducted over 6 years from FY-2005 through FY-2010.

10.3 Estimated Funding Resources

The estimated funding resources are $96,000 K through FY-2010.

11.0 DDT&E for Mars Uses

The use of lunar H_2/O for Mars applications strongly hinges upon the discovery of reasonable amounts of water in the Mars soil. This task is delayed until we should have those answers based on successful Mars lander missions. At a minimum, Lunar H_2/O could be used for the transport vehicles leaving the Earth-Moon systems to Mars. If Mars water is scarce, then there may be many uses of H_2/O as identified in Tables 1 and 2.

11.1 Work Statement

This 11.0 WBS Task Element will be conducted well after the program has been well established and we have better data on the availability of Mars water in the Mars regolith. After a determination of feasibility, this effort would begin establishing a necessary DDT&E effort for systems for Mars mission support that would use H_2/O resources from the Moon. There are three classifications of Mars systems in the WBS; they are:

(1) Mars flight transportation systems and propellant production
(2) Mars ground-based fuel cell or combustion-driven ground transport vehicles
(3) Non-propulsion Mars applications using Lunar ice or hydrogen.

Examples for each of these three categories are listed in Tables 1 and 2 and won't be repeated here. Specific work should wait until more is known.

11.2 Schedule

The work of this WBS Element would be conducted over 5 years from FY-2006 through FY-2010.

11.3 Estimated Funding Resources

The preliminary estimated funding resources are \$16,500 K through FY-2010.

12.0 Other Solar System Transport Vehicles

The use of lunar H_2/O for other solar system transport vehicles may have more significance than Mars transport vehicles. This task should be delayed until there is a mission that is attractive through using lunar H_2/O resources.

12.1 Work Statement

This 12.0 WBS Task Element would be conducted well after this program has been established and we have a better idea of the need and timing of other solar system missions. Examples of transport vehicles and applications in this category are given below.

(1) LH_2/LO_2 Propellants for Main and Auxiliary Chemical Propulsion
(2) O_2 for Solar Electric Propulsion
(3) H_2O for Nuclear Steam Rocket
(4) LH_2 for Nuclear or Solar Thermal Rocket Propulsion.

12.2 Schedule

The work of this WBS Element would be conducted over 4 years from FY-2007 through FY-2010.

12.3 Estimated Funding Resources

The preliminary estimated funding resources are $2,000 K through FY-2010.

13.0 Education and Outreach

Education and outreach to the general public/taxpayers has become an important part of NASA's mission. It would be a vital part of this program. In this task, the information generated by the overall program would be made available to the public. The work statement given below provides an excellent starting point for education and outreach.

13.1 Work Statement

The work of this 13.0 WBS Task focuses on education and outreach. There are a wide range of activities that can be introduced to convey information to the public taxpayers. For this program we have identified the following outreach activities:

- **Curriculum and Educational Materials.** Create materials to be distributed in two forms, classroom materials and materials for individual use.
- **Engineering and ISRU Experiment Design Lessons.** Create materials on the design and function of the individual experiments and ISRU missions, including their construction, the placement and function of all the instrument’s sensors and how this package will accomplish the experiment and production goals.
- **Chemistry Lessons.** Create ISRU materials on the chemistry of the Lunar environment and the processes used to create the H_2O, H_2, H_2O_2, and the chemical uses at the lunar base, etc.
- **Physics and Rocketry.** Create materials on the general concepts of rocketry as they relate to the Lunar H_2/O ISRU Missions.
- **Conventions/Workshops.** Distribute information regarding the program at all regional and National Science Teachers Association (NSTA) conventions as well as some major state conventions.
- **Technical Conferences.** Distribute information regarding the program at national conferences, including AIAA, ASME, SAE, etc.
- **Publications.** Papers written by the Program Public Affairs Officer will be distributed for publication in national Internet, education, and space publications.
- **NASA Educators.** Informational materials will be distributed through NASA Educators.
- **USRA.** Work closely with USRA to distribute information to the universities.
- **Space Grant Consortia and Universities.** Work with space grant consortia and universities to foster direct involvement by school in each state.
- **Direct Mailing.** In conjunction with NSTA, work to conduct a direct mailing to reach physics, chemistry, and physical science teachers who will benefit from the program.
- **Develop Partnerships.** Develop primary public partnerships with AIAA, Planetary Society, National Space Society, Mars Society, NASA Educators, etc.
- **Develop a Web Site.** A web site will be designed to allow teachers, students and the general public easy access to the program's materials and support information.

13.2 Schedule

The work of this WBS Element would be conducted over 10 years from FY-2001 through FY-2010.

13.3 Estimated Funding Resources

The estimated funding resources are $700 K through FY-2010.

14.0 Program Management and Documentation/Reports

This element of the program plan identifies the program management functions and program documentation that are believed necessary to manage and guide the ultimate goals for this program.

14.1 Work Statement

This task, 14.0 WBS has been broken down into the categories given below:

- **Program Management and Coordination.** Top management of the program would be at NASA/HQ, with the majority of the management staff located at the to-be-named NASA Center (obvious candidates include: JSC, KSC, MSFC, ARC, GRC, JPL). The government management team would be responsible for all program planning and program decision planning. All the major program planning charts, documents, road maps would be generated by this team. The management office would have its own dedicated procurement person such that contracts can be let and put in place quickly on either a competitive or non-competitive basis. The program office would involve itself significantly in the Small Business Innovation Research (SBIR) Program and should try to gain 5% of its total budget in additional SBIR work by small businesses. The program office would also use sole-source, competitive, NRA, and AO contracting methods.
- **Budget Control.** The Program office should have excellent budget control of what ever it can. A detailed budget planning software tool should be implemented to support the program.
- **Liaison and Public Affairs.** Liaison with the public and congress is a vital part of this WBS element. With the limits that are imposed upon government employees, the management staff needs to be sure that the public and congress is well informed about the program and its long-term benefits.
- **Reports/Publications/Brochures.** An important part of this activity is to generate well done reports, publications, and brochures. This function needs to make sure that contractor reports are done properly and that they all comply with a standard program report format. There is no need to have to do reports over for public distribution, when proper formats and adequate report input is given back to the contractor.

14.2 Schedule

The work of this WBS Element would be conducted over 10 years from FY-2001 through FY-2010.

14.3 Estimated Funding Resources

The estimated funding resources are $14,500 K through FY-2010.

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