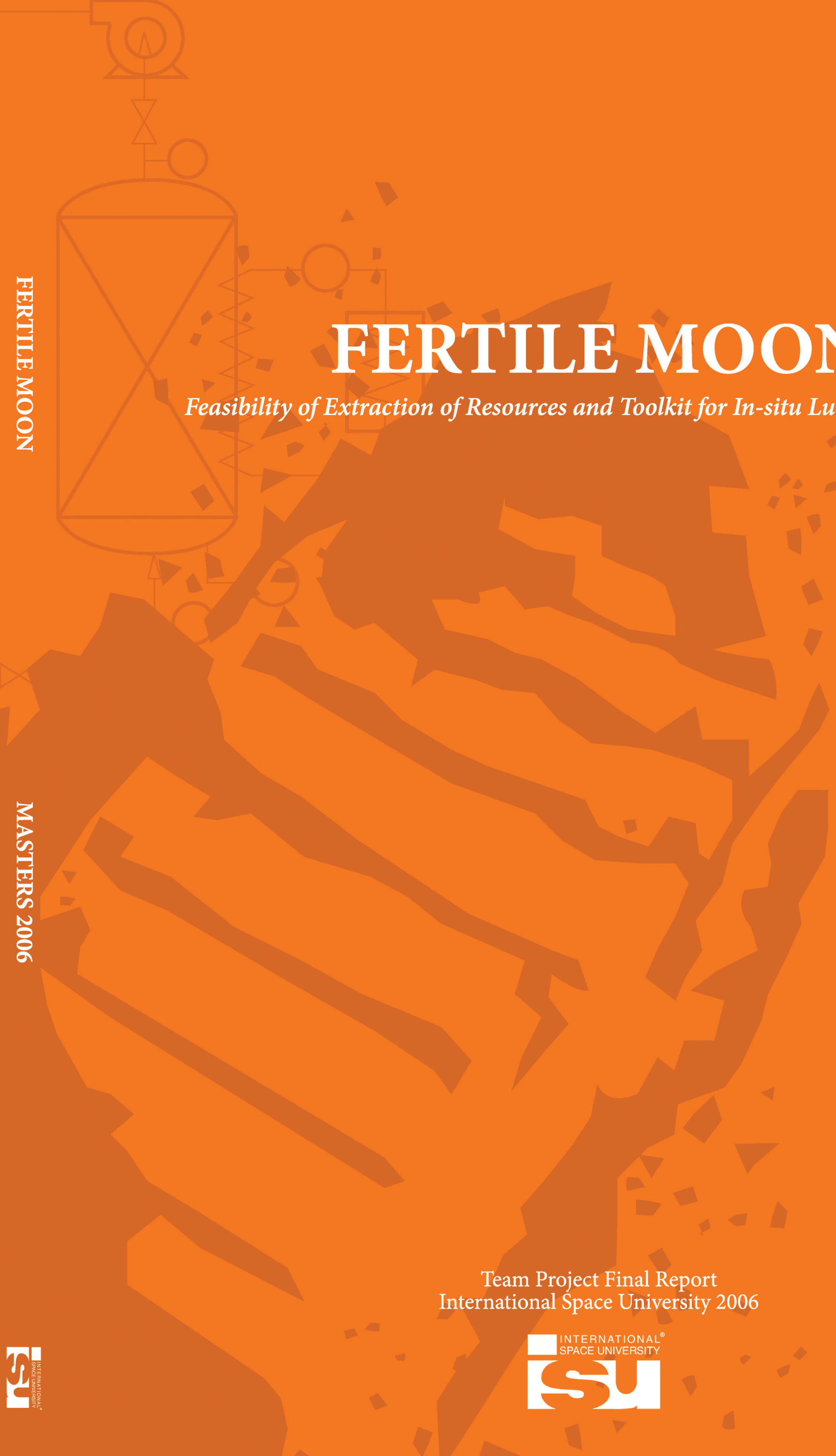

FERTILE MOON

Feasibility of Extraction of Resources and Toolkit for In-situ Lunar Exploration

Team Project Final Report
International Space University 2006

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FERTILE Moon

Feasibility of Extraction of Resources and Toolkit for In-situ Lunar Exploration

Final Report

International Space University

Masters Program 2006

The 2005/2006 Masters Team Project work was conducted at the ISU Strasbourg Central Campus.

An image of a footprint in the lunar regolith and an ISRU process schematic are shown, these represent humanities first use of ISRU technologies to support a lunar mission.

The Executive Summary, ordering information and order forms may be found on the ISU web site at http://www.isunet.edu/EN/77. Copies of the Executive Summary and the Final Report can also be ordered from:

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ABSTRACT

Humanity is beginning its quest to return to the Moon. The focus is not just on returning to the Moon, but on creating permanent settlements. This endeavor will require numerous new strategies in order to succeed. One strategy that is being closely examined is In-Situ Resource Utilization (ISRU) or using resources on the Moon to support these activities. The potential savings of ISRU is unknown since the concept remains in the early stages of development. This report introduces and describes the FERTILE (Feasibility of the Extraction of Resources Toolkit for In-situ Lunar Exploration) Moon Model as a possible aid to those wishing to examine the potential of ISRU.

After the introduction chapter discusses the need for creating the FERTILE Moon Model, the first part of the report discusses the reasoning behind the choice and value for each variable used in the model. Any assumptions that were put into the work are also discussed in these chapters. Not only are the scientific and engineering factors discussed, but also political and legal issues are mentioned. The second part of this report focuses on using the model to perform analysis. Examples are used from each of four lunar exploration development phases to show the potential of the FERTILE Moon Model. These examples are accompanied by discussion on the model's limitations and a sensitivity analysis.

The final section of the FERTILE Moon Report focuses on presenting possible avenues of future work regarding the model. It is the authors' sincere hope that the FERTILE Moon Model will be adapted and improved over the next several years to incorporate new data on ISRU. If the future work is realized, then this model will remain a powerful analysis tool for the foreseeable future.

FACULTY PREFACE

The Bushmen of the Kalahari in southern Africa are one of the most successful hunter-gatherer groups known to anthropologists. Despite living in one of the more arid and demanding environments in continental Africa, they have learned to exploit it to the maximum extent possible. From the dry soil and rugged vegetation they obtain water, food (insects, birds, reptiles, roots, berries), and materials to construct temporary wooden shelters. This environmental awareness and adaptation has not been realized over one, or even ten, generations. In fact, it is known that the Bushmen have lived in this part of Africa for something like 22,000 years. This represents many hundreds of generations of experience "living off the land".

In the context of extraterrestrial environments, this "living off the land" approach is becoming increasingly important. It is referred to as In-Situ Resource Utilization (ISRU), and is the subject of this International Space University (ISU) team project (TP). Rather than the parched Kalahari, the twenty-seven men and women in this TP have concentrated on aspects of ISRU in a substantially more hostile environment: the Moon.

Roughly 25% of students' time during the twelve-month Master of Science (M.Sc.) programs in 'Space Studies' and 'Space Management' is devoted to ISU's well-established interdisciplinary TP. This year, our students had a choice between two very practical projects: "Space weather" (TP1) and "In-Situ Resource Utilization" (TP2). In the first part of the Masters program, both teams completed a comprehensive literature review, which they presented in December, 2005. Based on the knowledge and insight which both teams acquired during this period, they then focused on a specific and innovative aspect of their chosen topic. In the case of TP2, they have developed a ground-breaking modeling tool, the FERTILE Moon Model, which should be of service to space professionals involved in the assessment of future, lunar ISRU activities. The model is fully described and evaluated in this Report. As mentioned, the approach is truly interdisciplinary and the TP considers engineering, scientific, managerial, legal, ethical, and other aspects of future ISRU activities.

An ISRU study on this scale is a substantial undertaking, and could reasonably take some years to develop to its full potential. However, given the constraints that TP2 faced, they have done a very solid job indeed and should be applauded on the overall quality and diversity of their work. It is clear that some members of this TP will work in the domain of ISRU during their professional careers. Like the early ancestors of the Bushmen, they will truly be pioneers of In-Situ Resource Utilization!

Associate Professor Hugh Hill on behalf of the Resident Faculty.

STUDENT PREFACE

We are on the verge of the next great step in human exploration. For the first time, nations are working together to expand the boundaries of civilization to the surface of other celestial bodies. This ambitious plan will require hard work and ingenuity to develop new tools and strategies to support each step. One of the strategies put forth is for our explorers to use the resources available to them in their new locale to achieve their goals. This is the concept of In-Situ Resource Utilization (ISRU).

We are the students of the International Space University's Masters of Space Studies and Masters of Space Management class of 2006. Our team consists of twenty-seven students from fifteen different countries and possesses a wide range of backgrounds to allow a truly interdisciplinary view. Our team strongly supports the goal of furthering human exploration and, to this end; we have chosen to undertake a team project to assist those testing the feasibility of ISRU.

Our project began in the fall of 2005 with a detailed literature review of all topics involving ISRU on the Moon and Mars. The second half of our project has been dedicated to creating a specific tool, the FERTILE Moon Model, to advance the study of ISRU's feasibility with respects to the Moon. We have worked for nine weeks in order to create the framework for this model and implement it in its basic form.

This report discusses what the FERTILE Moon Model consists of and how it can be used to assist in the analysis of ISRU. Trying to create an encompassing, interdisciplinary model in the time frame of this project was a challenging task, but we feel that we have been able to produce an excellent preliminary edition of the FERTILE Moon Model. It is our hope that this will not be the final version, but instead be used as a starting point and modified by future groups in order to ensure a powerful, lasting tool to support humanity on its next great quest to the stars.

- FERTILE Moon Team, Masters 2006, ISU

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LIST OF ACRONYMS

4BMS	Four Bed Molecular Sieve

A

AES	Air-Evaporated System
AMCM	Advanced Mission Cost Model
AR	Aero-Braking

B

BWE	Bucket Wheel Excavator

C

C	Carbon
CaLV	Cargo Launch Vehicle
CCM	Cooperation Cost Multiplier
CEV	Crew Exploration Vehicle
CF	Cooperation Factor
CHX	Condensing Heat Exchanger
CNSA	China National Space Administration
CNES	Centre National d'Etudes spatiales
CNRS	Centre National de la Recherche Scientifique
CO_2	Carbon Dioxide
COSPAR	Committee on Space Research
CRP	Carbothermal Reduction Process

D

DCF	Discounted Cash Flow
DPI	Development, Product, Installation

E

EC	European Community
ECSL	European Centre for Space Law
EDC	Electrochemical Depolarized CO_2 Concentrator
ELISSA	Environmental and Life Support Systems Simulation and Analysis
EOI	Earth Orbit Insertion
ESA	European Space Agency
ESAS	Exploration Systems Architecture Study
EU	European Union
EVA	Extra-Vehicular Activity

F

FEL	Front End Loaders
FERTILE	Feasibility of Extraction of Resources and Toolkit for In-situ Lunar Exploration
FSRI	Florida Space Research Institute

G

GUI	Graphical User Interface

H

H_2	Molecular Hydrogen
H_2O	Molecular Water
He	Helium
HLV	Heavy Lift Vehicle
HRI	Hydrogen Reduction of Ilmenite

I

IAEA	International Atomic Energy Agency
ICB	Immobilized Cell Bioreactor
IPR	Intellectual Property Rights
ISRU	In-Situ Resource Utilization
ISS	International Space Station
ISU	International Space University

J

JAXA	Japan Aerospace Exploration Agency
JSC	Johnson Space Center

L

LCROSS	Lunar Crater Observation and Sensing Satellite
LDC	Lunar Development Corporation
LEO	Low-Earth Orbit
LiOH	Lithium Hydroxide
LLO	Low-Lunar Orbit
LLOX	Lunar Liquid Oxygen
LOX	Liquid Oxygen
LPI	Lunar Planetary Institute
LSI	Lunar Science Institute
LSS	Life Support System
LUBSIM	Lunar Base Simulation Computer Code

M

MF	Multi-Filtration
MR	Mass Ratio
MSEP	Molten Silicate Electrolysis Process
MTCR	Missile Technology Control Regime

N

N	Nitrogen
NASA	National Aeronautics and Space Administration
NPV	Net Present Value
NORCAT	Northern Centre for Advanced Technology
NSF	National Science Foundation

O

OST	Outer Space Treaty

P

PHP	Hypertext Preprocessor

R

RO	Reverse Osmosis
RTG	Radioisotope Thermal Generators

S

SCOM	Space Operations Cost Model
SFWE	Static Feed Water Electrolysis
SMART-1	Small Mission for Advanced Research in Technology 1
SR	Structural Ratio
SQL	Standard Query Language
SWIH	Solar-wind Implanted Hydrogen
SWIS	Solid Waste Incineration System

T

TCC	Trace Contaminant Control
TCM	Trajectory Correction Maneuvers
TFB	Trickling Filter Bioreactor
TP	Team Project
TRASIM	Space Transportation Simulation Model
TRL	Technology Readiness Level

U

UN	United Nations
UNCOPOUS	UN Committee on the Peaceful Uses of Outer Space
US	United States
USA	United States of America
USD	United States Dollars
USSR	Union of Soviet Socialistic Republics

V

VB	Visual Basic
VCD	Vapor Compressed Distillation
VPCAR	Vapor-Phase Catalytic Ammonia Removal

W

WMB	Watson, Murray, and Brown

1 INTRODUCTION

An Analogy To Modeling In-Situ Resource Utilization

A group of people are preparing for a camping trip and have many things to plan and consider. One thing they know is that there are certain resources that they will need to bring. Firewood is one of the resources that the campers will need. Firewood is necessary for camp fires that will keep the campers warm and provide the heat for cooking food. The first question the campers must answer is how they plan to obtain their firewood.

There are numerous options available to campers who need firewood. They can purchase it need in the city before they depart and bring it with them. Or they can purchase the tools needed for using the wood available around their campsite. They would just need to bring the tools with them and then the only limit to the amount of firewood they have would be the amount of wood they can cut down. The campers could even do a combination of the above options. The next question is which option is the best for them.

On the surface, the decision of choosing an option appears as simple as finding out which one costs the least. Finding this out though is a rather complicated process. An example of one of the things that needs to be considered is how much firewood is needed. By investigating this question, the campers will find that the amount is dependent on how many people need to be kept warm and how much food they want to cook. If the campers only require a small amount of firewood, it might be cheaper to purchase the wood instead of the tools, but this might not be true for larger amounts of wood. So, the question remains; how do the campers know which option is the best for their particular camping trip?

If they had been on many camping trips in the past, they would be able to draw on their experience to make a choice, or if they knew people who had been camping in the past, they could ask them for advice. But what are the campers supposed to do if they have never been camping and did not know anyone who had been camping? They would need to find another tool to help them decide.

1.1 What Is In-Situ Resource Utilization?

In-Situ Resource Utilization (ISRU) is using resources from the campsite environment to supply the campers with firewood. ISRU has been referred to as "living off the land" or, more precisely, "using the resources of a place to assist in its exploration" (Portree, 2001). It is a way of supplying humans with the resources needed to survive the ultimate camping trip: the exploration and settlement of space.

With the current National Aeronautics and Space Administration (NASA)-led drive towards returning to the Moon, Mars, and beyond that includes the intention of creating a permanent presence on lunar surface, the idea of ISRU has come to the forefront of the space community. A study on capability roadmaps (Sanders, 2005) was released that defines the purpose of ISRU: "…to harness and utilize space resources to create products and services which enable and significantly reduce the mass, cost, and risk of near-term and long-term exploration".

The large number of different possible resources in space captures the broadness of the above definition of ISRU. In the context of lunar resource utilization, Pieters *et al.* (1999) define "in-situ resources" as "resources existing in the environment, in the atmosphere, or at the surface of a planetary body." For a discussion on all the different resources and options for ISRU, the reader is recommended to refer to the literature review "ISRU for the Moon and Mars" (ISU, 2005). The fact that space has potential resources that can support space exploration is not enough to justify using ISRU; their use must provide benefits over the traditional option of bringing everything that is needed from Earth.

1.2 Why ISRU?

If a group of campers require a large amount of firewood, then it is desirable for them to use the wood available to them at the campsite since the cost of a saw would be cheaper than purchasing all the wood. The same reasoning for chopping wood for a camping trip applies to using the concept of ISRU for space exploration. Instead of having to worry about purchasing the firewood, space explorers need to worry about the cost of launching supplies from the Earth.

The reason ISRU appears as a more favorable option now, compared to the missions to the Moon in the 1960's, is that the goals of space exploration have evolved. In the 1960's, the goal was to put men on the Moon, but there was no thought of them staying any longer than a few days. Now, countries are not only looking at sending people to the Moon, but having them stay and even settle there. The demands for these missions are much higher. For the first time, the high level of requirements for these types of missions makes alternatives to terrestrial supply attractive.

NASA has made a call for people to examine these alternatives and noted that in order to succeed in this next generation of space exploration, countries need to develop and use "innovative technologies, knowledge, and infrastructures" (NASA, 2004). ISRU is one of these innovative technologies and the Moon is the first place available for its implementation.

While lunar resource utilization can allow for a sustainable human presence beyond the Earth's orbit and reduce the cost of space missions, the effects and benefits of ISRU in different space exploration scenarios still need to be studied and analyzed (Diaz, 2005). This lack of certainty, along with the fact that ISRU has never been proven, makes it difficult for mission planners to begin considering it as an alternative to terrestrial supplied missions. To help the evolution of space exploration, the potential of ISRU needs to be better analyzed and new tools need to be developed to help in this analysis.

1.3 Using Modeling as a Tool for Analysis

In order to prove that ISRU is a feasible option for space exploration, it must compare well in terms of cost with more conventional options such as having 100% of the required resources supplied from Earth. To compare all the involved processes, it is necessary to analyze each one, or in other words, break each complex process into its simpler components. By varying these components, it is possible to see their effect on the cost of the process as a whole, which can help in the overall comparison. There are many tools to help people with this analysis. One tool is doing experiments and tests of the relevant systems; however, many systems are difficult to test. This is especially true for designing and testing equipment that needs to operate in extraterrestrial environments. Some times the systems cannot be physically accessed or the cost of running the systems for experiments in prohibitively expensive, whish is the case for ISRU. It is not feasible to run separate missions to the Moon to simply test the importance of a single variable on the cost of ISRU. Therefore, other tools are needed to assist in the analysis. One of these tools is the process of computer modeling.

A computer model is a powerful tool to investigate and analyze the effect of different variables and processes on a system that cannot be disturbed or physically handled. The strength of a model exists in its ability to test various scenarios and to increase the user's understanding of the overall system performance and cost. The influence of an input parameter on important outputs can be studied as often as necessary without the user having to deal with the costs of launching space missions. This is of interest as a small change on a mission requirement can have considerable and unpredictable consequences on the overall mission cost. The benefit of using a model to run simulations is that it allows the users to examine months and even years of activity in just the few minutes needed to compute the results.

It is not just the cost of running ISRU experiments that prohibits ISRU from becoming a regular part of future space missions; it is also the current way of thinking in the space industry. ISRU is an undeveloped concept and mission planners are very hesitant to include any processes that have not been proven previously in space. A problem arises since there have been no tests or missions involving ISRU, mission planners cannot rely on the use of ISRU technology to guarantee a missions success. A computational model can help to demonstrate whether or not ISRU is feasible and indeed cost-reducing for missions to the Moon without having to fly a single mission. This benefit of modeling is not a new concept, which is why several models have already examined ISRU and some related technologies in the past.

1.4 Background on the Moon and Related Models

Before discussing various models of ISRU on the Moon, it is necessary to understand the background knowledge that creates their foundation. Humanity's knowledge of the Moon is based mainly on the laboratory analysis of returned samples and on robotic exploration.

Regolith (lunar soil) samples were brought back to Earth by the United States' Apollo missions and the Soviets' Luna missions in the late 1960's and in the 1970's. The samples of lunar regolith are the main source of information about lunar geology and have provided a large portion of the knowledge of the lunar surface that exists today. Four major minerals, well-known to Earth geologists, and their sub-compositions, or 'end members', have been deduced from laboratory analysis of the returned samples, these are shown Table 1-1. It is important to note the presence of oxygen in all of the minerals noted in this table.

Table 1-1: Mineral Composition of Mare Regolith (Sanders, 2005)

Mineral	% of Regolith	End Members of Mineral	
Pyroxene	50%	$CaO \cdot SiO_2$	36.7%
		$MgO \cdot SiO_2$	29.2%
		$FeO \cdot SiO_2$	17.6%
		$Al_2O_3 \cdot SiO_2$	9.6%
		$TiO_2 \cdot SiO_2$	6.9%
Anorthite	20%	$CaO_2 \cdot Al_2O_3 \cdot SiO_2$	97.7%
Ilmenite	15%	$FeO \cdot TiO_2$	98.5%
Olivine	15%	$2MgO \cdot SiO_2$	56.6%
		$2FeO \cdot SiO_2$	42.7%

Along with the Apollo-era samples, satellites and robotic exploration missions have gathered information on the Moon. The key missions in gathering information include NASA's Clementine mission and Lunar Prospector mission as well as ESA's SMART-1 mission. These missions have supported the theory that the makeup of the regolith is also affected by micrometeorite impacts and the solar wind, which can impregnate the regolith with hydrogen or helium ions (Cameron, 1993). The concentration of these volatiles is shown in Table 1-2. These missions have also made the cold traps, the permanently shadowed areas in the craters of the South Pole, particularly interesting. It is possible that water exists in these areas in the form of ice. This concept was first brought up by the discovery of excess hydrogen at these areas by the Clementine and Lunar Prospector missions (Feldmann et al., 1998). Unfortunately, this data is not definitive in terms of proving whether the extra hydrogen is excess elemental hydrogen implanted by solar winds or if it exists in the form of water.

Table 1-2: Lunar Volatiles (Solar Wind and Water/H_2) (Sanders, 2005)

Volatile	Concentration
Hydrogen (H_2)	50 - 150 ppm
Helium (He)	3 - 50 ppm
Helium-3 (^3He)	10-2 ppm
Carbon (C)	100 - 150 ppm
Polar Water (H_20/H_2)	1 - 10%

There are also several other missions planned for the next decade that will improve and verify the data available on the composition of the Moon. The lack of conclusive data on the cold traps of the Moon highlights the fact that there is a lack of information on the make-up and geochemistry of the lunar surface. While theories and assumptions have been made throughout the scientific community, it should be realized that until further data has been gathered, the Moon's surface composition is still incompletely mapped. For further information the reader is directed to the literature review entitled "ISRU on the Moon and Mars" (ISU, 2005).

This base of lunar knowledge is the foundation on which several models have been created to analyze the possibility of using the resources on the Moon to support human space exploration. The first simulation model of the entire life cycle of a lunar mission (Koelle & Johenning, 1982) was called LUBSIM and simulated the mass flow, power, and manpower requirements of an advanced lunar base. The next model to be developed was a parametric cost model (Simon, 1984) that analyzed the production of liquid oxygen on the Moon. Simon also conducted a sensitivity analysis to evaluate alternative approaches and recommend certain near-term technology development activities. In 1989, Koelle developed a transportation simulation model, TRASIM, to analyze a fleet of space vehicles for an entire lunar base life cycle (Koelle, 1989). Since 1989, Koelle refined and used his latest work with Simon's model to study issues concerning the production and use of lunar propellant for surface and space vehicles (Koelle, 2003).

The next generation of lunar models started seven years after TRASIM when a parametric lunar base model (Eckart, 1996a) was developed that integrated all of the lunar base systems. His model focused on the annual re-supply masses of a small lunar base at different locations, thus identifying the systems (and subsystems) having the greatest mass impact on the overall base. In 1997, he studied the benefits and costs of manufacturing lunar products (propellants, raw material, feedstock and other selected products) on the lunar surface as well as the operation and performance of an extraterrestrial facility. In 2002, Blair et al. developed a model that integrated both an engineering and financial model to study the production of propellant from the water held in permanently shadowed lunar craters and to identify the technical and financial conditions under which such an endeavor could become financially viable (Blair et al., 2002).

Recently, additional models are being developed to expand and supplement those previously created. The Colorado School of Mines is working on the development of a model showing the potential ISRU production capabilities. This model is used to evaluate and compare the effects of ISRU for different lunar and Martian architectures (Diaz, 2005). The most recent development in lunar ISRU modeling is the creation of the FERTILE Moon Model.

1.5 The FERTILE Moon Approach

The FERTILE Moon Model has been developed to evaluate the economic feasibility of lunar ISRU technologies for hydrogen, oxygen, and water production. Engineering, scientific, financial, legal, and political inputs are used to compare and define break-even points between different ISRU solutions and a terrestrial solution based on costs. The focus on hydrogen and oxygen production was motivated by the fact that both can be used as propellant in chemical propulsion. Propellant production appears to be the first step in the development of a lunar base as it could allow for a decrease in the costs of importing the necessary equipment, materials and supplies to the Moon (Duke et al., 2005). According to recent studies (Siegfried & Santa, 1999), the availability of propellant on the Moon would reduce the total mass of a spacecraft traveling from Earth to Low-Earth Orbit (LEO) by more than a factor of two. The production of oxygen and hydrogen is not limited to propulsion purposes, but can also be used as life support consumables. Similarly, production of water from lunar resources is essential for life support systems (Duke et al., 2005).

One reason that this model differs from all the models developed in the past is that it does not limit itself to engineering or economic aspects, but considers legal and political aspects as well. It attempts to offer an innovative and interdisciplinary perspective. The FERTILE Moon Model helps in assessing the feasibility of different lunar mission scenarios and can assist in decision making for future lunar missions.

Attention was also paid to ensuring this model is a versatile and expandable tool. These traits are necessary because the concept of ISRU is still in its infancy. Not only is there limited knowledge on the specifics of ISRU, the possible uses and overall architectures involving ISRU are not completely known. Therefore, the FERTILE Moon Model must be able to look at the largest possible set of scenarios while being able to incorporate new ideas and knowledge as it becomes available.

The FERTILE Moon Report has been designed to follow a logical flow similar to that of the FERTILE Moon model architecture. This report consists of three connected parts that describe and discuss the FERTILE Moon Model. The first part of the report peels away the layers of the model to describe the functions and underlying theories. The second part focuses on the actual analysis of ISRU processes using the FERTILE Moon Model as the main tool. The third part takes the knowledge gained in the creation and use of the model and discusses what future work can be done to improve the accuracy of the results as more information becomes available in the future.

The “Modeling” chapter introduces the model and shows how it can be used as a tool for analyzing ISRU. The overall flow of the model and its three main layers are introduced before the discussion goes into more detail of each specific layer. The chapter finishes up with a discussion on the limitations of the FERTILE Moon Model.

The “Demand” chapter outlines the oxygen, hydrogen, and water requirements for various mission scenarios. This chapter assumes that there will be a similar minimum demand for hydrogen, oxygen and water no matter how the mission is supplied; be it done terrestrially or through ISRU. The first section of Chapter 3 outlines the demand produced in terms of the need for “return home” propellant, while the second section examines various life support systems.

The “Supply” chapter describes two different supply options as well as the processes, equipment, technologies and costs associated with them. The first section of the chapter analyze the factors demand the more conventional processes of supplying missions that involve bringing the resources needed from Earth. Once the options for terrestrially supplying a mission have been described to give the reader a baseline, the chapter moves onto discussing the various ISRU processes that are included in the FERTILE Moon Model as well as describing other factors for enabling ISRU.

The “Costing" chapter introduces the strategy behind the costing equations for the different elements that have been introduced in previous chapters. The first set of cost values in this chapter are given to the supply from Earth option; these values are mainly for the current launching costs of payload mass (bringing the resources from Earth) and for the electrolysis of water costs. The second set is the difficult task of costing the ISRU processes, the cost for this set have been divided to two categories, capital costs and operating/recurring costs. Capitol costs breakdown to many sub costs such as development, production, and installation costs. Operating/recurring costs breakdown as well to many sub costs such as spare parts, labor, mining and more. These cost values are extensively utilized in the analyses section for the feasibility assessment of ISRU.

The “Political, Legal, and Ethical Aspects” chapter moves the discussion to the more unconventional disciplines in terms of creating a model. One of the strengths of the FERTILE Moon Model is its attempt to examine how political, legal, and ethical issues affect ISRU. The reasoning and implementation of an international cooperation matrix into the model is first discussed. This is followed by a look at the inclusion of one of the more ‘black and white’ legal concerns, export control, into the model. Since not all legal issues can be answered by simple equations, the model was accompanied by a legal risk survey which is used to discuss the bounds created on ISRU by international laws. Similar to the 'fuzzy' issues of the legal ramifications, ethical concerns are discussed in terms of how they affect the feasibility of ISRU. The final section in this report briefly outlines some of the ethical issues that will affect the feasibility of ISRU. This chapter wraps up the description of the model and allows the report to move on to a discussion of how the FERTILE Moon Model can be used in the analysis of ISRU.

The "Analysis" chapter uses the FERTILE Moon Model as a tool to compare the various ISRU processes for different scenarios. This chapter shows the strengths of the model by discussing the various phases of a lunar ISRU architecture. Charts and graphs are presented to demonstrate the outputs from the model. Throughout the discussion, the boundaries and credibility of the analysis process are kept in mind and discussed. These boundaries highlight areas of improvement for the model which is discussed in the final part of the report.

The "Conclusions and Recommendations" chapter summarizes for the reader the main features and rationale that were applied to every layer in the model. The second part of this chapter is dedicated to showing what improvements could be made over the years to keep the model up to date. But first, Chapter 2 will introduce the reader to the overall structure of the FERTILE Moon Model.

2 MODELING

As described in the introductory chapter, the purpose of the FERTILE model is to aid the analysis of the feasibility of ISRU processes. The objective of the model is to create a decision making tool for ISRU that focuses on the demand, supply and cost of three resources. Hydrogen, oxygen and water were chosen due to their importance in early stages of lunar development.

Attention was paid to ensure that the model is a versatile and expandable tool. These traits are necessary because the concept of ISRU is still in its infancy. Not only is there limited data about ISRU, the possible uses and overall architectures involving ISRU are not completely known. Therefore, the FERTILE Moon Model must be able to address the largest possible set of scenarios while being able to incorporate new knowledge as it becomes available. The nature of the FERTILE Moon Model also incorporates an interdisciplinary perspective, simulating aspects of lunar missions including engineering, scientific, legal, political, economical, and ethical issues to provide the most comprehensive results.

Although the goals of the model were identified early in the development stages, integrating interdisciplinary issues is quite complex and has significant impacts on the model design. This chapter will describe how the FERTILE Moon Model was created, beginning with model development. Then it will be followed, in Section 2.2, by an overview of the model and its architecture and flow. Once the reader has the basic outline of how the model works, the chapter will move into introducing each of the three layers of the model: supply, demand, and costing, in sections 2.3 to 2.5 respectively. This will be followed by a section on the limitations of the FERTILE Moon Model before the Modeling Chapter concludes with a summary of what has been presented in Section 2.7.

2.1 Development

The decision to create the FERTILE Moon Model using Microsoft EXCEL™ with a limited amount of Visual Basic Code was chosen over two other options: Microsoft Access and PHP with SQL Server. This decision was based on several evaluation criteria as identified by the development team.

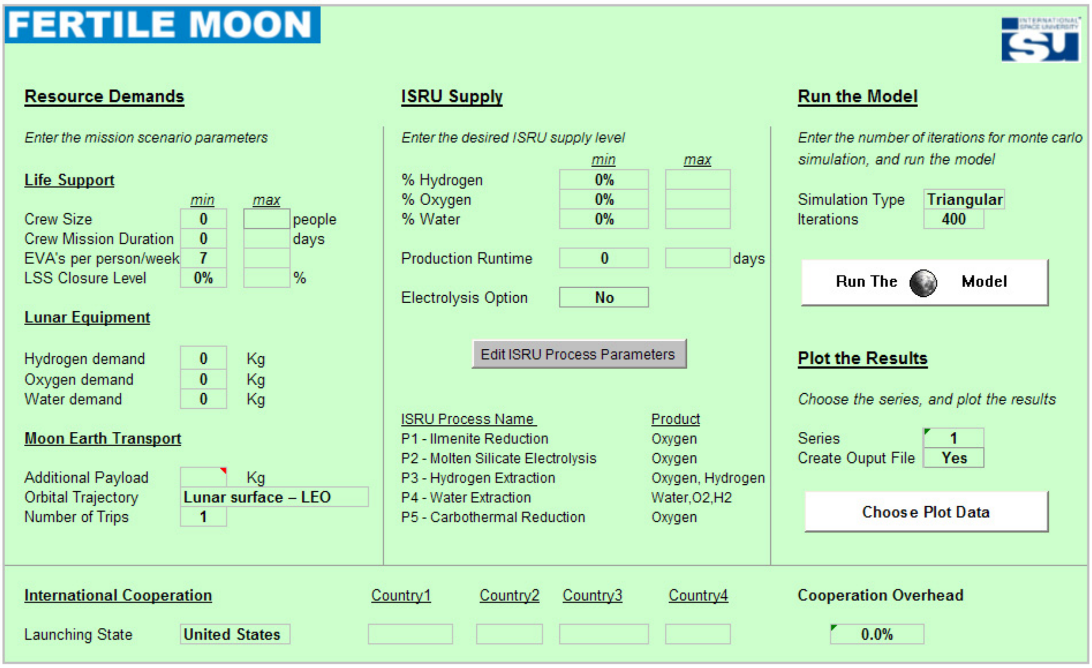
The following criteria were seen as key factors in the decision of choosing a modeling platform are listed below and their corresponding values are summarized in Table 2-1.

- Ease of Use: Due to the wide range of professionals that this model is being distributed to, it was not possible to assume any specific expertise in computing
- Ease of Development: To make updating the model easy
- Distribution: To make the project easy to widely distribute
- Performance: There was no demand for extremely powerful modeling options
- Future Extension: One of the features of the model is that it can be updated as new information becomes available
- Transparency for the User: This is required to allow users to verify the results of the model.

Table 2-1: Evaluation Criteria for Model Platform

	Ease of Use	Ease of Development	Distribution	Performance	Future Extension	Transparency for the User	Overall Score
EXCEL with limited use of VB Code	9	10	8	3	9	10	49
EXCEL with extensive use of VB Code	9	8	8	5	8	8	46
Access	8	6	9	6	8	7	44
PHP with SQL Server	8	6	9	6	7	5	41

One of the benefits of using Microsoft EXCEL is that it has a built in Graphical User Interface (GUI). This GUI allows the user to easily input all their desired parameters and run the model all from one screen as shown in Figure 2-1.



Enter the mission scenario parameters

Life Support

	min	max	
Crew Size	0		people
Crew Mission Duration	0		days
EVA's per person/week	7		
LSS Closure Level	0%		%

Lunar Equipment

Hydrogen demand	0	Kg
Oxygen demand	0	Kg
Water demand	0	Kg

Moon Earth Transport

Additional Payload		Kg
Orbital Trajectory	Lunar surface – LEO	
Number of Trips	1	

Enter the desired ISRU supply level

	min	max	
% Hydrogen	0%		
% Oxygen	0%		
% Water	0%		
Production Runtime	0		days
Electrolysis Option	No		

ISRU Process Name	Product
P1 - Ilmenite Reduction	Oxygen
P2 - Molten Silicate Electrolysis	Oxygen
P3 - Hydrogen Extraction	Oxygen, Hydrogen
P4 - Water Extraction	Water,O2,H2
P5 - Carbothermal Reduction	Oxygen

Enter the number of iterations for monte carlo simulation, and run the model

Simulation Type	Triangular
Iterations	400

Choose the series, and plot the results

Series	1
Create Ouput File	Yes

International Cooperation

		Country1	Country2	Country3	Country4	Cooperation Overhead
Launching State	United States					0.0%

Figure 2-1: FERTILE Moon Model's Graphical User Interface
This screen allows the user to input various mission parameters and access the model's results.

2.2 Overview

The goal of the FERTILE Moon Model is to evaluate the total costs for varying supply options based on different mission scenarios. The user has the ability to change three sets of inputs to set up the desired mission scenario. Figure 2-2 shows how each set of inputs focus on a particular layer of the model. The three layers of the FERTILE Moon Model are: the Demand Layer, the Supply Layer, and the Costing Layer. The internal components of each layer focus on calculating and estimating a different part of the process, but all three layers need to work together to create the desired outputs of the total costs of various supply options.

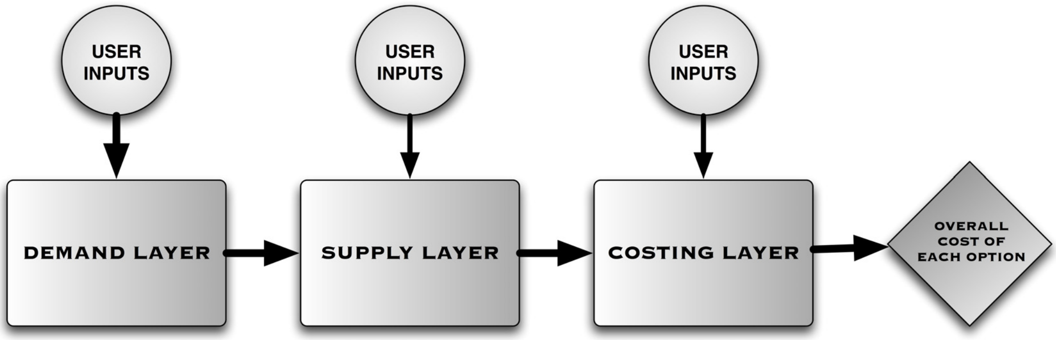


Figure 2-2: An Overview of the Processes in the FERTILE Moon Model

While the overall process behind the FERTILE Moon Model appears simple, each layer contains formulas and equations that use the relevant user inputs to create the necessary information for the next stage. The Demand Layer evaluates the overall demand for oxygen, hydrogen and water based on the inputted mission parameters. This information is then passed to the Supply Layer, which evaluates several parameters related to supplying the resources necessary to meet the calculated demands. These parameters are based on the relevant inputs that define what supply options are used. The Supply Layer then passes these parameters to the Costing Layer which calculates the total cost of each option from the information collected. The outputs of the Costing Layer can then be used to create graphs which will help analyze the feasibility of ISRU as discussed in Chapter 6.

2.3 Demand Layer

The Demand Layer is the first step in the FERTILE Moon Model and is dependent on the inputted mission parameters and predefined constants. There are three subsets of inputs that affect the Demand Layer: transportation, life support systems and excess demand. Each one of these is made up of individual inputs that have effects on the total demand of hydrogen, oxygen, and water as shown in Figure 2-3.

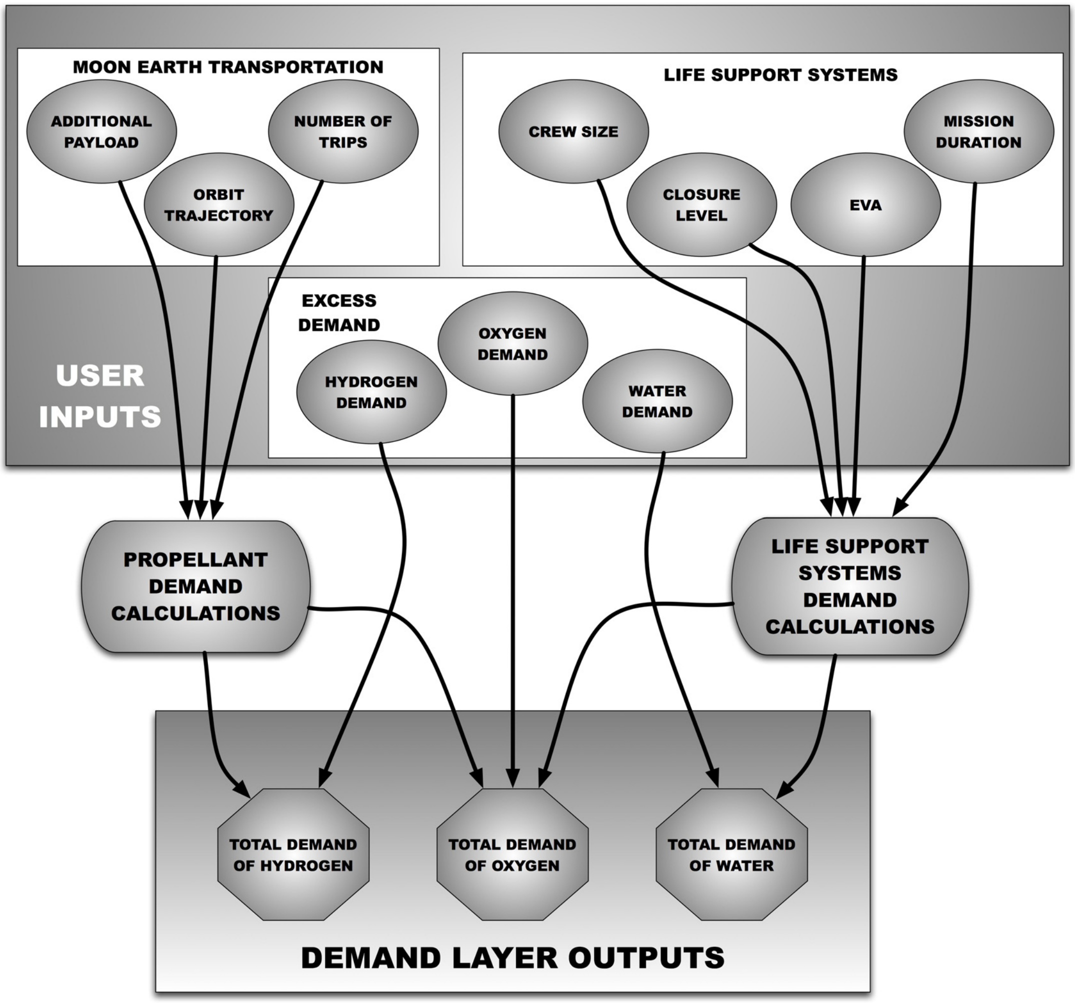


Figure 2-3: The Components of the Demand Layer

The Demand Layer determines the total mass, in kg, of oxygen, hydrogen, and water required for a particular lunar mission. The final Demand Layer outputs are calculated by adding up the three subsets described earlier. The excess demand subset is relatively simple as the user directly inputs the mass of each resource needed during the mission (e.g. for re-supply, as a reagent, etc.). The other two subsets, transportation and life support, combine their respective inputs with specific constants for use with specific Demand Layer equations to calculate the respective portion of the overall demand. A discussion of these calculations, focusing on the theory and reasoning behind the equations, is found in Chapter 3.

2.4 Supply Layer

Once the requirements for each of the three resources are calculated by the Demand Layer, it is necessary to use these values to calculate all the relevant parameters for supplying the resources. This is the job of the Supply Layer, which uses the demand outputs with several user inputs to calculate the necessary values as shown in Figure 2-4.

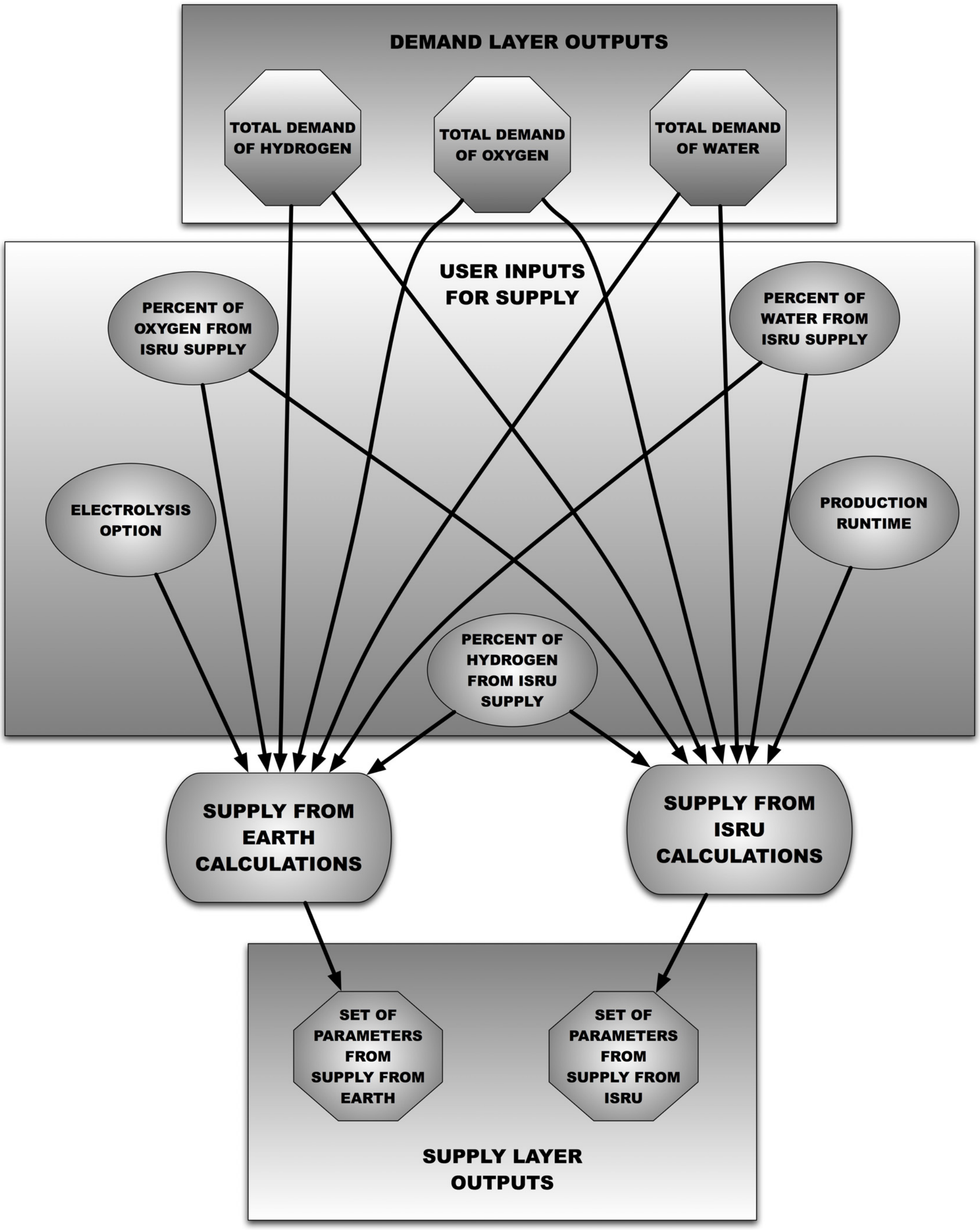


Figure 2-4: The Components of the Supply Layer

This layer is where one of the best examples of the FERTILE Moon Model's versatility exists. As the figure above shows, three of the user inputs for the Supply Layer relate to the amount of ISRU that will occur on the specific mission. ISRU processes are undeveloped at present and it is highly unlikely that any missions in the near future will be completely supplied in-situ. A model that only compares completely terrestrially supplied missions to completely in-situ supplied missions would be flawed and of limited use. These inputs also provide a tool for users to analyze whether or not there is a balance, between ISRU and conventional supply methods, which will be best for the mission.

The demand requirements are split between the two options for supply based on the inputted percentages for each resource. The Supply Layer then performs calculations using these values along with relevant constants and other inputs, which determine certain lower level options, and define the parameters for each supply from Earth and supply from ISRU. The parameters for the ISRU supply portion are calculated for five specific processes to assist in the analysis of each option. This is another level of versatility and ability to adapt that the FERTILE Moon Model has. The model is not confined to a single ISRU process, since there are still many theoretical processes that could be used, and other processes can be added as they become important. A discussion of these processes and the calculations, focusing on the theory and reasoning behind the equations, is found in Chapter 4.

2.5 Costing Layer

The Costing Layer is where the FERTILE Moon Model turns its internal set of parameters into useful information that can assist in the analysis of the feasibility of ISRU. The Costing Layer takes the outputs of the Supply Layer and integrates them into several costing equations to calculate the cost, in United States Dollars (USD), of supplying the particular mission with the required amount of supply from ISRU and the specified amount of supply from Earth, as shown in Figure 2-5. In order to make analysis easier and more complete, the FERTILE Moon Model costs the use of ISRU for each process (see Chapter 4 for description of these processes) that is in the model. Along with each ISRU process, the model calculates a baseline case for the mission that does not include any supply from ISRU. This is done in order to analyze the advantages of disadvantages of each ISRU process in terms of cost.

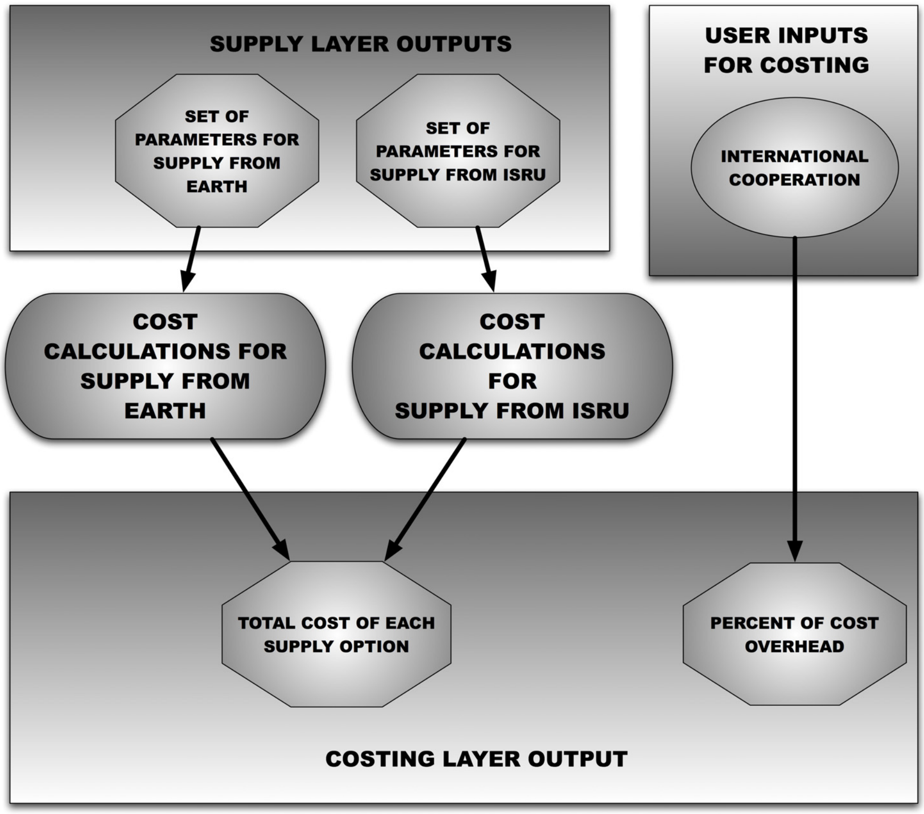


Figure 2-5: The Components of the Costing Layer

Along with applying internal equations to the supply parameters to calculate the total costs, the Costing Layer is where the interdisciplinary aspect of the FERTILE Moon Model takes effect. The Costing Layer incorporates user inputs regarding international cooperation and the countries involved in the specific mission to create an overhead cost that is important in costing actual mission instead of just theoretical ones. There is also a check performed with respect to the legality of the specific mission based on export control issues. These interdisciplinary aspects are discussed in Chapter 5 and further discussion on further inclusion of legal, political, and ethical aspects occurs in Chapter 6. A discussion into the reasoning behind the equations of the Costing Layer is presented in Chapter 5.

2.6 Limitations

Similar to all models that have been developed, the FERTILE Moon Model has several limitations. The restrictions of this project's timeframe and scope have placed several limitations on the model. This led to the FERTILE Moon Model focusing on the production of hydrogen, oxygen, and water. There is no discussion or analysis of the other elements and resources that can be achieved through ISRU even though all the resources, including hydrogen, oxygen, and water, are connected by common elements such as regolith collection and processing. A similar limitation was the restriction of the current model to a certain level of complexity such as incorporating only five ISRU processes. Also, the integration of the interdisciplinary aspects was kept to a minimum, as the "fuzzy issues" of law, politics, and ethics can be difficult reduced to equations.

The other difficulty that led to limitations of the model was the fact ISRU processes are underdeveloped technologies, the amount of accurate data is either extremely limited or non-existent. Due to this high variability and lack of accuracy or information for some of the variables, it was decided to implement a statistical simulation method called Monte Carlo.

This restriction causes the model to only provide the user with trends and estimations and no exact results. The lack of accurate information has caused several assumptions to enter the model. These assumptions are discussed in Chapters 3 to 5. Since ISRU is not highly developed and is currently a hot topic in the space community, the model's timeframe is limited to the years: 2005 – 2035. As more complete date is produced and new ideas are created in the space community, the FERTILE Moon Model will become outdated. However, because of the model's ability to be easily adapted, the implementation of the future work discussed in final chapter of this Report, has the possibility of allowing the FERTILE Moon Model to be a critical tool in the analysis of ISRU for many years to come.

2.7 Summary

This chapter introduced the FERTILE Moon Model's structure, development process, layers, versatility and limitations. The model uses excel spreadsheets with embedded visual basic code to ensure easy and widespread use. In order to incorporate user inputs for various mission scenarios and phases, the FERTILE model was divided into 3 layers; demand, supply, and costing. Each of these layers allows user inputs and contains the equations necessary to calculate the relevant data. The flow of the layers are in such that the Demand Layer feeds into the supply which in turn feeds into the Costing Layer to output results that allow the user to compare the various processes on all layer levels

At this point, the reader should have an overview of the FERTILE Moon Model and should be ready to examine the internal equations and theories for each specific layer. The following chapters will examine these aspects in detail before undertaking the analysis of different mission scenarios for four phases of lunar development.

There are also two additional sources of information available on the use and structure of the FERTILE Moon Model. The copy of the model, which can be found on the FERTILE Moon CD or the website, http://www.fertilemoon.com, is accompanied by a User Manual. This manual focuses on instructing the user how to navigate the GUI and how to create any plots that may assist in their analysis.

3 DEMAND

The first step to creating a model to help analyze the feasibility of ISRU is to determine the mass required for each resource. For the FERTILE Moon Model, it is the Demand Layer that calculates the required amounts for hydrogen, oxygen, and water. As shown in the figure, there are three set of user inputs for the Demand Layer. The first set is used to calculate the hydrogen and oxygen demands for transportation from the Moon back to Earth. The second set is used to calculate the oxygen and water demands for Life Support Systems (LSS). The final set is direct inputs that account for any excess requirements the user may have. The sum of the requirements for these three sets of inputs creates the total mass required for hydrogen, oxygen, and water.

As mentioned earlier, propellant production appears to be the first step in the development of a lunar base. In-situ propellant production can help in reducing the cost of transporting equipment and resources during interplanetary travels and is thus of primary interest to any lunar mission planer (Zubrin, 1996). Life support systems are also essential to ensure a sustainable human presence on the Moon. Many plans for returning to the Moon include the idea of having people living for extended periods and, because of this, it is important to examine how ISRU affects the oxygen and water requirements for the life support systems.

This chapter will discuss the two components of demand in the FERTILE Moon Model: the Moon to Earth transportation demands and life support system demands. For transportation, the three possible mission types will be examined in Section 3.1.1. This will be followed by a description of how the FERTILE Moon Model uses this information to work out the hydrogen and oxygen demands from the amount of propellant needed. The transportation section will finish with a discussion of the relevant limitations. The life support system requirements will be discussed in Section 3.2. The three classes of life support systems used by the FERTILE Moon Model are explained before a discussion on how water and oxygen demands are met. The section closes with a discussion of assumptions and limitations regarding life support systems.

3.1 Transportation Propellant Demands

The FERTILE model integrates the in-situ production of propellant by determining the amounts (in kg) of hydrogen and oxygen that would be required in various mission types for returning supplies from the Moon to Earth. With its focus on being as versatile as possible, the FERTILE Moon Model allows the propellant demands to be calculated for a range of payload masses based on the user's requirements. The model also allows calculations for three different return trip mission types. The overall mass of the propellant is a function of the orbits involved, the trajectory used, spacecraft mass, and propellant characteristics as shown in Figure 3-1.

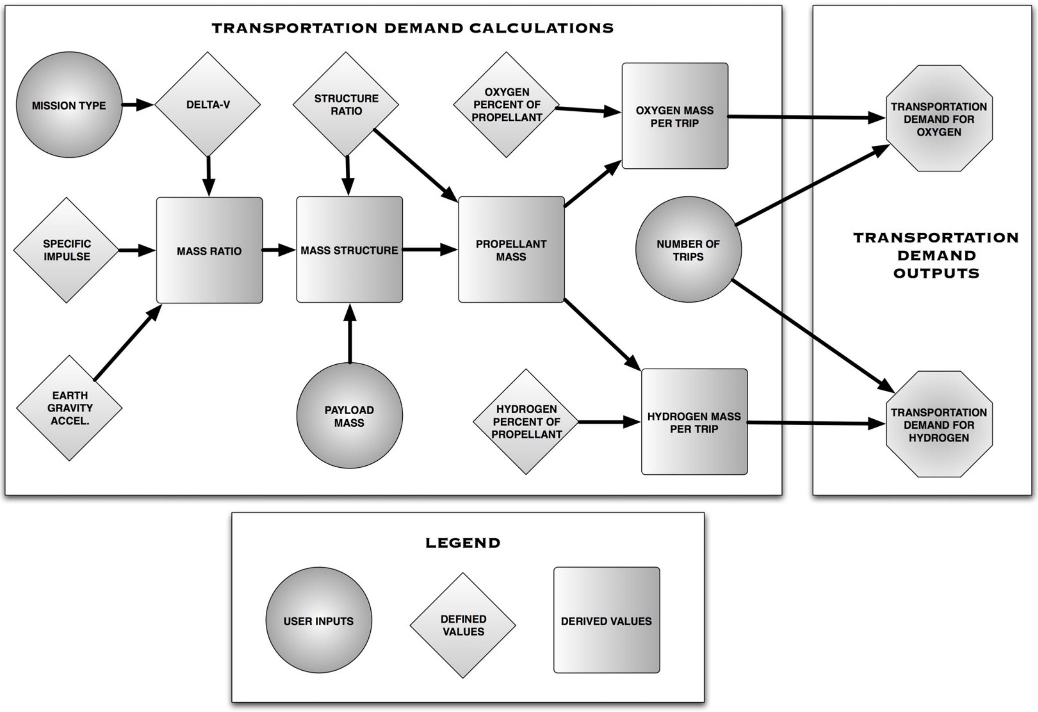


Figure 3-1: The Moon to Earth Transportation Demand Calculations

3.1.1 Mission Types Considered

Many space agencies are considering plans that involve space stations in Low Lunar Orbit (LLO) or Low Earth Orbit (LEO) to support interplanetary space travels by allowing tasks such as re-supply. In order to allow for as much versatility as possible, the FERTILE Moon Model allows the user to choose one of three mission types for which the resource demands will be calculated. It is assumed that LLO is 100km of altitude and LEO is 400km. The three mission types that can be investigated are:

- Lunar Surface to LLO (Scenario 1): This mission type accounts for the transportation of payloads from the surface of the Moon to LLO. This calculation can be useful in examining the possibility of re-supplying an orbiting spacecraft or space station.
- LLO to LEO (Scenario 2): This mission type accounts for the transportation of payloads from LLO to a space station in Low Earth Orbit (LEO). This calculation can be useful in examining returning from a lunar orbiting spacecraft to Earth assuming a rendezvous at an Earth orbiting space station to transfer into a re-entry vehicle.
- Scenario 3 - Lunar Surface to LEO: This scenario is a combination of the previous two, representing a complete trip from the lunar surface to LEO for a payload. (Figure 3-2)

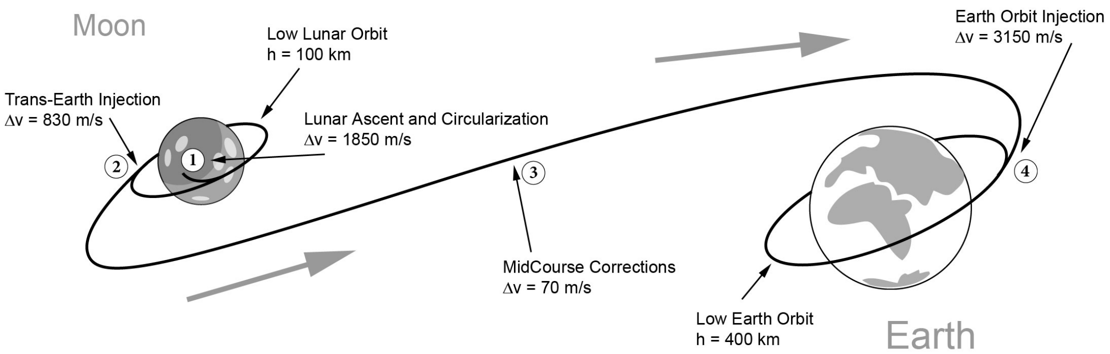


Figure 3-2: Generic Trajectory Used to Travel from the Lunar Surface to LEO

The trajectory shown above can be divided into four steps representing the different maneuvers planned for a typical Hohmann transfer. These steps are described as follows:

1. Lunar Ascent and Circularization: The vehicle lifts off the surface of the Moon and enters into LLO.
2. Trans Earth Injection: The spacecraft reaches the lunar escape velocity and sets its course towards the Earth with an elliptical trajectory.
3. Midcourse Maneuvers: Small trajectory corrections are performed.
4. Earth Orbit Injection: The spacecraft performs a braking maneuver for its final insertion into LEO.

Among the several orbit transfer techniques existing, the Hohmann transfer is the most efficient way for a spacecraft to transfer from one's planet to another and was therefore selected for use in the FERTILE Moon Model. The transfer time considering such a technique is about 5 days with a delta-V of approximately 4 km/s.

The delta-V is defined as the total change of speed required to change from one orbit to another. The delta-V values used by the FERTILE Moon Model are taken from standard average values used in previous missions and may include a safety margin. It should be noted stand values were used because the complexity of incorporating such aspects as departure dates was beyond the scope of this current project. For the same reasoning, it is assumed that there is no inclination changes involved in the mission types.

The delta-V budget used in the FERTILE Moon Model for the four steps is shown in Table 3-1.

Table 3-1: Delta-V values for Steps in Moon to Earth Transportation

Step in the Return to Earth	Delta-V (m/s)
Lunar Ascent	1800
Circularization	50
Trans Earth Injection	830
Midcourse Maneuvers	70
Earth Orbit Injection	3150

Based on the delta-V values calculated above, the delta-V budget for each mission type used in the FERTILE Moon Model can be calculated. (Table 3-2)

Table 3-2: Delta-V Budgets for Each Mission Type

Scenario	Start Point	Destination	Delta-V (m/s)
1	Lunar Surface	LLO	1850
2	LLO	LEO	4050
3	Lunar Surface	LEO	5900

3.1.2 Calculation of Propellant Resource Demands

The main task of the transportation demand section is to use the delta-V values described above to determine the amount of oxygen and hydrogen that is required for the selected mission type. This process involves performing four calculations to determine:

1. Mass Ratio
2. Structural Mass
3. Mass of Propellant for a single trip
4. Transportation demand on oxygen and hydrogen requirements.

Mass Ratio

The mass ratio for a spacecraft is defined as its total initial mass, m_0, divided by its final total mass, m_1, as shown in Equation 3-1.

$$MR = \frac{m_0}{m_1}$$ Equation 3-1

To determine the mass ratio from the required delta-V of a mission type, Tsiolkovsky's Rocket Equation is used (Equation 3-2). For the FERTILE Moon Model, a specific impulse (I_{sp}) of 450s is defined. This value corresponds to a liquid oxygen/liquid hydrogen engine. Due to the scope of the project, no other propellant type is considered.

$$\frac{m_1}{m_0} = e^{\frac{-\Delta v}{I_{sp} g_0}}$$ Equation 3-2

The initial mass of a spacecraft consists of the mass of the structure (spacecraft subsystems), the mass of the payload, and the mass of the propellant. The final mass of the spacecraft does not include the mass of propellant since it was used up during the mission. Therefore, the mass ratio can be written in the forms of Equation 3-3 or Equation 3-4.

$$MR = \frac{m_{payload} + m_{structure} + m_{propellant}}{m_{payload} + m_{structure}}$$ Equation 3-3

$$MR = 1 + \frac{m_{propellant}}{m_{payload} + m_{structure}}$$ Equation 3-4

The mass ratio, in the form of Equation 3-4, is used next as an input to determine the mass of the structure (i.e. the mass of the spacecraft with no propellant or payload).

Structural Mass

The calculation for the structural mass involves three inputs: the mass of the payload, the mass ratio, and the structural ratio. Equation 3.5 is an expression of the structural ratio, SR. (NASA Glenn, 2005).

$$SR = \frac{m_{structure}}{m_{structure} + m_{propellant}} \qquad \text{Equation 3-5}$$

For the FERTILE Moon Model, the structural ratio is set to a value of 0.1. This is a typical value assumed for spacecraft design. The value states that the mass of propellants required is nine time greater than the dry mass of the spacecraft (without payload). The SR value is combined with the mass ratio and the payload mass, which is a user input in the model, to calculate the structural mass of the spacecraft as shown in Equation 3-6.

$$m_{structure} = \frac{SR(MR-1)}{(1-MR \cdot SR)} m_{payload} \qquad \text{Equation 3-6}$$

Mass of Propellant

For the final step, the required propellant mass is deducted using the structural ratio and the calculated structural mass of the spacecraft as shown in Equation 3-7.

$$m_{propellant} = (\frac{1}{SR} - 1) m_{structure} \qquad \text{Equation 3-7}$$

By developing all the terms and isolating the propellant mass required, we finally obtain the following relation, Equation 3-8, which is used in the FERTILE Moon Model to calculate the propellant demand based on the structural ratio, delta-V, specific impulse, and payload masses.

$$m_{propellant} = \frac{(1-SR)(e^{\frac{\Delta v}{I_{sp} g_0}} - 1)}{(1 - SR \cdot e^{\frac{\Delta v}{I_{sp} g_0}})} m_{payload} \qquad \text{Equation 3-8}$$

Hydrogen & Oxygen Demands

The final demands for hydrogen and oxygen are found by using the hydrogen to oxygen ratio for the propellant type to calculate the mass of hydrogen and oxygen needed for a single trip. This value is then multiplied by the number of trips that the user of the FERTILE Moon Model desires for their specific mission to find the total requirements. The value of the hydrogen to oxygen ratio is set at 1:6.5 for the model.

3.1.3 Zeros and Poles of the equation

The equation 3-8 has zeros in SR=1 (100% is structure) and delta-v=0 (no energy required) and a pole (asymptote) in the following condition:

$$1 - SR \cdot e^{\frac{\Delta v}{I_{sp} g_0}} = 0 \rightarrow SR = e^{\frac{-\Delta v}{I_{sp} g_0}} \qquad \text{Equation 3-9}$$

From the initial mass ratios, it can also be seen that the pole is reached when *SR=1/MR*. In those cases, it is impossible to obtain the required delta-V. Values of *SR* greater than *1/MR* also make the solution impossible since mass becomes negative.

The asymptotic behavior of the total mass versus delta-V is caused by the interrelation of the structure's mass ratio and the propellant mass of the spacecraft, the SR making the structural mass increase with increasing propellant mass (Figure 3-3). The mass ratio (MR) is then bounded by the inverse of SR. It must be mentioned that the relation between these factors may change when considering different type of spacecraft, the structural mass varying from 5% for cargo-type spacecraft to 20% for crew-type spacecraft. The default value implemented in the model corresponds to cargo-type spacecrafts, and has a value of 10%.

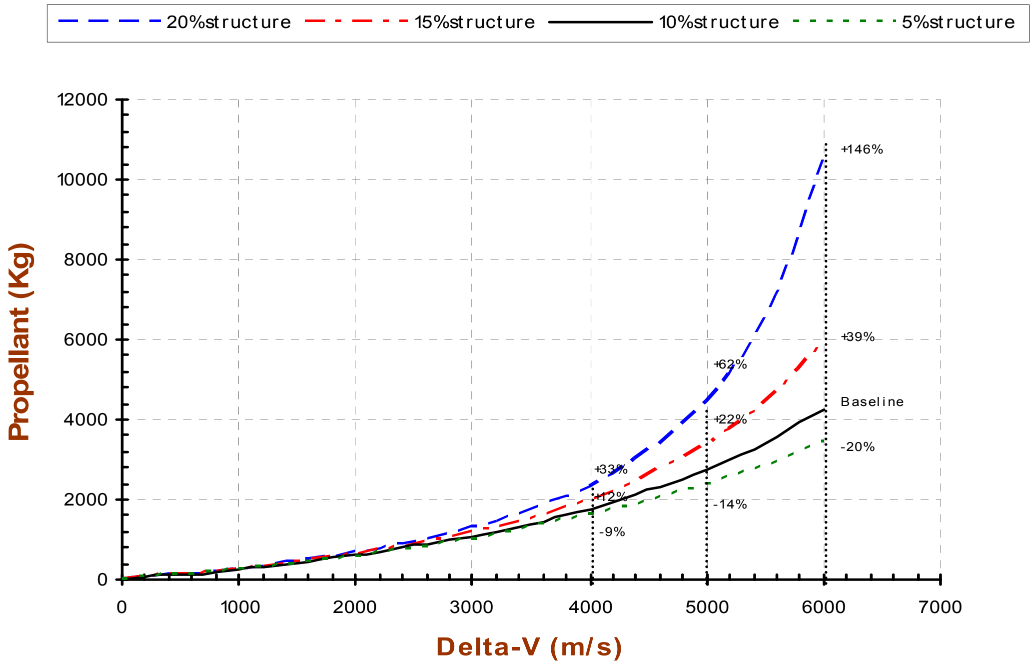


Figure 3-3: Variation of Propellant Required for Different Delta-V Values
Variation from 5% to 20% for structural ratio with an I_{sp} = 450 and Payload Mass = 1000 kg.
(One Stage Only)

According to Figure 3-3, a delta-V below 4 km/s does not affect the propellant requirement significantly, regardless of the structure coefficient. However, a delta-V greater than 4 km/s significantly increases the demand for propellant when considering a structural coefficient of 10%, and makes a trip from the lunar surface to LEO completely unfeasible for a structure coefficient of 20%. Thus, the current implementation of the model limits scenarios to the transportation of cargo. Therefore, another stage should be considered to compensate the extra weight of the structure for missions including crew transportation.

3.2 Life Support Systems

One of the major goals of ISRU is to support human missions by minimizing the amount of resources that must be brought along for re-supply. Human needs directly influence ISRU in that they determine how much resources must be acquired in order to insure crew survival. The human body can be regarded as a subsystem, with inputs and outputs as well as its own physical requirements. Figure 3-4 lists these parameters and average values for each of them. The needs for other elements, such as entertainment or comfort, are not addressed since they do not influence the LSS requirements and are not directly related to the FERTILE Moon Model.

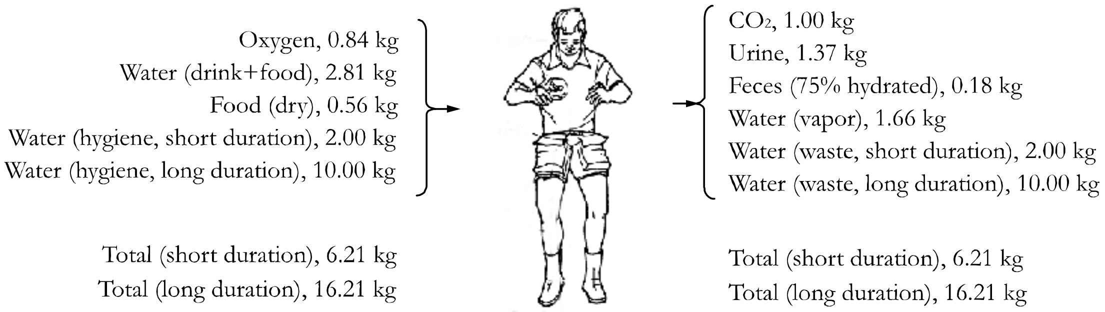


Figure 3-4: Human Water, Oxygen, and Food Production (adapted from Wieland, 1994)

Oxygen and water are the two resources that the FERTILE Moon Model calculates for based on LSS. Before discussion the actual demands, it is necessary to look at the types of LSS being used. Then, the water demand and oxygen demand can be examined.

3.2.1 Classes of Life Support Systems

The life support system is divided into five different tasks: air management, water management, waste management, food production and storage, and crew safety. For air, water and waste management, physico-chemical processes can be applied, whereas food production is a bio-regenerative system. The food production will again be integrated in the overall water, air and waste cycle (Eckart, 1996b) – increasing the system's complexity as the closed-loop system becomes more complete and the need for external supplies decreases.

The LSS components can be divided in two groups: regenerative functions, which include air revitalization, water recovery and food production as well as waste reduction, and non-regenerative functions, which are mostly monitoring devices such as trace contaminant control (TCC) units or fire detection systems.

As seen in Figure 3-5, the level of loop closure (expressed in percentage of re-supply mass savings) of the LSS is mostly based on the level of recovery of water and the revitalization of air (80%). The remaining 20% can be obtained by processing waste, producing food and spare parts, and compensating or preventing all forms of leakage.

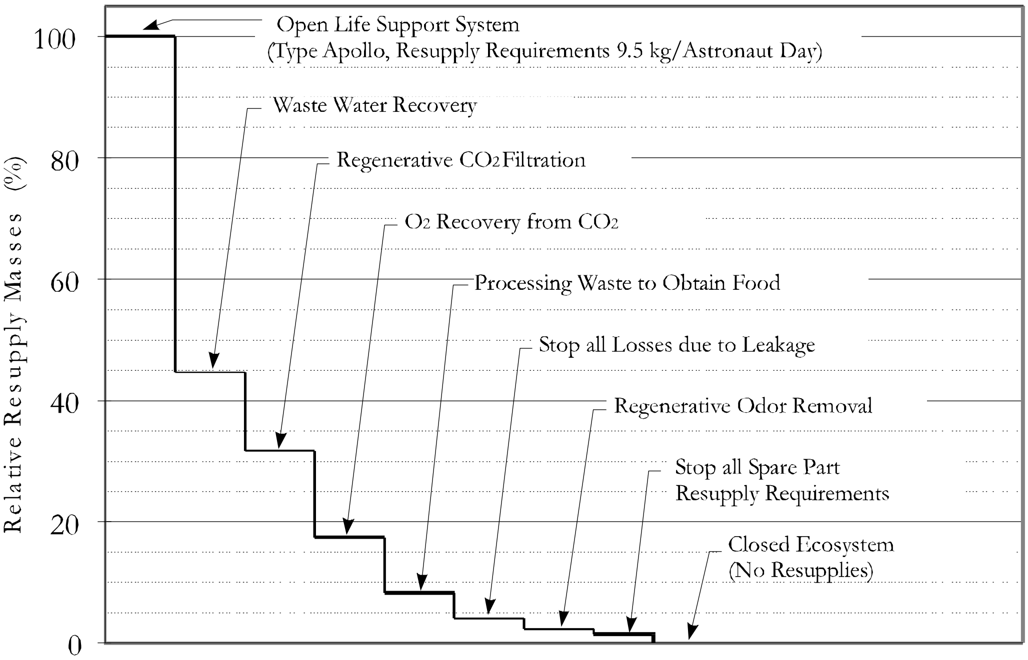


Figure 3-5: Re-supply Steps for Closing Loops in LSS (adapted from Messerschmid, 1999)

For a given duration, specific levels of loop closures are reasonable and achievable. Therefore, three classes of LSS were designed to cover major mission types and to allow the user an easy data input into the model. These LSS were simulated by using the ELISSA (Environmental and Life Support Systems Simulation and Analysis) tool (Osburg & Ganzer, 2006), which was developed for space station LSS design at the Institute of Space Systems at the University of Stuttgart, Germany.

As seen on Table 3-3, the first LSS is minimally closed, and is suggested for short missions with few crewmembers. The second LSS is similar to the one used on the International Space Station (ISS), which consists of a physico-chemical regenerative systems with minimal autonomous food supply provided by a salad machine (Kliss et al., 2000), mainly for psychological and comfort purposes. It is designed for up to three-month missions of up to 12 crewmembers. The third LSS includes an algae reactor and higher plant growth facilities for long duration missions of more than three months and a crew size of up to 30 people.

Table 3-3: Description of the Three LSS Classes

System Number	Duration (Days)	Loop Closure (%)	Crew Size (Persons)	Mission Description
LSS1	0-14	≤20%	≤4	Above CEV-class
LSS2	15-90	≤60%	≤12	ISS-class
LSS3	91-365	≤90%	≤30	Lunar Settlement-class

Life Support System 1

For short duration missions (1-14 days), the suggested LSS possesses very few regenerative technologies. A lithium hydroxide (LiOH) filter captures the excess CO_2, which is then vented into space. A trace contaminant control (TCC) unit and a Condensing Heat Exchange (CHX) unit are connected in order to maintain atmospheric composition and moisture level. Hygiene water is treated by Multi-Filtration (MF), thus enabling high water re-supply savings.

The hygiene water needs allocated for short-term missions of 2 kg/person/day is used only for hands and face washing. Showers will not be available and wet towels will be used instead. Food will be exclusively supplied from Earth in a dehydrated form. A potable water budget of 2.8 kg per person per day is allocated to food preparation and drinking. Wastes of all kind will be stored on board.

Figure 3-6 represents the simplified schematics of LSS 1, with the four major tasks involved: water, food, waste and atmosphere management. The major storage tanks, LSS sub-systems and mass flows are displayed. The thickness of the connecting lines does not represent the mass-flow-rate, but the importance of the task with respect to the ISRU related resources water and oxygen. Due to the low level of loop closure there are only regenerative technologies involved in the water and atmosphere sections.

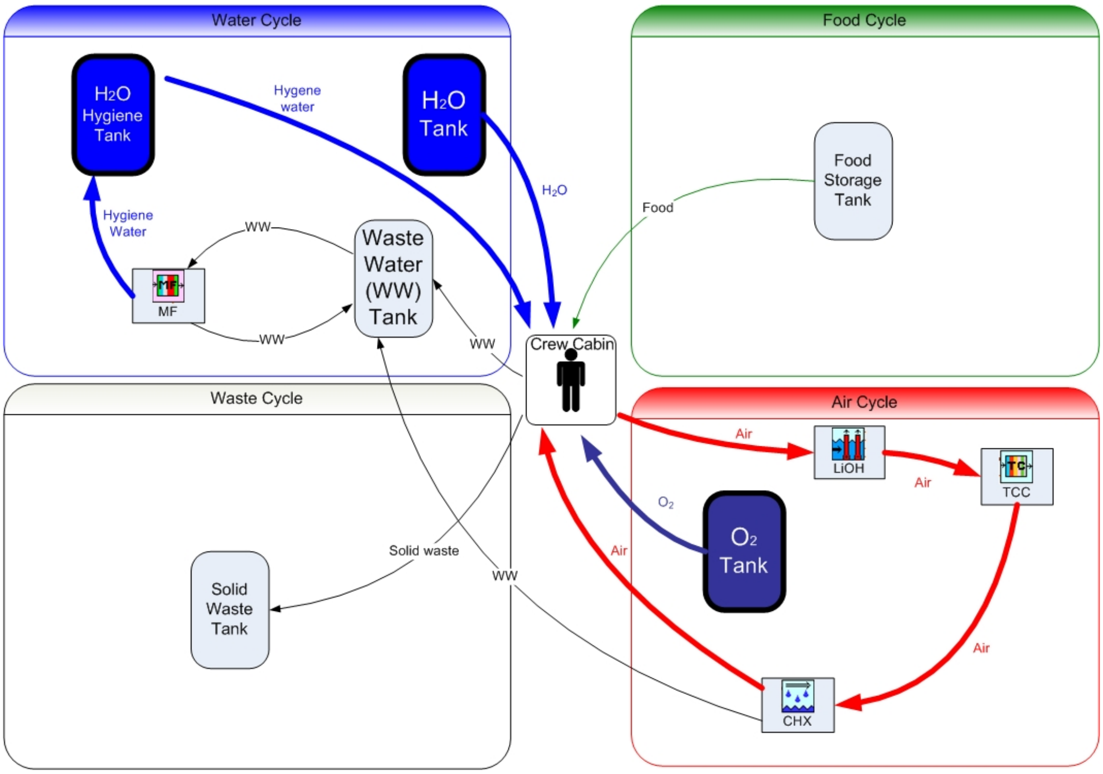


Figure 3-6: Simplified System Schematic for LSS 1

By running the simulation with the ELISSA model for a four-person crew, a steady decrease in potable water and oxygen tank levels over mission lifetime (14 days) is observed. The 20% of loop closure enable small re-supply mass savings, thus the overall mass requirements over the mission duration are 200 kg of water and 50 kg of oxygen. An additional 10 kg of oxygen is initially required to fill the habitat volume.

Life Support System 2

The life support system used for 14-90 day missions is similar to the LSS used on the ISS. Slight modifications bring the loop closure up to 60%. With the addition of a small biological component, the comfort level and the psychological support of the crew is increased. This so called salad machine provides fresh lettuce and tomatoes to vary the diet of the astronauts (Kliss & MacElroy, 1990).

In Table 3-4, the physico-chemical and biological systems, which are included in the 14-90 day mission's LSS, are listed. The overall system is more complex than for short duration missions, but it provides a higher loop closure.

Table 3-4: Technologies Used in LSS 2

Air Cycle	Water Cycle	Waste Cycle	Food Cycle
• Four Bed Molecular Sieve (4BMS) for CO_2 reduction • Static Feed Water Electrolysis (SFWE) for oxygen generation • Condensing Heat Exchanger (CHX) for temperature and humidity control • Trace Contaminant Control (TCC)	• Vapor Compressed Distillation (VCD) • Multifiltration	• Stored in Tanks	• Dehydrated food from Earth (water content 53%) • Salad machine • 2x0.7m² Lettuce • 2x0.7m² Tomato

Figure 3-7 represents the simplified schematics of the LSS 2. In this LSS, the additional regenerative technologies employed for air and water management, as well as the biological system for food production significantly increase the overall complexity. As in the previous schematic (Figure 3-6), the highlighted loops demonstrate the water and oxygen dependent loop for the ISRU relevance of the LSS.

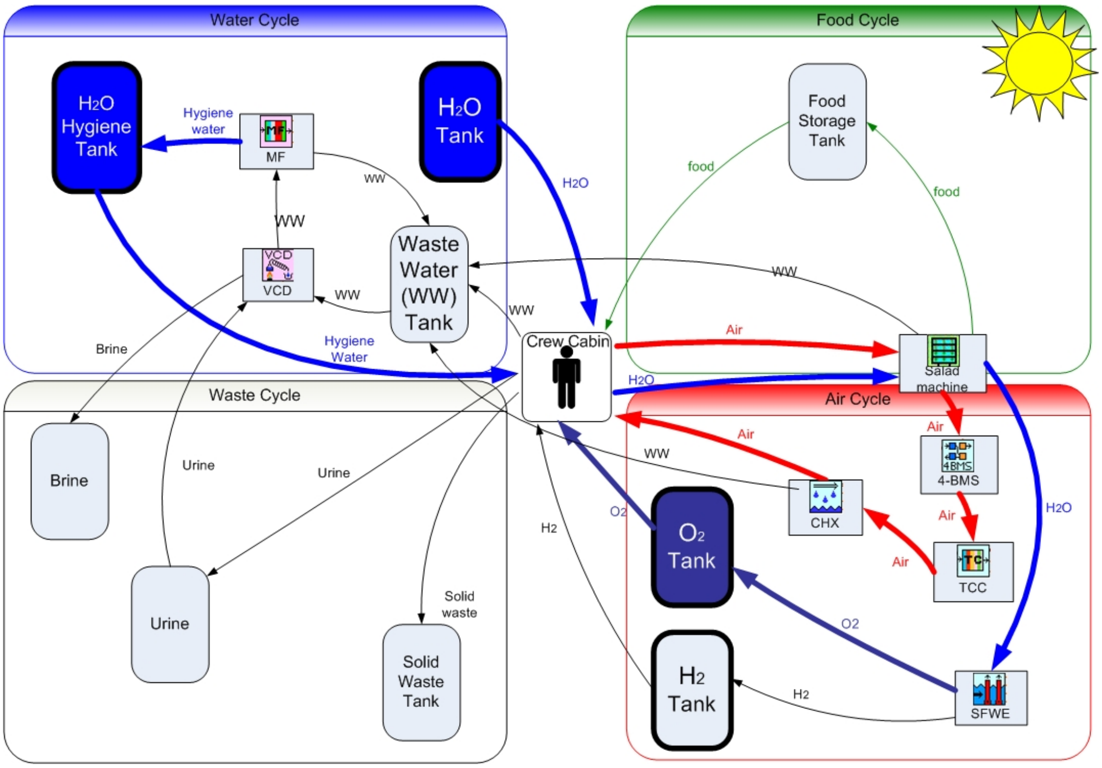


Figure 3-7: Simplified System Schematic for LSS 2

The LSS 2 was tested using the ELISSA model to simulate a 90-day mission with a six-person crew. Oxygen and water tank levels showed steady decrease, though less pronounced than for LSS 1, due to the higher (60%) loop closure. The hydrogen tank levels steadily increased over time as a by-product of water electrolysis for oxygen production to reach a maximum of 120 kg. 2500 kg of water and only 20 kg of oxygen were required over the whole mission lifetime. An additional 100 kg of oxygen is initially required to fill the habitat volume.

Life Support System 3

The major difference in the long term LSS with respect to the former one is the integration of bio-regenerative components, which will reduce the re-supply mass for food, thus increasing the stations autonomy. This mission scenario is for long-term missions of more than 90 days and for crews of over 12 members.

The use of physico-chemical and biological systems (as shown in Table 3-5) significantly increases the complexity of the overall system, but the variety of technologies guarantee high synergism and redundancy levels.

The use of dehydrated food from earth in addition to the produced fresh food insures nutritional variety and diet balance for the crew. Therefore dry-mass values of 0.25 kg of algae, 0.25 kg biomass from higher plants and 0.06 kg of food from earth are calculated per astronaut and day.

Table 3-5: Techonolgies Used in LSS 3

Air Cycle	Water Cycle	Waste Cycle	Food Cycle
• Electrochemical Depolarised CO_2 Concentrator (EDC) • Static Feed Water Electrolysis (SFWE) • Photobioreactor (PRB)	• Vapor-Phase Catalytic Ammonia Removal (VPCAR) • Air-evaporated system (AES) • Immobilized Cell Bioreactor (ICB) • Trickling Filter Bioreactor (TFB) • Reverse Osmosis (RO)	• Solid Waste Incineration System (SWIS) • Sabatier reactor (Saba)	• 53% hydrated food from Earth • 600m² Greenhouse

Figure 3-8 represents the simplified schematics of LSS 3. In this LSS, the waste management technologies and closed biological food production systems considerably increase the overall loop closure value (90%) of the system, and thereby its complexity and synergism. The highlighted lines symbolise the ISRU relevant loop with one exception: the EDC in the air-loop is a back-up system as the greenhouse is processing enough CO_2 to maintain the required atmosphere composition.

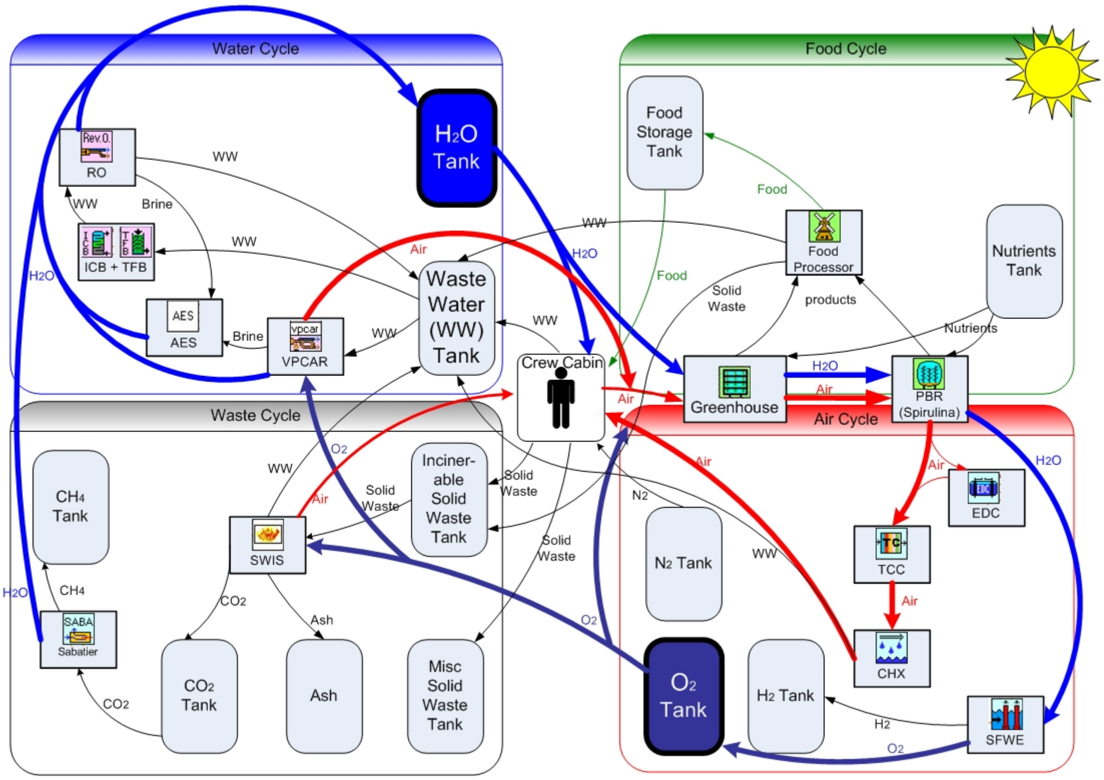


Figure 3-8: Simplified System Schematic for LSS 3

The LSS 3 was tested using the ELISSA model for a one-year mission with a 30-person crew. The 90% loop closure value implies little or no re-supply requirements. Although the water tank levels oscillate through different crop growth cycles, the overall quantity in the system remains constant. 5000 kg of water are initially required to fill the system. A fine-tuning of the SFWE maintains the oxygen tank levels constant throughout the mission's lifetime. Between 200-300 kg of oxygen will be required through the year, plus an additional 800 kg of oxygen, which is initially required to fill the habitat's volume.

A food production on the surface of the Moon may allow important mass savings. For a crew of 30 people, 13 t of food could be produced per year. A re-supply of 2 t of dehydrated food and 4 t of nutrients is required. This enables a mass saving of 6 t. The nutrient re-supply can be drastically reduced with a composting unit as described in the future development section.

3.2.2 Water Demands

For the FERTILE Moon Model, the water management system has two separate components: the potable water loop and the hygiene water loop. This is mainly due to the psychological issues linked to drinking water regenerated from urine. This system offers the possibility of having different loop closure options of the two loops, thus enabling a finer control of the overall loop closure value. The hygiene water is used for hygienic washing, showering, cleaning clothes, and washing dishes. The potable water is used for drinking and for food preparation. There is also a third component that affects the water demands and that is the demand of water for Extra-Vehicular Activities (EVA). (Figure 3-9)

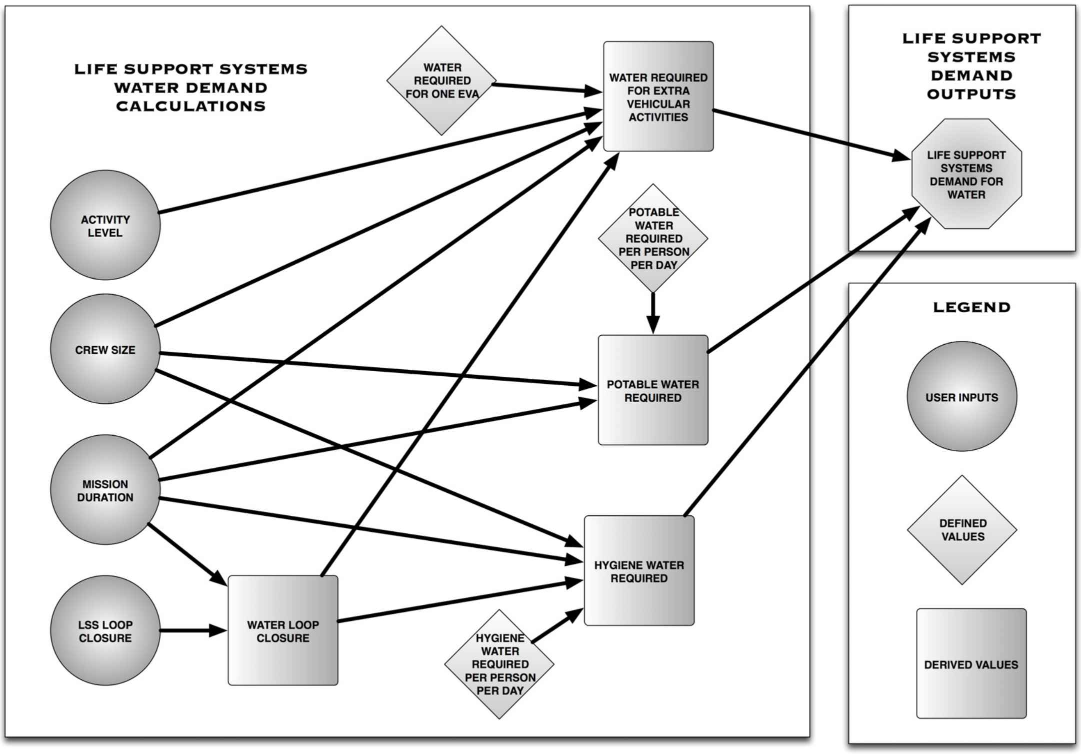


Figure 3-9: LSS Water Demand Calculations

Potable Water

The calculation for the amount of potable water depends on four factors. The first factor is the percentage of water loop closure which is calculated based on the class of LSS being used, as discussed above, and the user input for the overall LSS loop closure. The next two factors are the mission parameters, of crew size and mission duration, which the user inputs on the main GUI of the FERTILE Moon Model. The last factor is the defined value of the amount of potable water required per person per day. This value is set to 2.8 kg.

Hygiene Water

The calculation for the amount of hygiene water is similar to the calculation for potable. The demand is also dependent on the water loop closure percentage, the mission duration, and the crew size. For this calculation, the defined value is the amount of hygiene water required per person per day. This value is set to 2 kg for missions using LSS 1 and 10 kg for missions using LSS 2 and 3.

EVA Requirements

Humans on the Moon will perform EVAs in order to assemble ISRU facilities, to perform equipment maintenance and to complete scientific work. EVAs are performed for a standard duration of 8 hours per person-day (Horneck, et al, 2001). The resource requirements for EVAs include the water needed for cooling. This data is taken into account in the calculation of the overall water demand for ISRU missions.

The water demand for EVAs is dependent on the mission duration and crew size as well as the activity level. All these values can be set by the FERTILE Moon Model user for their specific mission design. The current requirement for suit cooling is 5.4 kg of water. However, by anticipating better suit technology in the future, an average value of 4 kg is retained.

3.2.3 Oxygen Demands

The oxygen demand for life support is also calculated from three different sources. (Figure 3-10) The first source is the actual life support oxygen that is required by the crew. There is also a certain amount of oxygen based on creating a livable atmosphere in the habitats and, finally, there is a requirement based on the EVAs similar to the water demand calculation.

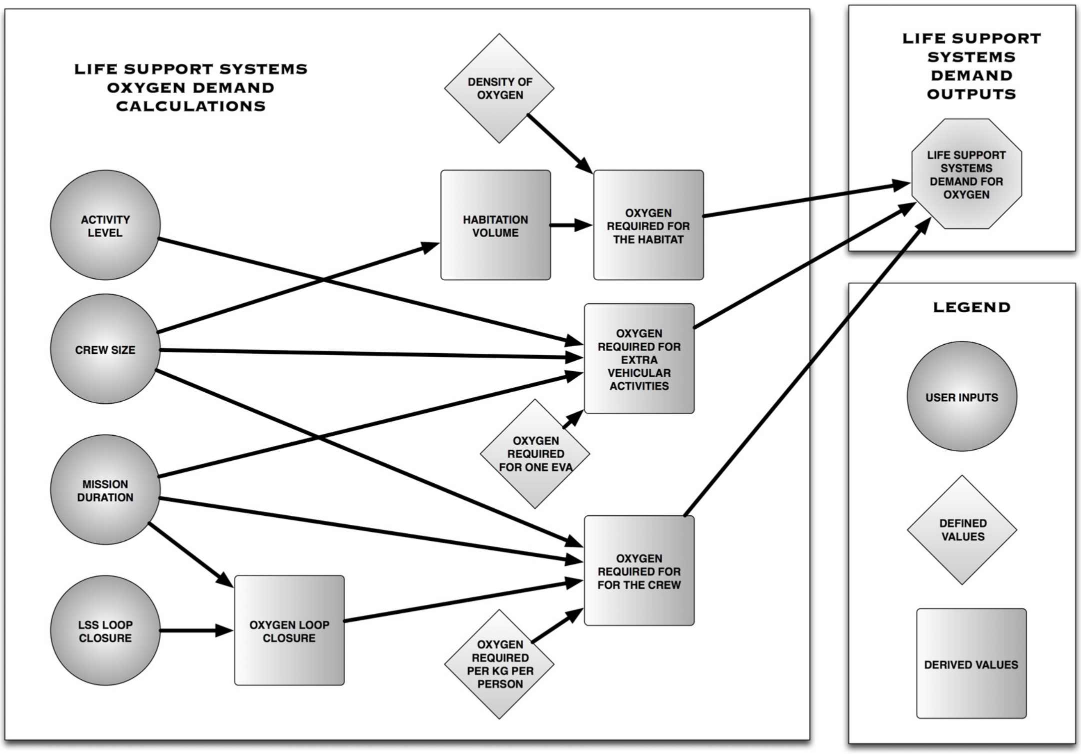


Figure 3-10: LSS Oxygen Demand Calculations

Crew Requirements

Each member of the crew requires a certain level of oxygen. The amount of oxygen required by a crew member in one day is dependent on factors such as the mass of the astronaut. To reduce the complexity for this stage of the project, it was necessary no not use the average range of human body masses (41 kg – 98 kg), but instead to use the average human body mass of 70 kg. Using this value, the amount of oxygen required per person per day was defined as 0.84 kg. Using this value with that of the oxygen loop closure (again based on the user input for LSS loop closure and LSS class) along with the mission parameters of crew size and mission duration, the FERTILE Moon Model is able to calculate the amount of oxygen needed to meet this requirement.

Habitation

The habitat volume determines how much air must be supplied initially. It influences the crew comfort level and overall habitability. For physiological and practical reasons, an atmospheric pressure of 101.3 kPa is required without regards to the crew size and mission duration. Spending long durations in an oxygen-enriched atmosphere poses a serious health threat for the crew due to the increased fire and intoxication risk. Thus, a 21% oxygen atmosphere, as on Earth, has been chosen. The remaining 79% of the atmospheres composition is made up from nitrogen and other trace gasses, however these are not considered here since it does not fit in the scope of this Report.

Depending on the mission's duration, different gas volumes are needed to pressurize the habitat. Table 3-6 shows how the habitat volume and required mass of oxygen change as a function of mission duration (Stoff, 2004; Hoffman et al., 1997; Bengtson, 2005). The required oxygen mass is calculated based on the previously mentioned 21% oxygen atmosphere at a pressure of 101.3 kPa.

Table 3-6: Volume of Air & Oxygen Required for Habitats

Mission Duration (days)	Estimated Habitat Volume (m^3/person)	Required Oxygen Mass (kg/person at 20ºC)
0-14	5	1.4
15-90	58	16
90-365[1]	93	25.7

[1] volume includes space for growing higher plants

Oxygen leaks from the habitat and from the extravehicular activity (EVA) suits are negligible and are not accounted for in the model (Handford, 2002). Oxygen loss due to airlock operation for EVA operations is more important and is taken into account in the model.

EVA Requirements

Safety protocol requires at least two crewmembers in EVA at any time. A two-crewmember airlock has an empty volume of 4.25 m^3 with a free gas volume of 3.7 m^3; the two suited crewmembers fill the remaining volume. About 10% of the free gas within the airlock is lost to space and not recovered by the airlock compression pump during depressurization (Handford, 2006). Therefore, 0.11 kg of oxygen is lost per EVA.

This defined value is combined with the crew size, mission duration, and activity level user inputs on the FERTILE Moon Model to determine the EVA portion of required oxygen.

3.3 Summary

Any tool that is used to analyze the feasibility of ISRU must first be able to calculate the required demands of the resources involved. This chapter outlined two of the major areas for which ISRU for hydrogen, oxygen, and water could be most beneficial, namely life support systems and transportation from the Moon to Earth.

The first aspect considers the propellant demand for the return from the Moon. A general approach is derived from the Tsiolovsky's Rocket Equation, based on a generic single-stage return vehicle. This approach considers a single trajectory divided into three segments for which propellant requirements can be computed separately depending on the requirements of the FERTILE Moon Model user. These segments account for travel from the Moon's surface through LLO to LEO. A wide range of missions can be described using that generic approach by having the user specify the payload mass.

Due to the intrinsic complexity of life support systems, three guidline LSS are proposed as templates to guide the user in choosing realistic values for adapting new mission scenarios to the model's inputs. These LSS aim to cover the needs of typical missions varying from a few days to a year. According to a loop closure level of 0% to 80%, the yearly demand per person varies from 57000 kg to 170 kg for water, and from 300 kg to 70 kg for oxygen respectively. (Figure 3-11)

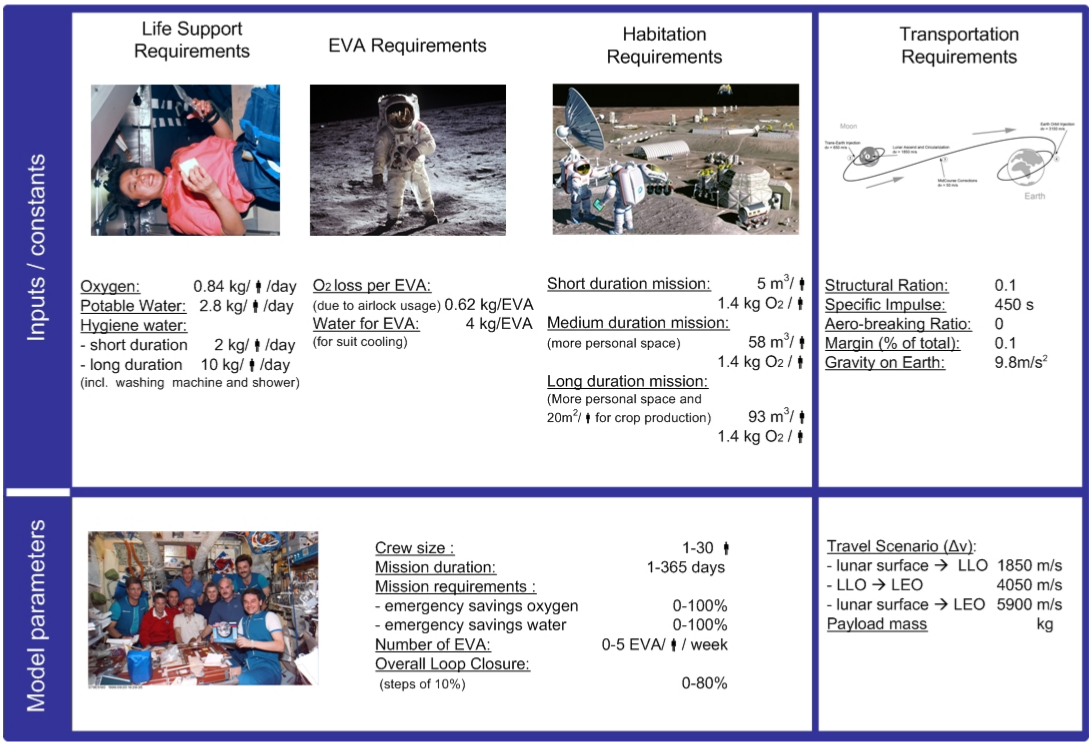


Figure 3-11: Inputs into the FERTILE Moon Model

Integrating these two mission-related aspects into the model is the first step in assessing the potential of ISRU. They are essential in evaluating the minimum quantity of resources required for a wide variety of mission scenarios based on the inputs of return mission types and payload masses for transportation and crew size, mission duration, loop closure for LSS. The values that are outputted from the Demand Layer form the base on which both the supply and costing layers operate from.

4 SUPPLY

Now that the relevant resource demands have been described for different lunar exploration scenarios and architectures in Chapter 3, the focus of this current chapter is to analyze and compare the different options available for resource supply. The supply options used in the FERTILE Moon Model is divided into two categories or "strategies":

- Supply from Earth
- Supply from the Moon

The first strategy, Supply from Earth, is considered to be the baseline approach and will be discussed in section 4.1. This used as the baseline for comparison due to the historical convention of transporting all necessary resources from the Earth for crewed missions.

Then, the supply from the Moon in Section 4.2, will discuss the possibility of producing the necessary resources in-situ through various chemical processes. This option is considered to be more innovative but also riskier than supplying the resources from Earth.

Several elements are common to both supply strategies, including water electrolysis, liquefaction, storage, and power generation. These common elements are discussed first in the baseline approach, supply from Earth, and then the reader is referred back to this discussion from Section 4.1 as these subjects arise in Section 4.2. The goal of this chapter is to describe the Supply Layer in the FERTILE Moon Model which determines the parameters necessary for costing the supply methods, which is presented in chapter 5.

4.1 Supply from Earth

During the Apollo Program, all required resources for its relatively short-duration lunar landing missions were produced on Earth and delivered to the Moon along with the crew, including life support consumables, energy, and the rocket propellants required to return the crew to Earth. While the Apollo Program is the only historical example of crewed lunar exploration, in fact, most mission designs, from the earliest concepts described in science fiction literature to NASA's current Exploration Systems Architecture Study (ESAS, 2005), envision that the vast majority of mission resources are supplied from Earth. Therefore, this traditional strategy of "terrestrial supply" can and should be taken as a baseline against which to compare any other strategy for satisfying the mission resource requirements described in Chapter 3.

Hydrogen, oxygen, and water will be brought to the Moon in one of two forms: simply as water to be broken to hydrogen and oxygen as required or as separate components already as liquid hydrogen, oxygen, and water. This section will describe these forms of the transported resource, as well as a short discussion of the storage and processing technologies required to utilize the water, hydrogen and oxygen brought from Earth.

4.1.1 Direct Importation of Resources

For the case where water, oxygen and hydrogen are brought separately from Earth, these resources will be brought to the lunar surface as liquids. Hydrogen and oxygen are both much denser as liquids and thus they will occupy a significantly lower volume. Liquid oxygen and hydrogen could then also be used directly as propellant, for power production and in life support systems.

4.1.2 Electrolysis of Water from Earth

In the case of only bringing water from Earth, a further processing step is required to produce hydrogen and oxygen, for example electrolysis. Once oxygen and hydrogen have been produced they can be liquefied and stored. To ultimately calculate the cost of this option, the FERTILE Moon Model must first have information such as the specific mass and power of the electrolysis facility.

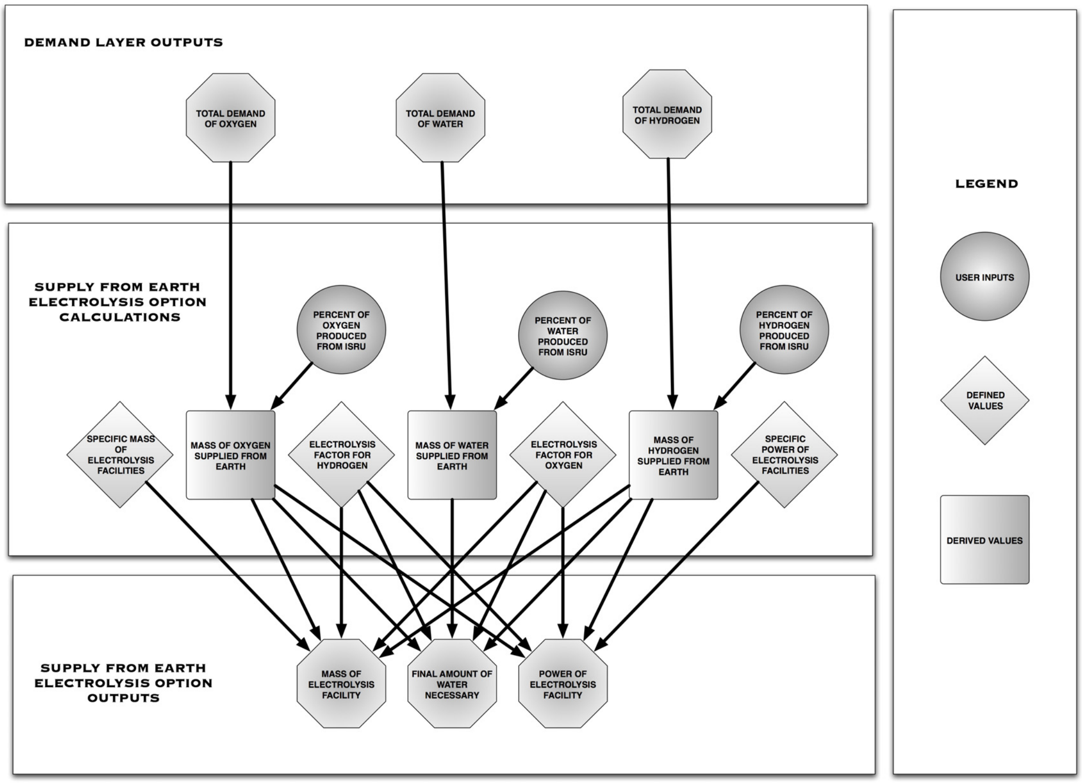


Figure 4-1: Supply Layer Calculations for Supply from Earth: Electrolysis Option

Overview of the Electrolysis Process

This section will only briefly outline the electrolysis process, which is shown in Figure 4-2.

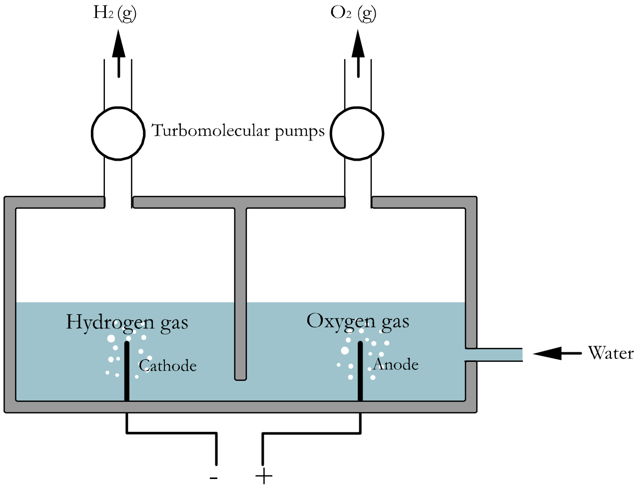


Figure 4-2: Schematic Diagram of the Electrolysis Process

The chamber is filled with water, and an electric current is applied across two platinum electrodes (Maier, 2005). The current allows water molecules to split into gaseous hydrogen and oxygen via:

$$2\,H_2O \Leftrightarrow 2\,H_2 + O_2 \qquad \text{Equation 4-1}$$

Hydrogen is produced at the cathode while oxygen is produced at the anode.

There are alternatives to electrolysis, for example the De Beni Carbon-Iron Process (Eagle Engineering Inc., 1988). Although such processes may involve less energy than electrolysis they increase the overall complexity thus requiring more equipment. The FERTILE Moon Model assumes that electrolysis is the only process used for the production of hydrogen and oxygen.

Specific Power of Electrolysis

The dissociation free energy of water is 249 kJ per mole of water (Teeter, 1987), and thus the minimum specific power of the process is calculated as:

$$\frac{249\text{ kJ} \big/ 3600\text{ s}}{0.018\text{ kg}_{H_2O}/\text{mol}} = 3.84\text{ kWhrs}/\text{kg}_{H_2O} \qquad \text{Equation 4-2}$$

Running the system at a higher specific power will increases the quantity of water electrolyzed during any given time. After the electrolysis, turbo-molecular pumps are used to pump the gases towards their respective storage tank, which are then cooled, liquefied, and stored.

Specific Mass of the Electrolysis Facility

The FERTILE model considers various levels of life support, transportation requirements and extravehicular activity. Specifically, it considers a range of total consumption of oxygen from approximately 4.7 kg over a 3-day period to 100 tons per year. As a result of varying levels of demand for oxygen the specific mass of the electrolysis and liquefaction system will also vary, in turn changing the transportation cost. The specific mass of the electrolysis system will range from 65 to 2200 kg per kg of water electrolyzed per hour (Teeter, 1987). Figure 4-3 shows how the specific mass of the electrolysis system varies with the oxygen demand. At low consumption levels the specific mass increases significantly, this is due to the inverse relationship between the specific mass and the oxygen consumption.

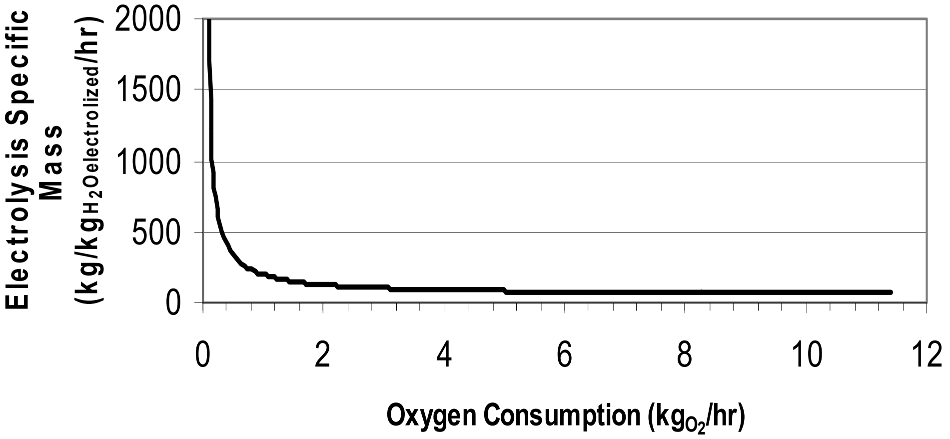


Figure 4-3: Specific Mass of the Electrolysis System as a Function of Oxygen Consumption

Liquefaction and Storage

The specific mass and power for the liquefier and storage facility are also a function of the demand for oxygen and vary in a similar fashion to the specific mass of the electrolysis system. The values for these parameters are given in Table 4-1.

Table 4-1: Specific Mass and Power for Liquefaction and Storage

Storage and Liquefaction of:	Specific Mass (kg/kg$_{H_2O}$/hr)	Specific Power (kW/kg$_{H_2O}$/hr)
Oxygen	11-2000	0.086 - 15
Hydrogen	6.6 - 1150	

Power Systems

The values calculated above can then be used to estimate the mass of the power system. The mass of the system will be highly dependant on the chosen power system, for example solar or nuclear. Figure 4-4 below shows that the choice of power system is primarily a function of the desired power level and required duration of use.

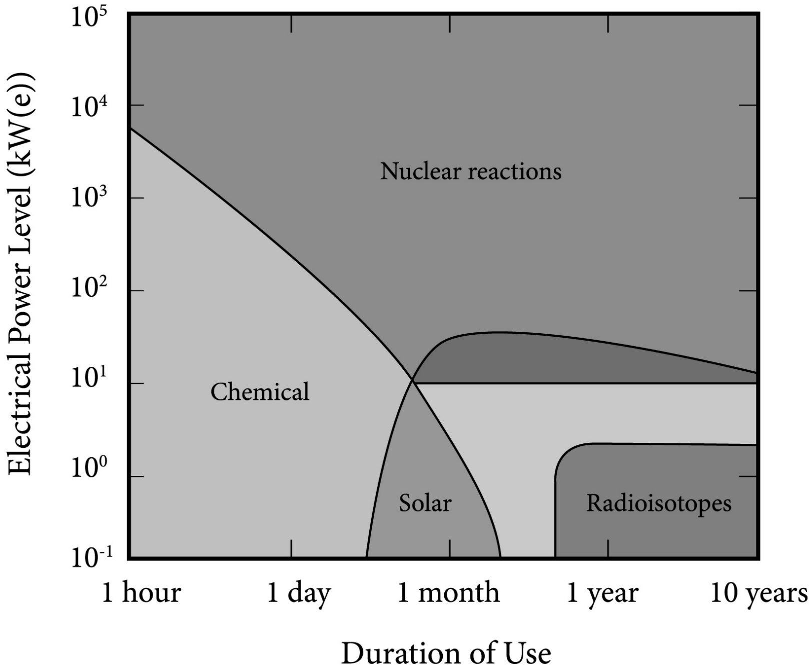


Figure 4-4: Regime of Possible Space Power Applicability (IAEA, 2005)

Since the transportation of these power systems to the Moon is the main cost associated with power, an estimation of the mass of the major power system types was made. Table 4-2 summarizes the specific mass of the three power systems used in the FERTILE Moon Model.

Table 4-2: Summary of Specific Masses for Various Power Systems

Equipment	Electrolysis System	Liquefaction & Storage of O_2	Liquefaction & Storage of H_2
Specific Power Required (kW/kg H_2O/hr)	3.9	0.086 – 14.9	0.086 – 14.9
Solar Power System			
Power per Unit Area (W/m²)	182 – 338		
Mass per Unit Area (kg/m²)	0.28 – 0.85		
Electrical Power Density (W/kg)	331 – 771		
Mass (kg/kg H_2O)	4.98 – 11.6	0.111 – 44.9	0.111 – 44.9
RTG Power System			
Electrical Power Density (W/kg)	3.3 – 5		
Mass (kg/kg H_2O)	768 – 1,150	17.2 – 4,460	17.2 – 4,460
Nuclear Power System			
Electrical Power Density (W/kg)	1.49 – 195.3		
Mass (kg/kg H_2O)	19.7 – 2,570	0.44 – 9,950	0.44 – 9,950

4.2 ISRU Supply Section

Now that the baseline resource supply has been outlined, it is necessary to undertake the description of the lunar supplied resources. This section will describe all aspects relating to the in-situ resource production on the Moon. For the purpose of this study, only five processes were selected and implemented into the FERTILE Moon Model to perform the necessary ISRU tasks, noting that there are more processes that may meet the demand for the resources described above.

Section 4.2.1 introduces this subject and provides a background of previous work related to in-situ production of these three resources Section 4.2.2 provides an overview of all the processes related to the supply of these resources and describes the methodology and reasoning for down-selecting to five particular processes for inclusion in the model. Sections 4.2.3 through 4.2.7 describe each of the five selected processes in detail. From these processes and their associated equipment, Section 4.2.8, identifies the key parameters for assessing the economic feasibility of ISRU supply of these resources. Next, Section 4.2.9 describes the equipment required to carry out the selected ISRU processes. Finally, section 4.2.10describes the results of the research into determining the values of these key parameters for the selected processes.

4.2.1 ISRU Supply Background

The concept of supplying resources necessary for space exploration from local resources has been a part of the space vision since its earliest intellectual, scientific, and engineering pioneers. The first person to seriously incorporate the possibilities of utilizing space resources was Konstantin Tsiolkovsky in his science fiction work "On the Moon", published in 1892, and especially his "Dreams about Earth and Sky", published in 1895 (Tsiolkovsky, 1979). The study of the use of space resources more began more formally in 1962, however, with the establishment in the United States of the "Working Group on Extraterrestrial Resources," which met annually until 1970. The first experimental work on extracting useful resources from lunar simulant materials began in 1961 at Aerojet Corp. in but was halted in 1964 (Rosenberg 2002, 2003).

In 1984, NASA held a summer study on space resources, the output of which was published as Space Resources. Additionally, much of the work on ISRU to-date was summarized and presented in 1985 at a symposium, hosted by the U.S. National Academy of Sciences, called "Lunar Bases and Space Activities of the 21st Century" (Duke, 1985). Papers from a Second Conference on Lunar Bases and Space Activities of the 21st Century, held in 1988, were peer-reviewed and published in 1992.

The most significant comprehensive publication to-date on the engineering aspects related to ISRU supply of hydrogen, oxygen, and water is the work done by Eagle Engineering, Inc. under contract with NASA and published in 1988 (Eagle Engineering Inc., 1988). As many authors working on ISRU have since then, we draw heavily from this reference.

4.2.2 ISRU Processes and Down-Selection

More than 20 processes for the extraction of hydrogen, oxygen, and water from lunar materials have been proposed. Most of these proposed processes were reviewed in Taylor and Carrier (1992), and the authors offered a rough evaluation and ranking of the relative potential of these processes. These processes are categorized and listed, along with their most relevant references, in Table 4-3.

Table 4-3: Bibliographic List of Lunar Oxygen Extraction Processes

Process	Reference
Solid/Gas Interaction	
Ilmenite or other mineral reduction with hydrogen	Williams (1980); Gibson & Knudsen (1988); Fazzolari & Wong-Swanson (1989); Shadman & Zhao (1991); Lynch (1992); Bullard & Lynch (1994); Allen et al. (1996); Knudsen et al. (1992); Taylor et al. (1994); Gibson et al. (1994);
Ilmenite reduction with C/CO	Rosenberg et al. (1964); Zhao & Shadman (1991)
Ilmenite reduction with methane	Friedlander (1985)
Glass reduction with hydrogen	Allen et al. (1994)
Reduction with hydrogen sulfide	Dalton & Hohman (1972)
Extraction with fluorine	Burt (1988); Seboldt et al. (1991)
Carbochlorination	Lynch (1989)
Chlorine plasma reduction	Lynch (1989)
Silicate/Oxide Melt	
Molten silicate electrolysis	Haskin (1989); Colson & Haskin (1991, 1993); Keller (1991a,b, 1992); Haskin et al. (1992)
Fluxed molten silicate electrolysis	Keller (1987)
Caustic dissolution and electrolysis	Dalton & Hohman (1972)
Carbothermal reduction	Rosenberg (2000); Rosenberg et al. (2001)
Magma partial oxidation	Waldron (1979)
Li or Na reduction of ilmenite	Semkow & Sannells (1987)
Pyrolysis	
Vapor phase reduction	Steurer & Nerad (1983); Senior (1992)
Ion (plasma) separation	Steuer & Nerad (1983)
Plasma reduction of ilmenite	Allen et al. (1988)
Aqueous Solutions	
HF acid dissolution	Waldron (1982)
H_2SO_4 acid dissolution	Sullivan (1991)
Co-Product Recovery	
Hydrogen/helium water production	Bustin & Gibson (1992); Duke et al. (1998)

It was decided to limit the FERTILE Moon Model to include of only five ISRU processes. The aim in selecting these five processes was not necessarily to choose the five most preferred processes, but rather to choose a set of processes that incorporated a wide range of physical, engineering, and economic attributes which could be modeled. First and foremost, we set the requirement that these five processes must, when combined, be able to produce all three of the resources within the scope of our current study. A second criterion for selection was availability of information about the processes.

Bearing this in mind, our methodology for selecting processes was to quickly examine the field of literature related to ISRU and select the five processes for which the most information was available and spanning the three resources within our scope. Although some hundreds of journal articles and conference abstracts concerning ISRU exist, during our literature review, we identified seven major studies, which described many ISRU processes to varying degrees of comprehensiveness.

We identified one general process each for the production of hydrogen and water, as well as three specific processes for the production of oxygen. Due to the varying degree to which these studies discuss each process and also due to the high number of "minor studies" that deal with one or only a few different processes, our methodology is clearly not the most accurate or robust way to determine availability of information, but it was the quickest available method to down select to five processes and begin our focused research within the limited timeframe of this study. We remained open to the possibility of modifying our selection, if our detailed examination of the literature resulted in that another process, not initially selected, provided more complete information for input into our model.

An overview of each of the five selected processes is given in the following sections.

4.2.3 Process 1 - Hydrogen Reduction of Ilmenite

One of the most promising processes to obtain lunar oxygen is the hydrogen reduction of ilmenite. Ilmenite ($FeTiO_3$) is the most abundant (non-silicate) oxide mineral on the Moon, with highest concentrations in the mare regions, where it can account for as high 15-20% percent by volume of some basaltic rocks (Apollo 12 and 17 samples, Heiken et al., 1991). Ilmenite content in the regolith can vary significantly, as seen in Table 4-4. For a detailed discussion of ilmenite on the Moon, the reader is encouraged to consult Section 5.2.1 of Heiken et al. (1991).

Table 4-4: Modal Proportion of Ilmenite (Heiken et al., 1991) (in 90-20 µm fraction of lunar soil samples)

Sample Set	Ilmenite Concentration (vol. %)
Mare Samples	
Apollo 11	6.5
Apollo 12	2.7
Apollo 14	1.3
Apollo 15	0.8
Apollo 17, Mare	12.8
Highland Samples	
Apollo 15	0.4
Apollo 16	0.4
Apollo 17	3.7
Mare Average	**4.8**
Highland Average	**1.5**

The fundamental chemical reaction of interest is:

$$2\ FeTiO_3 \Leftrightarrow 2\ Fe + 2\ TiO_2 + O_2$$ Equation 4-3

In this reaction, oxygen makes up 10.4% by weight of the right side of the equation (the products). The direction of this reaction varies as a function of temperature and oxygen partial pressure (Taylor et al. 1972). The reaction can be driven further to the right by using hydrogen as a reducing agent, which is expressed by the following reaction:

$$FeTiO_3 + H_2 \Leftrightarrow Fe + TiO_2 + H_2O$$ Equation 4-4

The kinetics for the reaction in Equation 4-4 are considerably faster than similar reactions for silicate minerals. In order to achieve adequate reaction rates and conversion efficiencies, the temperature must be kept at around 700 to 1000˚C (Taylor & Carrier, 1992). Above about 1200°C, the solid particles begin to stick together which, in practice, would cause the fluidized bed to slump and fluidization to cease as well as make the particles hard to transport between beds and out of the reactor. Therefore, the range of operable center-bed temperatures is approximately 700°C – 1200°C. Practical reactor pressures are expected to be from 200 to 2,000 kPa.

The reaction is slightly endothermic, absorbing 40.6 J/mol at 900°C, with a partial pressure equilibrium ratio P_{H2O}/P_{H2} of about 0.1. According to Gibson and Knudsen, the overall energy cost for this process is about 1.2 kJ per gram of oxygen produced (Zacn, n.d.). Metallic iron and rutile are also by-products of this reaction. Further reduction of the rutile to titanium is energy intensive and not usually considered.

Once water is produced in the reaction of Equation 4-5 oxygen can readily be extracted by electrolysis, which involves the following reaction:

$$2\,H_2O \Leftrightarrow 2\,H_2 + O_2 \qquad \text{Equation 4-5}$$

The details of water electrolysis, which is involved as a final step to many ISRU supply processes, are discussed in Section 4.2, as it is also involved in the issue of supplying hydrogen and oxygen to the Moon by delivery of water from the Earth. Here it is only important to point out that although water is an intermediate "product" in the above hydrogen reduction reaction, it is not a true ISRU product, per our definition. This is because the hydrogen must be supplied via other sources (see discussion on consumables below). The true product is the oxygen atom, liberated from its ionic bond within the crystal structure of ilmenite.

Since the amount of oxygen that can be produced by this process only about 10 wt% of the ilmenite reactant, about 90% of the reduced feedstock must be removed as solids on a continual basis, which poses a significant design challenge. This assumes a production rate of 910 kg/day, and a plant size of 28,000 kg (including PV array) (Reynerson, 2004.).

Some authors like Williams have tested a fixed-bed process, using a cold trap for buffering the water pressure over the reaction at the water liquid-vapor equilibrium, thus enhancing the oxygen yield. In this experiment, a 90 g sample of pure ilmenite was crushed and sieved to 150 μm. The water yield rate was 0.8 mg/min. The size and the power requirement of this process are suitable for a small test plant (Schroeder, 1994). For this process, it is considered that the feedstock requires a beneficiation process to separate the ilmenite from the rest of the regolith. The options for beneficiation are discussed in Section 4.2.9.

Consumables

As mentioned above, some of the hydrogen required for this reaction must be supplied via other sources, namely those options for supply of hydrogen from Earth discussed in Section 4.2. A small amount of in-situ hydrogen is produced in the hydrogen reduction process due to the evolution of solar-implanted hydrogen from the feedstock. This source of hydrogen is discussed in more detail below in Section 4.2.6. Here we note only that, according to the stoichiometry of the above equation, for every 1 ton of oxygen produced 31 kg of hydrogen is required (Astronautics Corporation of America, 1987, p. B-4). Some portion of this hydrogen will be recycled back into the reaction chamber. Consumable recycling will be discussed further in later sections.

It is presumed that an initial amount of hydrogen would need to be brought from Earth, but it is important to consider losses of such a hardly containable element by leakage or venting that imply some little additional re-supply mass (Taylor & Carrier, 1993).

4.2.4 Process 2 - Carbothermal Reduction of Lunar Regolith with Methane

The most abundant minerals on the Moon are silicates, such as olivine and pyroxene (See Table 1-1). In 1961, Sanders Rosenberg and Gerald Guter proposed a process for extracting oxygen from lunar silicates, which they named the "Aerojet Carbothermal Reduction Process" (Rosenberg, 2002). This is a three-step process which, using the silicate forsterite (Mg_2SiO_4) as an example, involves the following chemical equations:

Step 1: Reduction of silicates using methane

$$Mg_2SiO_{4(l)} + 2\,CH_4 \Leftrightarrow 2\,MgO + Si + 4\,H_2 + 2\,CO \qquad \text{Equation 4-6}$$

Step 2: Recovery of methane and water production

$$CO + 3\,H_2 \Leftrightarrow CH_4 + H_2O \qquad \text{Equation 4-7}$$

Step 3: Water electrolysis and hydrogen recovery (reagent recovery)

$$2\,H_2O \Leftrightarrow 2\,H_2 + O_2 \qquad \text{Equation 4-8}$$

Step 2 is identical to the Sabatier process, and Step 3 again is water electrolysis, which is discussed in 4.1.2. Therefore, here we will focus our attention on Step 1. It is sufficient to mention that the methane product of Steps 2 is recycled back into Step 1, whereas the hydrogen product of Step 3 is fed back into Step 2.

In Step 1, lunar silicates are mixed with methane gas and heated to about 1600°C, which reduces the silicates to a mixture of iron and silicon metal and magnesia and aluminum slag, and produces an output stream of carbon monoxide and hydrogen gas. This process can use unbeneficiated lunar mare and highland materials, because silicates are an abundant component of nearly all lunar soil (Seboldt, 2001).

We note that as this process involves Sabatier processing of carbon monoxide to form methane, the carbothermal reduction process contains a strong synergy with Mars exploration, for which many have proposed processing of carbon oxides in the Martian atmosphere to produce methane and water for fuel and life support consumables (Zubrin & Wagner, 1996).

According to experiments performed by Orbital Technologies, Inc. (Orbitec, 2000), at least 9% of the regolith mass can be recovered as oxygen with virtually no loss of carbon (at 1630° C processing temperature) (Rice et al., 1996). Higher processing temperatures may allow up to 28% of the regolith mass to be recovered (Orbitec, 2000).

Consumables

At these operating conditions, the carbothermal reduction process is estimated to have a consumption ratio of 0.1 t/t O_2/yr of reagents. Also, the electrodes consumption caused by the electric arc heat is between 5 to 10 kg/ton of O_2, which translates to converting about 0.75% of the carbon flow in the total process into electrodes.

Advantages/Disadvantages

One of the advantages of this process is that it can be used with various types of olivine and pyroxene, which are very abundant in the lunar mares. Its disadvantage, however, is that it is a vertical process and this implies great challenges for its facility construction on the Moon. Although according to Taylor & Carrier (1993), it will be important to consider the option of constructing several small plants instead of building only one large plant.

4.2.5 Process 3 - Molten Silicate Electrolysis

The third process for oxygen extraction considered in the FERTILE Moon Model, is fundamentally different from the first two. Rather than involving a purely chemical process, Molten Silicate Electrolysis involves an electro-chemical process, similar in principle to water electrolysis (See Section 4.1.2). The process can still be represented by a fundamental chemical equation, namely:

Cathode reactions:

$$Fe^{2+} + 2e^{-} \Leftrightarrow Fe^{0} \qquad \text{Equation 4-9}$$

$$Si^{(IV)} + 4e^{-} \Leftrightarrow Si^{0} \qquad \text{Equation 4-10}$$

Anode reactions:

$$4(SiO^{-}) \Leftrightarrow 2(Si\text{-}O\text{-}Si) + O_2 + 4e^{-} \qquad \text{Equation 4-11}$$

As can be seen from the above equations, the primary products at the cathode are metals, namely elemental iron and silicon. At the anode, the primary product is gaseous oxygen. This process is visualized schematically in Figure 4-5 below.

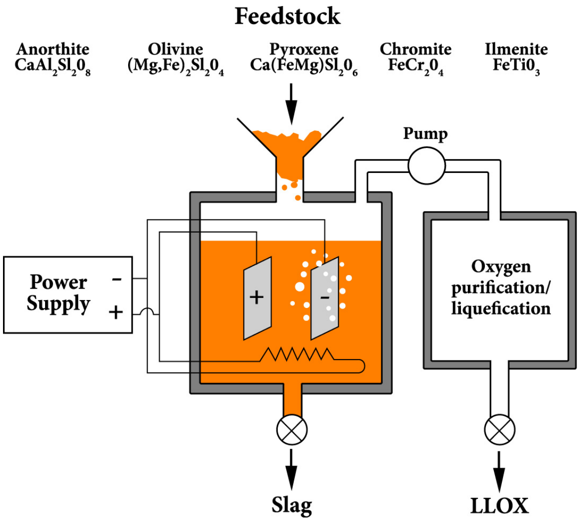


Figure 4-5: Molten Silicate Electrolysis Process. Reproduced. (Taylor & Carrier, 1993)

4.2.6 Process 4 - Hydrogen Extraction

Since Eugene Parker's theoretical prediction of the solar wind in 1958, scientists expected that the lunar surface, lacking a substantial atmosphere or magnetic field, would be bombarded by particles from the solar wind, namely protons (hydrogen nuclei). These incident particles are implanted typically in the outer 50 nm of lunar regolith grains, and can remain in these grains for billions of years unless otherwise disturbed (Walker, 1975).

On average materials at the lunar surface have been exposed to the solar wind for ~10 million years, accumulating many solar-wind particles during that time. As these materials are blanketed by ejecta from micrometeoroid impacts, this solar-wind implantation stops, but also becomes protected from losses due to future micrometeoroid disturbances. The study of loss/retention of solar-wind particles is an interesting and unfinished area of research (Schmitt et al, 2000), but for the purposes of our current model we are mainly interested in the question of how such particles can be utilized.

As early as 1979, researchers began suggesting that in certain lunar materials, concentrations of solar-wind implanted hydrogen (SWIH) could be high enough, such that those materials could be a useful "ore" for hydrogen (McKay & Williams, 1979). SWIH in the lunar regolith varies greatly with soil maturation, grain size, grain shape, and mineral composition. For example, it is well-documented that soil grains smaller than 20 µm have a hydrogen concentration greater than the grains larger than 20 µm (Carter, 1985), as can be seen in Figure 4-6.

From these facts, it is clear that in order to maximize the efficiency of hydrogen extraction, a site of high soil maturity should be chosen, and input feedstock should be beneficiated to concentrate the smaller size fractions. In this way, it should be possible to refine a process feedstock to a hydrogen concentration greater than 100 wt. ppm.

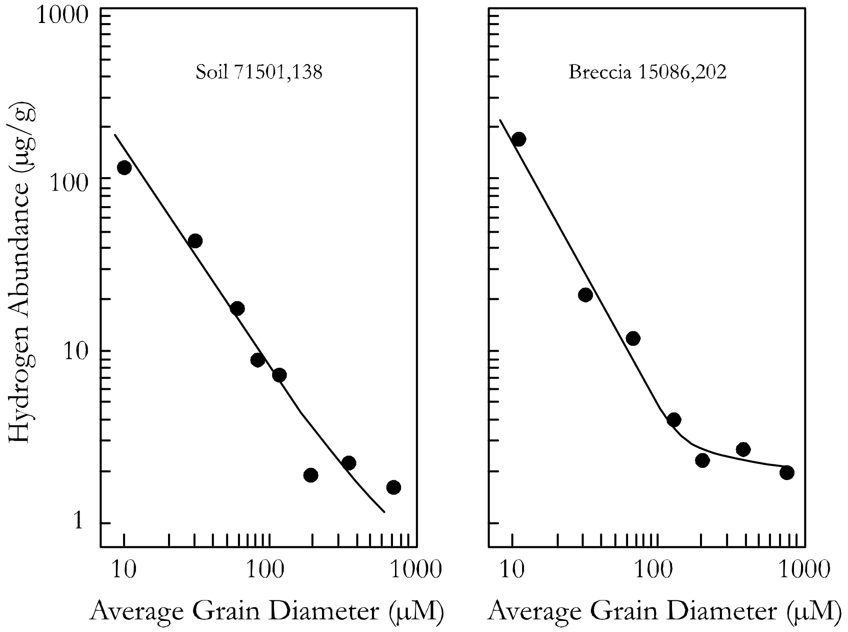


Figure 4-6: Hydrogen Abundances in Apollo Samples (Bustin and Gibson, 1992)

The actual process of hydrogen extraction is quite simple. SWIH can readily be extracted from lunar materials by heating it to sufficient temperatures. Approximately 80% of the hydrogen is released at 600°C and (Carter, 1984), and at 900°C, all of the hydrogen is released (Taylor & Carrier, 1993; Bustin & Everett, 1992).

4.2.7 Process 5 - Water Production

The production of water on the Moon from polar "icy-regolith" deposits remains a promising alternative to oxygen or hydrogen extraction because of the comparatively low temperature to which the regolith must be heated and the absence of a need for any chemical processing. Thus, compared to the four processes described above, there are no major technological challenges required to produce water from icy regolith, apart from the possible difficulties of operating in permanently shadowed craters. When comparing water production against the above processes, however, one must keep in mind the disadvantage that the existence of icy regolith at the lunar poles has not yet been demonstrated.

The Question of Water on the Moon

Early analyses of the behavior of volatiles on the Moon indicated that, due to its low molecular weight and ionization energy, water could not survive on the lunar surface for extended periods of time (Spitzer, 1952; Kuiper, 1952; Öpik & Singer, 1960; Vestine, 1958). Thus, at the onset of the space-age when scientists and engineers first began widely working on systems that could conceivably take humans to the Moon, most scientists believed that the Moon has no water at or near its surface.

Watson, Murray, & Brown (WMB) (1961) showed that the mass removal rate of any volatile on the surface of the Moon "is determined by the temperature of its solid phase at the coldest place on the lunar surface." What WMB argued is that water molecules, more so than other constituents of the supposed lunar atmosphere, should migrate towards "cold traps," provided by permanently shaded areas at the bottom of craters near the Moon's poles. These molecules would eventually form water ice deposits because the mass loss rate is limited by the evaporation rate of this solid phase (water ice). Since then, their theory of "lunar volatile behavior" has been debated extensively, as reviewed in Carruba & Coradini (1999).

It was not until 1998, with the flight of the U.S. spacecraft Lunar Prospector, that WMB's theory received at least partial confirmation. In this mission, a neutron spectrometer detected higher concentrations (on the order of 10 times higher than equatorial regions) of hydrogen at the lunar poles, which could indicate the presence of water (Feldman et al., 1998). It is important to note that no data has determined in what form that this polar hydrogen is bound, but it seems plausible that it could be in water form, at least enough to begin considering possible ways in which a polar source of water could be utilized.

In 1998, Duke et al. published an evaluation of the potential for mining and processing of lunar polar ice. They identified three possible architecture options for such operations, which will be discussed in more detail in Section 4.2.8 when we examine the equipment needed for water production. In this section, however, the element common to all three of these options will be discussed.

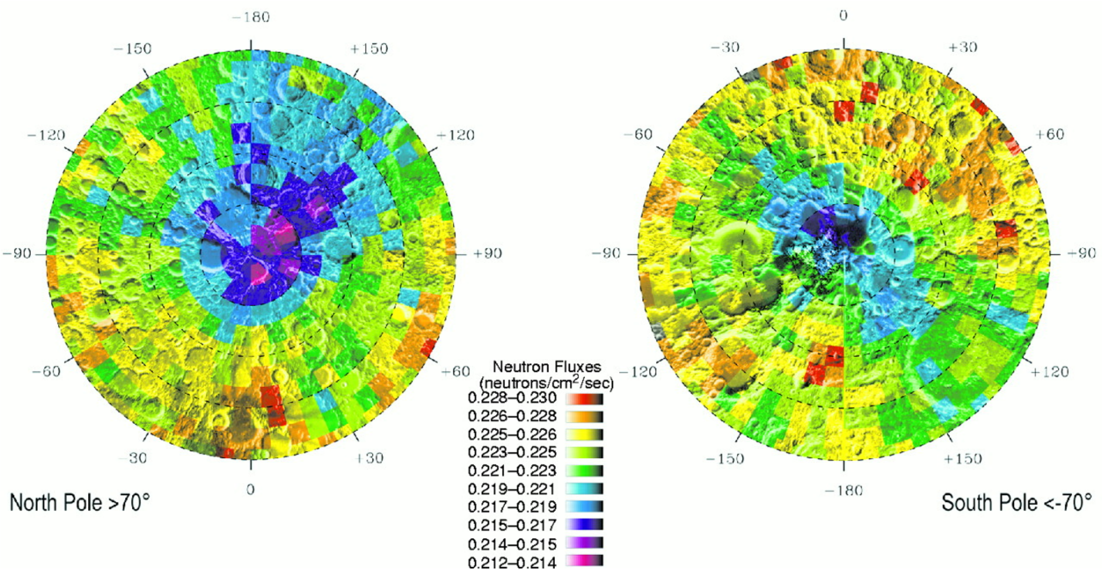


Figure 4-7: Epithermal Neutron Flux at Lunar Poles (Feldman et al., 1998)
Measured by Lunar Prospector. Hydrogen concentration is inferred from this data.

This common element comes from the fact that any ice present in permanently shadows at the Moon's poles must be converted into a form, namely liquid water, which can readily be accomplished by heating the regolith to above 200 K under vacuum (Blair et al., 2002) by electric heating, microwaving, or solar radiation. Obviously the latter would have to be done outside of the permanently shadowed crater, unless solar energy could be beamed from some distant location and targeted to an in-situ processing facility.

The feasibility of water production on the Moon depends strongly on the concentration and distribution of water in the permanently-shadowed craters at the poles. There is no consensus in the research community as to at which concentration water could be economically mined from lunar regolith, but for the purposes of this study, we have assumed that 1% by weight to be a reasonable baseline concentration, as was used by Blair *et al.* (2002) study of the economic feasibility of extracting polar water for commercial use in LEO.

If precursor missions demonstrate unequivocally that water is present at these concentrations, then the authors believe that water production trades favorably against the alternatives under study. Although we do not know at present what the concentration of water at the poles is, one key question that the FERTILE Moon Model is able to quantitatively analyze is, as a function of water concentration, just how well water production compares to oxygen and hydrogen extraction.

4.2.8 Key Parameters for the Model

There are many properties associated with IRSU supply processes and equipment, as they are described in the literature, used to characterize and compare different methods of extracting hydrogen, oxygen and water. For the twenty processes described in Taylor & Carrier (1992), the authors use qualitative descriptors to compare different extraction processes on the basis of technology maturity, number of steps involved, process conditions, and feedstock requirements. Their evaluation of our selected processes is listed in Table 4-5. Please note that the descriptor valuations are somewhat counter-intuitive; the most favored condition/requirements receive the highest value, as described below the table.

Table 4-5: Evaluation of Selected Processes

Process	Technology[1]	No. of Steps[2]	Process Conditions[3]	Feedstock[4]
Ilmenite reduction with H_2	8	9	7	3
Carbothermal reduction	6	3	3	10
Molten Silicate Electrolysis	6	8	5	10
Hydrogen Extraction	7	9	8	1
Water Production	7	9	8	1

[1] Technology: 1= major technologic development required; 10=no major unknowns

[2] No. of steps: 1=many (>5); 10=one step

[3] Process conditions (temperature, energy, plant mass, corrosion): 1=severe; 10=low

[4] Feedstock requirements: 1=huge quantities; 2=mare, beneficiated (ilm) 5=mare, unbeneficiated; 10=any feedstock, unbeneficiated

Since the purpose of a model is to most accurately reproduce a system's behavior using its simplest and most known attributes, one primary goal of our research was to identify which parameters, by which ISRU processes and equipment are described, are most important in determining the behavior of ISRU systems, namely their effectiveness in producing resources versus the cost of doing so. We have identified three primary parameters for each process that we initially expect to:

- Specific Mass
- Efficiency
- Specific Power

Specific Mass

Since the cost of transporting materials from Earth to the lunar surface (See Chapter 5) dominates other costs, such as manufacturing the materials on Earth into flight-ready hardware, the mass of facility equipment, which must be transported to the Moon is believed to a parameter of primary importance in establishing the cost of carrying out the targeted ISRU processes. Facility equipment includes the initial hardware sent to the lunar surface to install the integrated ISRU extraction, processing, and storage system. Note that this total equipment mass does not include mining equipment or power generation equipment, which are dealt with separately in the parameters efficiency and specific power, respectively.

Some processes require consumables, such as hydrogen, methane, or electrode materials, which are not available in sufficient quantities from lunar resources, and therefore must be delivered from Earth, contributing to the total required mass to be delivered. Spare parts will also contribute to the "recurring" mass required for ISRU processes, as they must be delivered from Earth to maintain ISRU systems. We will see in Section 5.2.3, how these recurring mass requirements, being fundamentally different from the initial facility mass that is required for each process, are dealt with individually in our mass/cost calculations.

In addition to delivery costs, mass is also an important indicator of development and production costs of equipment and facilities. Mass, when combined with a complexity factor, is used in parametric cost estimation models for many different industries to determine such costs. This method of cost modeling will be discussed in further detail in the Cost Chapter, it is essential to highlight the importance of mass for not just delivery costs, but also development and production costs.

Knowledge of the mass of a particular facility, system, or piece of equipment, however, is not enough to establish its effectiveness versus its costs. In addition, we must know how effective a given mass of equipment is in achieving its intended purpose. For example, an excavator's purpose is to excavate regolith and/or rocks, and transfer that material to another piece of equipment in the ISRU supply chain. One primary indication of its "effectiveness" is its excavation rate (e.g. kg regolith/hr). Similarly, an ISRU processing facility's intended purpose is to receive regolith and/or rocks as a feedstock and to extract useful end products, such as hydrogen, oxygen, or water. Even though the purpose of different equipment varies, all systems within the ISRU supply chain ultimately support the purpose of making useful end-products available for consumption. Therefore, all measures of effectiveness can ultimately be converted to some rate of production of a useful product (i.e. kg_{O_2}/hr).

Finally, to compare the cost indicator, in this case mass, of different systems or equipment against their effectiveness, we define a parameter "specific mass," as the mass of that piece of equipment per the production rate that it is capable of supporting. The standard unit of specific mass is ton of equipment per ton of product produced per year (t equipment/(t_{O_2}/yr)).

Efficiency

Another parameter that appears to be of primary importance is the "efficiency" of useful product extraction. Efficiency is defined as the mass of useful product produced per unit mass of unprocessed feedstock (e.g. ton of O_2 per ton of unbeneficiated regolith). This parameter determines the amount of mining which must be conducted in order to produce a given amount of product. Since mining equipment is expected to be a significant portion of the mass and power required for ISRU operations, this parameter is expected to have a large effect on ISRU process cost.

Specific Power

The final parameter, which we initially expected to be of significant importance, is specific power. Power refers to any energy rate used by an ISRU system, including mining equipment, processing/reaction chambers, liquefaction and electrolysis systems, and storage tanks that require active cooling. Specific power is defined as the power required per product production rate of a particular system. For example, a molten silicate electrolysis cell requires a certain power to operate at a certain oxygen production rate, whose units would be kW-hr/(t_{O2}/yr). Again, specific power is ultimately a measure of cost versus effectiveness. Other measures of effectiveness, such as excavation rates of mining equipment, can be normalized against the level, which that excavation rate contributes to product production for a given process. We show in Section 3.4 how specific power is used to calculate how the required power of a process contributes to its capital and operating costs.

One final note on power is that some processes require a distinction between required electric power versus thermal power. This is because the method of producing electric power is, in general, different from that to produce thermal power, and the two have different associated conversion efficiencies as discussed in Section 4.1. For instance, heating of feedstock to 1000°C is more efficiently achieved using a solar concentrator or nuclear thermal generator than by electric resistance or induction heating. This difference is handled in our calculations by converting all power requirements to electric-equivalent power, using the ratio of thermal power conversion to that of electric power conversion.

On the Scalability of Specific Mass and Specific Power

In identifying the specific mass, efficiency and specific power parameters, which are useful for modeling the total mass and requirements of different ISRU processes, a large assumption has been made that these values are constant over a wide range of production rates. This is only true if the relationship between, for example, plant mass and production rate is linear and the y-intercept of this relationship is reasonably close to zero. It is assumed that is correct, based on a sensitivity analysis on plant mass and power for the hydrogen reduction process to production rate carried out by Eagle Engineering, Inc (1998). It was found that this relationship was roughly linear over the ranges for production rate of 12 to 60 tons of O_2 per year and 1700 to 18000 tons of O_2 per year. The y-intercepts are also sufficiently small, such that if one compared the values of plant mass with y-intercept equal to zero to the given value for the y-intercept, there would be only a small difference (<10%) between the two values for plant mass. Thus, it is assumed both the specific mass and specific power are reasonably constant over these ranges of production rates.

It should be noted that there is no available information concerning the scalability of mass and power over the ranges of production rate between 60 tons of O_2 per year and 1700 tons of O_2 per year, an important range for the demand scenarios considered in the model. The authors believe, however, that because the adjacent lower and higher ranges are linear, it is reasonable to assume that plant mass and power are linear over a significant portion of this range as well.

The limitation to this method of calculating plant mass and power requirements from specific mass is we are limited to being able to compare data over only limited ranges of production rates (approximately one order of magnitude). Until a general scaling equation for plant mass and power as a function of production rate is determined, however, this remains the only relatively simple method available to model plant mass and power, without resorting to the rather complex set of full scaling equations used in Eagle Engineering, Inc. (1998).

4.2.9 Equipment

This section discusses the needs for equipment in the ISRU supply chain. The aim of this discussion is to provide a general description of the functions, requirements, and options for ISRU supply equipment, as well as to present our research into the key parameters for each piece of equipment, as described above in Section 4.2.8, which have been incorporated into our model.

The equipment in the ISRU supply chain can be divided into seven functional groups:

1. Mining equipment
2. Beneficiation systems
3. Extraction/Processing facilities
4. Water electrolysis equipment
5. Liquefaction and Storage equipment
6. Power systems
7. Surface transportation equipment (for maintenance of facilities)

Note that not all of this equipment is needed for all of the processes. Also, as groups four through seven are common to Supply from Earth and Supply from the Moon, they were discussed previously in Section 4.1. Therefore, here we will only reference information from that section as needed.

Mining Equipment

Mining equipment includes any machines required for the excavation and transportation of ISRU feedstock from its original location to the next phase in the ISRU supply chain, namely a beneficiation facility or directly to the extraction/processing facility. Mining equipment can be further divided into two functional groups:

1. Excavators
2. Haulers

We will briefly describe the proposed options for both of these groups and present the relevant data extracted from the literature for use in our model. A detailed discussion of each of these options is beyond the scope of our study, and where possible, we refer the reader to appropriate literature for more information.

Much of the mining equipment proposed is based on terrestrial mining systems, and concepts for adapting them to lunar operations have been proposed by various researchers. Dale Boucher of the Northern Centre for Advanced Technology, Inc. (NORCAT) has called this modification process “VAMPS,” which includes the following objectives:

1. Eliminate Volatiles, e.g. drilling fluids aren’t preferable on the Moon.
2. Automate, i.e. make extensive use of robotics.
3. Miniaturize and redefine the Paradigm.
4. Stabilize (Taylor, 2004).

For haulers, two options exist: the traditional dump truck-type hauler and a conveyer-belt system. Note that some mining equipment can also be used for site preparation, which could include leveling and clearing of a potential mining site.

Beneficiation Systems

Beneficiation refers to the process of separating and concentrating desired portions of an ore or feedstock. Two basic types of beneficiation systems have been proposed: size separation and magnetic separation. Beneficiation is an important step in the ISRU process that, in general, requires more research, but this research is beyond the scope of our current study.

Processing Facility

ISRU processing/extraction facilities represent the core of ISRU technology, and therefore, this section will go into slightly more detail. Again, however, a full discussion of the past, current, and future needed developments is beyond the scope of our study, and instead we will focus on those known aspects of ISRU facilities which are important for our model.

As described above, the five chosen ISRU processes differ from each other to varying degrees. In terms of required equipment, however, they contain several key similarities. First, all processes require heating of the feedstock to a particular temperature characteristic of that process. This heating will take place in some type of reaction/extraction chamber or vessel, or in the case of molten silicate electrolysis, an electrolysis cell.

The size and mass of this reaction/extraction chamber can be expected to be some function of the temperature required for the reaction/extraction, the amount of feedstock required to be heated, and the reactivity of that particular feedstock at those temperatures.

Another similarity between the five processes is that they all require a trade-off between batch processing and continuous processing of feedstock. Continuous processing can be expected to be more technically challenging, especially for processes which require large mass flows of feedstock at high temperatures. The benefit of continuous processing, however, is that it could allow higher production rates and possibly less labor/oversight costs. At this point in the infancy of ISRU technologies, however, it is too early to say which processes will incorporate continuous processing, so this aspect will have to be incorporated into a future version of our model.

Some companies like CARBOTEK have actually ventured to design and develop a physical plant for this process (Knudsen *at al.*, 1992). The main components of the plant are shown in Figure 4-8. The ilmenite, stored in a hopper, is conveyed by a belt to the fluidized bed, where it reacts with the hydrogen coming up through the bed. The product gas containing water exits through the top of the fluidized bed and enters the solid-state electrolytic cell, where the oxygen is bled off to cryogenic storage and the hydrogen is recycled through the bed. The spent ore is discharged alternately into one of two hoppers, which may be locked and pumped out to recover adsorbed hydrogen.

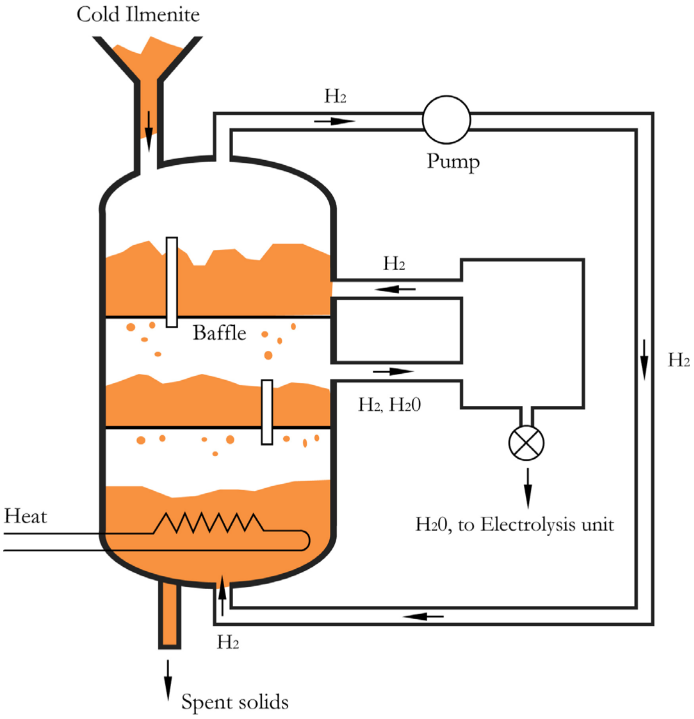


Figure 4-8: Plant Schematic for HRI-CARBOTEK (Knudsen et al., 1992)

The process developed by CARBOTEK utilizes a fluidized-bed reactor and a solid-state electrolysis cell that electrolyzes water in the vapor state. At 900°C, a stream of hydrogen is forced through a fluidized bed of ilmenite particulate to achieve a reasonable reaction rate. If all hydrogen reacted according to the ilmenite reduction equation and was recovered subsequently during the electrolysis step, it could be reused indefinitely without the need for additional hydrogen. In practice, however, as explained before, there are small losses, and this requires some hydrogen make-up.

A prototype of the CARBOTEK plant has been tested in reduced gravity operated in a KC-135 NASA research airplane experiment at 1/6 g_0 and found to operate predictably. There appear to be no serious microgravity issues associated with the solid electrolyte process, but a number of design problems with gas-phase electrolysis cells (principally zirconium) remain. Liquid-state electrolysis, on the other hand, is well developed and extensively used on submarines in Earth gravity. It is not clear, however, how well these or similar units would operate at reduced gravity. Thus, which form of electrolysis can ultimately be used is an open question. The prototype from CARBOTEK is registered under the US Patent number 5,536,378 (Gibson & Knudsen, 1996).

Finally, to give the reader an impression of the processing equipment required for each process, we include the following engineering drawings and/or schematics for each process. In some cases, these represent pilot production facilities and not full-scale production plants. Several processes are not developed enough to allow for accurate depictions of a full-scale production facility. For the case of hydrogen reduction of ilmenite, however, an artist's rendition of a full-scale facility is given in Figure 4-9, and the other four processes can be expected to involve a similar layout.

Figure 4-9: Hydrogen Reduction Facility
(Eagle Engineering Inc., 1998)

4.2.10 Unified Table

Now that the five processes have been described, as well as their required equipment and the key parameters associated with these processes and equipment, this section will describe the research carried out in order to determine the values for these parameters for each of the processes. The purpose of this research was to find the most reliable values possible for input into our model. Due to the time limitations of our study, our approach was to consult the widest range of literature available.

By far, the most useful one was Eagle Engineering, Inc. (1998), which is, in essence, a compilation of many individual previous studies. The limitation of the study by Eagle Engineering Inc. (1998) is that the authors of this study did not document all of the assumptions and details of these previous studies when citing their data. In fact, the authors note that data for process mass and power "is difficult to attain from literature on a consistent basis for comparison purposes…In some cases,…adequate data is not yet available to produce a plant design for meaningful equipment mass estimates. In other cases, process mass and power estimates may not include mining, beneficiation, complete processing, oxygen liquefaction and storage, or power system estimates." Thus, we realized that data from literature must be used with great caution.

In order to better understand the literature cited in Eagle Engineering Inc. (1998), we attempted to obtain all of the reports referenced in this study. This proved difficult, as many were old and/or obscure publications, or in some cases referring to unpublished work by a particular researcher. More time and resources would be required to obtain all of the relevant references, and in particular, this task would require the assistance of the wider ISRU/lunar research community.

Noting these limitations, we had other options but to proceed cautiously with the limited available data. From this data we converted all values to the standard units described in Section 3.2.9. Where more than one set of values was available for a particular process, we used the average value for each parameter. In at least one case, we had a dataset for a particular process with several data points (for a single parameter) lying close to each other but also one or two points lying significantly outside this grouping. In these cases, we ignored the outlying values in the average.

The results of this literature research are summarized in Table 4-6 listing the average values for the three key parameters for each of the five processes. We also list the type of feedstock the process requires and the product(s) it produces. These values were inputted into the model, providing the primary input dataset required for the ISRU supply portion of our analysis.

Table 4-6: Unified Table of ISRU Processes

ISRU Process	Feedstock	Output	Specific Mass	Specific Power	Efficiency
			$\frac{MassFacility\left(t\right)}{ProductionRate\left(t/year\right)}$	$\frac{PlantPower\left(kW\right)}{ProductionRate\left(t/year\right)}$	$\frac{MassProduct\left(kg\right)}{MassFeedstock\left(kg\right)}$
Hydrogen Reduction of Ilmenite	Mare soil Basalt rock	O_2	0.15	1.93	1.41%
Carbothermal Reduction of Silicate	Lunar soil (Olivine)	O_2	0.1	23	26%
Molten Silicate Electrolysis	Lunar soil	O_2	$6.5 \cdot 10^{-2}$	1.5	21.4%
Hydrogen Extraction	Lunar soil	H_2	3.4	124	0.004%
		O_2			0.007%
Water Extraction	Lunar soil	H_2O	$3.9 \cdot 10^{-2}$	16.4	1%

Another aim of our research was to estimate to some extent the uncertainty inherent in this input dataset. In the few cases where multiple reliable data values were available, we calculated the standard deviation of this dataset, which provides some measure of the uncertainty. In most cases, however, uncertainty had to be estimated liberally, based on our qualitative assessment of the reliability of these rather old engineering calculations. It is clear from our literature research that more detailed engineering study and "hard" engineering experimentation, including tests in simulated or real lunar gravity, are required, not only to decrease the uncertainty in these key parameters, but also to access the level of uncertainty itself.

Although we judge the reliability of the above data as very suspect, we proceeded with our modeling analysis with the encouragement of the ISRU research community, arguing that the methodology and modeling architectures we were developing is perhaps more important than the quantitative results of our model, especially at this stage of engineering and scientific knowledge. We feel that the above dataset represents quantitatively the best available knowledge of our selected ISRU processes possible within the time and resource constraints of our current study.

4.3 Summary

This section presented the available options for supplying the crews with necessary resources for various phases of lunar missions. In the supply from Earth strategy, two options are possible:

1. Transport hydrogen, oxygen and water separately.
2. Transport water only and produce hydrogen and oxygen on the lunar surface by electrolysis

As for supply from the Moon, many options are possible, but five chemical processes have been chosen for study and incorporation into our model. These processes are outlined below:

1. Hydrogen Reduction of Ilmenite
2. Carbothermal Reduction of Lunar Regolith with Methane
3. Molten Silicate Electrolysis
4. Hydrogen extraction
5. Water extraction

In order to assess the economic feasibility of these processes, the key parameters were identified and calculated and are listed below:

1. Specific Mass: the mass of equipment required per production rate of product
2. Efficiency: the mass of feedstock needed per unit mass of product
3. Specific Power: the power required per production rate of product

Based on these findings, the next chapter will describe the methods used for estimating the costs of supplying hydrogen, oxygen, and water for each of the supply options. These costing relations are integrated into the model, which are then able to compare the economical feasibility of various supply options against various resource demand scenarios and for different conditions of supply (e.g. Earth-Moon transportation cost, water concentration at lunar poles, etc.). Ultimately, the details presented in the above chapter for each process and for each step in the recourse supply chain determine the cost for supplying these resources. Therefore, these key physical parameters are integral in order to make decisions about how to supply the resources required for lunar exploration.

5 COSTING

As stated in the previous chapter, the aim of our study is ultimately to compare the costs of the two supply strategies considered, Supply from Earth and Supply from the Moon. Therefore, we must develop a method for estimating the cost of supplying our chosen resources as a function of the demand for that resource.

Cost estimation of ISRU activities is a relatively unchartered subject. Previous work on modeling lunar activities was discussed in Section 1.4, but the most applicable references for cost estimation of ISRU activities are Simon's (1984) parametric cost analysis of oxygen extraction from regolith. and Blair et al.'s (2002) work on water extraction from icy-regolith. We used these two works as starting points to develop our methodology for estimating general ISRU activities.

This chapter describes the cost estimation methods employed in our model, starting in Section 5.1 with those cost elements related the Supply from Earth strategy. Section 5.2 describes the costs associated with the Supply from the Moon strategy. First, Section 5.2.1 provides an overview of how the different portions of the ISRU supply chain were broken up into separate cost elements. Our methodologies for each of these cost elements, which are categorized as either capital costs or operating costs, are then described in more detail in Sections 5.2.2 and 5.2.3. Finally, Section 5.3 provides a summary of our integrated approach to estimating the cost of supplying hydrogen, oxygen, and water on the Moon.

5.1 Supply from Earth

Though hydrogen, oxygen, and water were delivered to the Moon as supplies for lunar exploration during the Apollo Program, a generalized estimation of the cost of delivering these resources to the Moon is not a simple task. This section describes our methodology for estimating the cost of these resources to the Moon, the so-called Supply from Earth strategy as discussed in Section 4.1. It begins with the cost of Earth-Moon transportation (Section 5.1.1), followed by the cost of water electrolysis including the power systems required for electrolysis, and finishing with a comparison of the costs for the different Supply from Earth options.

5.1.1 Transportation from the Earth

The procedure for determining the specific terrestrial supply launch cost to the surface of the Moon is outlined in this section. This evaluation is based on the LEO capability of existing and selected proposed launch systems along with the launch cost.

From LEO, two stages are assumed to be incorporated in the launch system for trans-lunar orbit injection and lunar orbit landing respectively. This option results in a lower vehicle mass despite the added complexity but the expended stage can potentially be used for its material and/or for storage of ISRU produced resources. Both stages are liquid oxygen and liquid hydrogen engines with a 450 sec specific impulse and 10% and 15% inert mass fraction for the first and second stage respectively. The higher inert mass fraction for the second stage is largely to account for the lunar landing gear. The liquid hydrogen and liquid oxygen combination is used as it delivers a high specific impulse. Resorting to this option, as opposed to a liquid methane and liquid oxygen engine which has a higher density, on the order of 10% inert mass fraction for the second stage, but lower specific impulse of approximately 370 sec is more advantageous from the specific cost perspective. These engine parameters are surmised to be reasonable in the proposed timeframe as both the Space Shuttle Main Engine (Boeing, 2006) and the Pratt & Whitney RL10 engine (Pratt & Whitney, 2006) exhibit such characteristics. The assumptions can thus be considered conservative.

It is important to note that this evaluation does not consider the upper stage engine costs. Also, the volume requirement of these stages is not factored in the computations. A multistage option such as the one herein will undoubtedly increase the cost due to the added inter-stages and complexity. A 5% delta-V margin is incorporated in the study to partially counterbalance these added costs, which ultimately results with an aggressive approach consistent with the study as a whole.

The launch systems used in this study are those which have the capability to deliver cargo to the lunar surface along with those which were identified to have a reliable cost. It is important to note that launch costs are often subject to negotiation where, for instance, if a package with the launch provider for the spacecraft, ground operations and insurance is purchased, the launch cost will likely be lower than that quoted in publicly available references. The data provided in Table 5-1 is an average of the cost range quoted by Isakowitz (2004).

Once the cost per kg to the surface of the Moon is established, these values are corrected for inflation to 2005 US dollars. The average cost is then based on selected launch systems, which are characterized with specific launch costs below USD 75,000/kg. It should be noted that by doing so, the economy of scale is taken as an advantage. The lower limit is set at those launch systems which can deliver a minimum of 500 kg to the surface of the Moon for practicability purposes. This study, largely based on existing launchers is in fact inherently conservative as it is based on current technologies and is expected to increase in efficiency within the 30 years proposed timeframe of the applicability of the FERTILE Moon Model. The lunar surface payload capacity of various launchers and their respective specific cost are outlined in Table 5-1.

Table 5-1: Terrestrial Supply Specific Transportation Costs to the surface of the Moon

Nationality	Launcher	Lunar Surface Payload (kg)	Specific Cost (USD E.C. '05) (kUSD/kg)	Average Specific Cost (kUSD/kg)
China	LM 2C	561	41.4	46.2
China	LM 2E	1333	42.5	
China	LM 3A	842	61.4	
China	LM 3B	1572	39.5	
Europe	Ariane 5ECA	2788	51.9	60.4
Europe	Ariane 5ES	2101	68.9	
India	GSLV	702	54.2	43.8
India	PSLV	519	33.5	
Japan	H2A 202	1405	51.5	50.8
Japan	H2A 2022	1518	51.1	
Japan	H2A 2024	1658	49.9	
Multinational	Zenit 3SL	1691	57.0	57.0
Russia	Dnepr-1	523	18.8	33.7
Russia	Proton K	2773	34.8	
Russia	Proton M	2947	25.0	
Russia	Soyuz 2	1109	42.3	
Russia	Soyuz FG	982	47.7	
Ukraine	Cyclone 3	575	40.4	32.6
Ukraine	Zenit 2	1953	24.7	
US	Atlas IIIB	1508	49.3	36.4
US	Atlas V 401	1702	42.4	
US	Atlas V 521	2876	28.6	
US	Delta IV H	3361	44.2	
US	Falcon V	707	17.5	
Worldwide		-	-	42.4

The worldwide average launch cost is determined at USD 42,400 (E.C. 2005)/kg to the surface of the Moon. It is important to note that the launch cost for the proposed US Space Shuttle derived Cargo Launch Vehicle (CaLV) was not identified in literature. However, according to (Wright, 2005), an estimate of USD 2 billion (E.C. 2005) per flight is proposed. The same source indicates that this is in fact the Saturn V cost per flight in 2005 dollars. Following further investigation and discussions with experts in the field, USD 2 billion (E.C. 2005) for both the CaLV and Saturn V flight costs are unreasonably high. Since no additional values were identified in literature, the CaLV cost per flight was not incorporated in the study but could be included once the data becomes available.

5.1.2 Electrolysis Costs

The cost of the electrolysis process can be divided in two parts. First, the cost of the equipment used to electrolyze water, liquefy the oxygen and hydrogen, and store the resources. The second part is the cost of the power required for the electrolysis and the liquefaction processes. Table 5-2 describes the specific cost of electrolysis, liquefaction and storage.

Table 5-2: Electrolysis, Liquefaction, and Storage Costs (Blair, 2002)

Equipment	Specific Cost (USDx10^6/kg of O_2 per hour)	Specific Cost (USDx10^6/kg of H_2 per hour)
Electrolysis System	10.8	10.8
Oxygen Liquefier	1.54	-
Hydrogen Liquefier	-	20.7
Water Storage Tank	0.00017	0.00017
Oxygen Storage Tank	0.00074	-
Hydrogen Storage Tank	-	0.0026
Total	**12.3**	**31.5**

An estimation of the mass and cost of these power systems was made. Table 5-3 summarizes the specific mass and cost of the three power systems used in the FERTILE Moon Model.

Table 5-3: Specific Mass and Cost of the Different Power System Types

Equipment	Electrolysis System	Liquefaction & Storage of O_2	Liquefaction & Storage of H_2
Specific Power needed (kW/kg$_{H_2O}$ /hr)	3.84	0.086 – 14.9	0.086 – 14.9
Solar power system			
Power per unit area (W/m^2)	182 – 338		
Mass per unit area (kg/m^2)	0.28 – 0.85		
Estimated cell cost (kUSD/kg)	20 – 150		
Power per unit mass (W/kg)	331 – 771		
Mass (kg/kg$_{H_2O}$)	4.98 – 11.6	0.111 – 44.9	0.111 – 44.9
Cost (kUSD/kg$_{H_2O}$)	**9.81 – 63.6**	**0.22 – 246**	**0.22 – 246**
RTG power system			
Power per unit mass (W/kg)	3.33 – 5		
Estimated cost ($/W)	7,000 – 20,000		
Mass (kg/kg$_{H_2O}$)	768 – 1,150	17.2 – 4,460	17.2 – 4,460
Cost (kUSD/kg$_{H_2O}$)	**26,900 – 76,800**	**602 – 297,000**	**602 – 297,000**
Nuclear power system			
Electrical Power density (W/kg)	1.49 – 195		
Mass (kg/kg$_{H_2O}$)	19.7 – 2,570	0.44 – 9,950	0.44 – 9,950
Cost (kUSD/kg$_{H_2O}$)	7,750	174 – 3,920,000	174 – 3,920,000

Table 5-4 summarizes the transportation cost of part of the electrolysis system used in the FERTILE model. The transportation costs were calculated using an average transportation cost of USD 47,500/kg.

Table 5-4: Transportation Costs for the Electrolysis System

Equipment	Specific Mass ($kg/kg_{H_2O}/hr$)	Specific Transportation Cost ($kUSD/kg_{H_2O}/hr$)
Electrolysis System	65 – 2,200	2,800 - 94,000
Liquefaction & Storage of O_2	11 – 2,000	470 – 85,000
Liquefaction & Storage of H_2	6.6 – 1,150	280 – 49,00
Solar power system		
Electrolysis System	4.98 – 11.6	210 - 490
Liquefaction & Storage of O_2	0.111 – 44.9	4.7 – 1,900
Liquefaction & Storage of H_2	0.111 – 44.9	4.7 – 1,900
RTG power system		
Electrolysis System	768 – 1,150	33,000 - 49,000
Liquefaction & Storage of O_2	17.2 – 4,460	730 – 190,000
Liquefaction & Storage of H_2	17.2 – 4,460	730 – 190,000
Nuclear power system		
Electrolysis System	19.7 – 2,570	840 - 110,000
Liquefaction & Storage of O_2	0.44 – 9,950	19 - 420,000
Liquefaction & Storage of H_2	0.44 – 9,950	19 - 420,000

5.1.3 Considerations for the Choice of Resources to Transport

This section will discuss the advantages and disadvantages related to bringing either only water and relying on electrolysis for the production of oxygen and hydrogen versus bring all the required oxygen, hydrogen and water from Earth.

Table 5-5 shows some basic information on the properties on hydrogen, oxygen and water. 88.81% of the mass of water is made up by oxygen; the remaining 11.19% is made up by the two hydrogen atoms.

Table 5-5: Molar Mass and Density of Liquid H_2, O_2 and H_2O (Air Liquide, 2005)

Resource	Molar mass (g/mol)	Density at 101.3kPa (kg/m^3)
Water, $H_2O_{(l)}$	18.02	1000[1]
Oxygen, $O_{2(l)}$	32	1141[2]
Hydrogen, $H_{2(l)}$	2.02	70.97[3]

[1] at 4°C (277.15K); [2] at -183°C (90.15K); [3] at -253°C (20.15K)

It appears that it is the mass of the resources, and not their respective volume, that is the main driver for the selection of which resource to send to the Moon. The launchers considered in the FERTILE Moon Model have a fairing volume estimated between 50 and 500 m^3 and a maximum payload mass around 4000 kg. In considering this mass, hydrogen, the less dense of these resources, occupies 56.4 m^3. Although this value does not consider the volume occupied by the tank, it is felt that this is a sufficient argument to only consider which resource to bring to the moon on the basis of mass. The volume occupied by water and hydrogen is even less.

To compare the cost of these resources via the two different methods, a margin has been included to the payload mass of the launcher in order to simulate the storage tank for liquid oxygen and hydrogen. Indeed these two resources need a special tank in order to keep them in the liquid phase. This tank mass has been evaluated at between 8 and 10 kg per cubic meter of stored resource in using the average cost of an actual composite liquid oxygen tank and the most recent Space Shuttle external tank (Dumoulin, 2000). This represents a margin of 0.85% for LOX and 11% of the total mass of the payload for liquid oxygen. The liquid oxygen tank's mass is then negligible in comparison to the mass of oxygen stored; this is the same case as the water tank.

The storage of oxygen and hydrogen represents an extra mass during the launch, which will increase the overall cost of transportation per kg. The average transportation cost is estimated at USD 42,400/kg for oxygen and USD 47,500/kg hydrogen.

The cost of hydrogen, oxygen and water on earth, has been found to be USD 3.60/kg for liquid hydrogen and less than USD 0.08/kg for both water and hydrogen. These costs are negligible compared to the transportation cost: therefore, the cost to bring hydrogen, oxygen and water from Earth is mainly the cost of the launcher.

Table 5-6 shows some other advantages and disadvantages of the two methods of bringing resources from the earth to supply lunar missions.

Table 5-6: Pros and Cons of Each Supply from Earth Option

Method	Pros	Cons
$H_2 + O_2 + H_2O$	• Commonly sent into space as propellant for the Space Station, etc. • Tank construction well known	• Hydrogen is volatile & flammable • Liquid oxygen is a very powerful oxidizing agent
H_20 + Electrolysis	• Water takes up 1/3 of the volume that would be needed to contain the same mass of liquid hydrogen and oxygen • Water is chemically inert • Water (liquid or ice) can also sustain high payload accelerations during launch • Once the equipment is on the Moon, only water need to be re-supplied	• Electrolysis quite expensive (mainly due to the energy used to electrolyze water), • Will be useful when on-orbit electrolysis become a viable alternative (cf. + above) • Need to bring all equipments on the Moon, which are quite heavy and will probably need launches specially dedicated to bring them

5.2 Costing of Supply from ISRU

This section describes our methodology for estimating the costs of the ISRU Supply strategy, i.e. producing hydrogen, oxygen, and water from lunar materials. First, we categorize different portions and traits of the ISRU supply chain into separate cost elements, defined below in Section 5.2.1. These cost elements are described in greater detail in Sections 5.2.2 and 5.2.3, and finally, our work on ISRU cost estimation is summarized in Section 5.2.4.

5.2.1 Breakdown and Definitions of Cost Elements

In order to begin the difficult task of estimating the costs of a complicated and unproven set of lunar activities, we first considered how the costs could be broken up into separate, functional cost elements. We naturally divided these cost elements into two categories, capital costs and operating/recurring costs.

Capital costs can be further broken down into development and production costs ($C_{D\&P}$), and installation costs (C_{Inst}, including transportation to the Moon). Furthermore, we separated the costs for the ISRU processing facility (including excavation, resource extraction, liquefaction, and storage equipment) from the power supply equipment, since they can be dealt with somewhat independently. Total capital costs are simply a summation of these two categories.

$$\text{Capital Costs} = C_{D\&P} + C_{Inst}$$ Equation 5-1

Next, operating costs are divided up into the following categories: maintenance/delivery of spare parts (C_{Maint}), labor costs (C_{Labor}), including ground support and astronaut labor, and delivery of consumables (C_{Consum}) i.e. reagent or electrodes for reactions. Again, we can separate the operating costs of the ISRU processing facility from that of the power supply. Therefore:

$$\text{Operating Costs} = C_{Spare} + C_{Consum} + C_{Energy} + C_{Labor} + C_{Mining}$$ Equation 5-2

All of these cost elements are summarized in Table 5-7 below, including the individual parameters of which we assumed these cost elements to be a function.

Table 5-7: Cost Elements involved in estimation of ISRU supply costs
This includes the parameters affecting the cost elements

Cost Element	**Symbol**	**Factors Involved in Parametric Costing Term**
Capital Costs		
Development and Production	$C_{D\&P}$	Mass and complexity of ISRU facility
Installation (including assembly)	C_{Inst}	Mass and complexity of ISRU facility, specific Earth-Moon transportation cost (USD/kg; see Section 5.1.1)
Recurring Costs		
Spares	C_{Spare}	Complexity of ISRU process
Consumables (reactant, electrodes, etc.)	C_{Consum}	Consumable consumption rate (kg/yr), specific Earth-Moon transportation cost (USD/kg)
Energy	C_{Energy}	Specific power of ISRU facility (see Table 4-6), specific cost of power (USD/kW; see Section 5.1.2)
Labor	C_{Labor}	Teleoperation costs, EVA costs
Mining	C_{Mining}	Mass and type of mining equipment, process efficiency, specific Earth-Moon transportation cost (USD/kg)

Complexity is a parameter often utilized in parametric cost estimation. For our study, complexity is defined as a function of the number of steps involved in the associated ISRU process and the severity of the process operating conditions, as described in Table 4-5. We use the same values for these two factors as Taylor and Carrier (1993), scaled from 1 to 10. Complexity (which we abbreviate, K) is then taken to be the average value of these two factors, but then the scale 1 to 10 must be reversed, such that the lowest level of complexity (K=1) reflects a low number of process steps and relatively benign process conditions; the highest level of complexity (K=10) likewise reflects that the process involves many steps and harsh operating conditions.

5.2.2 Capital Costs

As described above, capital costs can be divided into development and production costs, and installation costs, but we can also separate these costs for different portions of the ISRU supply chain. For simplicity, we separated the ISRU supply chain into only two separate portions:

1. ISRU processing facility (including systems for beneficiation, electrolysis, liquefaction and storage, etc.)
2. Mining equipment, including excavators and haulers

Two distinct methods were chosen for determining the capital costs associated with these portions of the supply chain, as described below.

ISRU Development and Production Cost

The development and production cost of an ISRU facility is assumed to include all the costs associated with research and development to bring the necessary technologies from their current Technology Readiness Level (TRL) to a flight-ready level (TRL=9), including production and testing of the first flight-unit. The Advanced Missions Cost Model (AMCM), developed by Johnson Space Center (Cyr, 2005). was used to estimate the development and production cost for an ISRU facility, utilizing Equation 5-3 below:

$$C_{Dev\,ISRU} = \alpha * Q^{\beta} * M^{\Xi} * \delta^{S} * \varepsilon^{1/(IOC-1900)} * B^{\phi} * \gamma^{D} \qquad \text{Equation 5-3}$$

The values for the constants in this equation are shown in Table 5-8 below:

Table 5-8: Value for Variables in Cost of Development of ISRU Equation

α	β	Ξ	δ	ε	ϕ	γ
5.65*10-4	0.594	0.66	50.6	3.8085*10-55	-0.355	1.569

Descriptions of the input parameters of Equation 5-3 and the assumptions made in our model to adapt the AMCM to ISRU facility costing are described below:

Q: Quantity or the total number of units to be produced, including all development units (simulators, ground-test articles and flight test articles) and all production units (flight units and spares). We assumed one production unit for all ISRU facilities.

M: Dry mass of the ISRU facility in pounds (1 pound = 0.453 kg).

S: Specification that designates the type of mission to be flown. Each mission type in the AMCM has a value associated with it that reflects the costs associated with that type of system. Since AMCM doesn't have a "mission type" category for ISRU, we had to chose some specification value based on the available choices. Noting that static spacecraft systems have a lower specification value than mobile spacecraft (landers, rovers, etc.), we chose a value of S=2, which is slightly lower than a manned habitat (S=2.13) and significantly lower than a planetary lander (S=2.46).

IOC: Initial operational year, i.e. the first year of operations. We assumed 2010 as the initial operating year for all ISRU processes, though we note that choosing any value over the range 2010-2040 does not significantly effect the result of this equation.

B: Block number, which indicates the number of previous modifications to a system design. For an entirely new design, as in the case of all ISRU facilities, a block number of 1 is used.

D: Difficulty, which is the relative programmatic and technical difficulty of developing and producing the element. This value ranges from -2.5 (extremely easy) to +2.5 (extremely difficult) in increments of 0.5. For this parameter, we used our previously defined complexity factor, only scaling our values to fit this range of values used in AMCM.

From the above parameters, one can deduce that the only parameters involved in the development and production cost equations used in are model that vary are the mass and complexity of the ISRU facility. For a particular ISRU process, complexity and specific mass are fixed, therefore to calculate the development and production cost for a particular ISRU facility, one needs only to scale it to the desired production rate.

Mining Capital Cost

As described above, mining was treated as separate from other ISRU facilities, as mobile mining equipment is significantly different in form and function from static ISRU facilities. Two types of mining equipment were considered, excavators and haulers, as described in Section 4.2.9.

Based on the mass of this mining equipment, development and production costs were calculated based on data from Blair et al. (2002), as shown in Equation 5-4.

$$\begin{cases} C_{dev\&prod\_Excavator} = 50 * M_{excavator} + 50100 \text{ [k\$]} \\ C_{dev\&prod\_Hauler} = 55.46 * M_{hauler} + 71800 \text{ [k\$]} \end{cases} \qquad \text{Equation 5-4}$$

The total capital cost is the sum of development and production cost, and Earth-Moon transportation cost (assuming no assembly on the Moon is required for mining equipment).

Finally, we note that both of these two portions of the capital costs involved in the ISRU supply chain can be converted and combined with the operating costs by considering the capital costs to be amortized over the lifetime of the associated equipment and adjusted for the Net Present Value of that capital. For both portions, ISRU development and production cost and mining capital costs, we assumed an equipment lifetime of 10 years and an interest rate of 24%. We note that this interest rate is an extremely conservative value, based on the fact that ISRU is at present an undeveloped and unproven technology. Future work includes analyzing the sensitivity of interest rate on the total supply costs. For government-funded projects, a lower interest rate can easily be inputted into the model.

5.2.3 Operating Costs

As described in Section 5.2.1, operating costs for ISRU facilities are broken down into five cost elements:

1. Spares
2. Consumables
3. Energy
4. Labor
5. Mining

Below the methods for estimating the operating costs for each of these cost elements are described in detail.

Spare Parts

To account for the maintenance requirements of ISRU facilities, we assumed spare parts would have to be delivered from Earth to the Moon at a baseline rate of 10% of the facility mass per year (Koelle, 1989). Depending on the particular ISRU process involved, however, we assumed this value will vary over a range of, again varying with the complexity factor of the ISRU process, as described in Section 5.2.1. Scaled to this +/- 5% range, the spare parts factor for each process is shown below in Table 5-9.

Table 5-9: Spare Parts Factor Based on the Complexity Factor for Each Process

ISRU Process	Spare Parts Factor (%)
Hydrogen reduction with Illmenite	7%
Carbothermal reduction of silicate	12%
Molten silicate electrolysis	9%
Hydrogen extraction	6%
Water extraction	6%

Finally, the cost associated with spare parts for each ISRU process is calculated based on the cost of transporting spares to the Moon at the above replacement rates.

Consumables

As described in Sections 4.2.3 to 4.2.7, some ISRU processes require consumables, such as reagents or electrode replacements. During our research of these processes, however, we found that information about consumption rates for each of the processes was not available. Therefore, the cost of consumables was not included in our model, but should be incorporated into future versions (see Future Work section). In the opinion of the authors, however, the above spare parts replacement rates are conservative enough to account for consumables, at least well within the error levels of our current model. Furthermore, the spare parts factors listed above scale well with the assumed consumption rate for each process, at least qualitatively.

Energy

The cost of providing energy costs to ISRU operations is simple is directly proportional to the specific power of the associated ISRU process. Our model calculates energy costs for ISRU in the same way that the costs of powering electrolysis equipment are calculated in Section 5.1.2. The specific power for each ISRU process, as listed in Table 4-6, replaces the specific power of the electrolysis process as listed in Table 5-3. Again a power threshold is set, such that above 10kW, we assume nuclear power will be used, while below 10 kW solar cells will be used.

Labor Operating Costs

Next, we must estimate the costs for labor associated with ISRU facility operations. We subdivided labor operations between teleoperation and EVAs. It is assumed that all normal operations are performed using teleoperation, whereas EVAs are needed only for maintenance. We assumed a baseline maintenance requirement of 100 hours per year (2.5 full-time work weeks of mainentance per year), based on experience with terrestrial industrial operations.

The teleoperation costs were calculated using the Space Operations Cost Model (SOCM), developed by NASA. The inputs to the model are summarized in Table 5-10.

Table 5-10: Summary of Model Inputs for Space Operations Cost Model

Variable	Input Value
Mission Characterization	
Mission Type	Planetary Lander
Mission Target	Small bodies
Number of Flight Systems	Variable
Cruise Time	1 month
Encounter Time	Variable
Programmatic Characterization	
Mission Risk Class	Discovery, moderate risk
Development Schedule	Long (> 4 years)
Payload Characterization	
Number of Instruments	No instruments - all instruments set to 0
Spacecraft Design Characterization	
Complexity / Attitude	Medium

This model is best suited for spacecraft operation costs and not for ISRU, however, several assumptions were made to adapt this model. The "Number of Flight Systems" variable was assumed to be a measure of the complexity of the operation of the facility, similar to as described above in Section 5.2.1. Table 5-11 below shows the number of number assigned for each ISRU facility, depending on their relative complexity and the plant mass.

Table 5-11: Facility Values Based on Complexity and Mass

PROCESS	NUMBER OF UNITS		
	SMALL 10 ton	MEDIUM 100 ton	LARGE 1000 ton
Hydrogen Reduction of Ilmenite	3	6	9
Carbothermal Reduction	4	8	12
Molten Silicate Electrolysis	2	4	6
Hydrogen Extraction	3	6	9
Water Extraction	3	6	9

The above variables, when inputted into the SCOM, are used to compute a set of 15 linear equations, which give the operating cost in k$ as a function of mission duration in months (Figure 5-1). Table 5-12 shows the values for the slope and intercept (A and B parameters, respectively) of the equations.

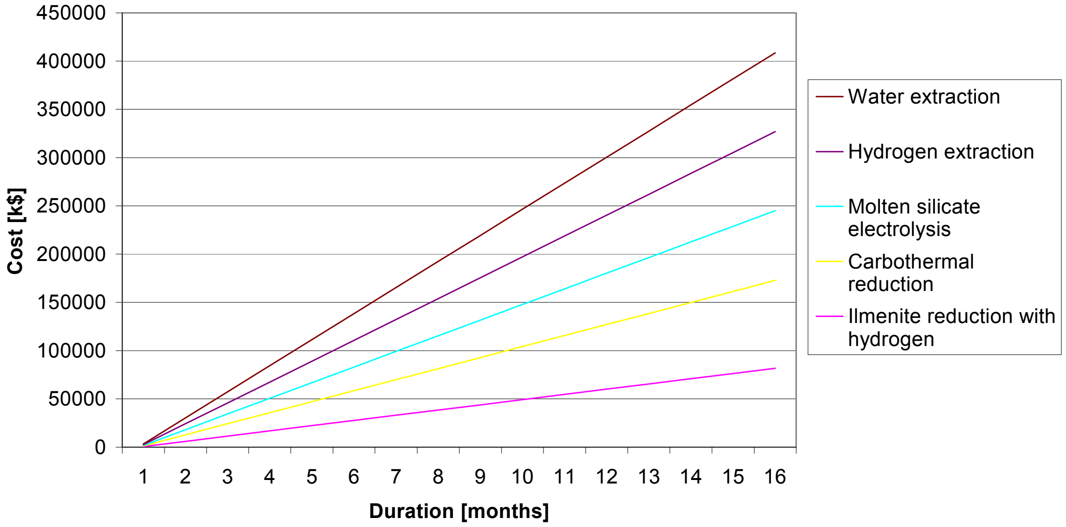


Figure 5-1: Graph of Cost versus Duration for ISRU Labor Costs

Table 5-12: Values for the Slope and Intercept

PROCESS	SMALL 10		MEDIUM 100		LARGE 1000	
	A	B	A	B	A	B
Hydrogen Reduction of Ilmenite	900.81	628.86	1211.5	842.4	1522.3	1057.3
Carbothermal Reduction of Silicate	1004.4	700.27	1418.7	985.98	1833.1	1271.4
Molten Silicate Electrolysis	797.11	557.2	1004.4	700.27	1211.5	842.4
Hydrogen Extraction	900.81	628.86	1211.5	842.4	1522.3	1057.3
Water Extraction	900.81	628.86	1211.5	842.4	1522.3	1057.3

Mining Operating Costs

The mining operating costs were derived using the same procedure as for the ISRU facility operating costs described above. The total mining cost per year corresponds to the sum of the operating costs and the amortized portion (one year out of total lifetime of equipment) of the mining capital costs, which were described above in Section 5.2.2.

5.2.4 ISRU Cost Estimation Summary

The methods for estimating the costs of ISRU activities described above represents a first-attempt at calculating all conceivable costs involved in such operations. We took a conservative approach, noting that costs of space projects are often underestimated. As engineering information about the ISRU facilities and lunar mining equipment improves, the costs estimations can be improved, using the same or refined methods, implemented in future versions of our model.

5.3 Summary

In this chapter, we described our methods for estimating the costs of supplying hydrogen, oxygen, and water for each of the supply options. These costing relations are integrated into our model, which is then able to compare the economics of various supply options against various resource demand scenarios and for different conditions of supply (e.g. Earth-Moon transportation cost, water concentration at lunar poles, etc.).

As noted above, the ISRU cost estimations are considered to be on the high-end (i.e. they account for considerable unknowns and can be expected to decrease as more information becomes available.), while the Supply from Earth cost estimations are considered to be on the low-end compared to Apollo-based transportation costs. Thus, when we compare the costs of ISRU Supply versus Supply from Earth, a conservative handling of the large uncertainty of ISRU is built-in to these estimations. This should be kept in mind when studying the results of these comparative analyses, which are the subject of the following chapter.

6 POLITICAL, LEGAL, AND ETHICAL ASPECTS

As noted in the introduction chapter, there have been several models already created to help with the analysis of ISRU, but the FERTILE Moon Model has several innovative features that give it an advantage over the previous models. One of these features is the use of an interdisciplinary approach to modeling. The FERTILE Moon Model not only looks at engineering cost issues, but also the affects of such fields as policy, law, and ethics.

This chapter will start with a brief discussion on international policy before describing how the FERTILE Moon Model accounts for cost overheads created when States partake in international cooperation. Section 6.2 introduces the possible threats to a State's participation in ISRU missions from the viewpoint of international law. The section discusses the ISRU legal risk survey that accompanied the FERTILE Moon Model in order to inform users of the areas of legal contention that have to be addressed before committing to ISRU missions. Section 6.3 will highlight some of the ethical aspects that the FERTILE Moon Model must also consider in order to be truly interdisciplinary.

6.1 International Policy

ISRU has been brought to the forefront of international politics again with the New Vision of Space Exploration within the United States. Political statements such as this can cause the might of a nation to be pushed behind a project, while the next statement may cause the entire concept to be abandoned. This is the power of policy has on space activities and therefore, policy cannot be ignored when discussing the feasibility of an idea.

The national space agency policies on ISRU are motivated by different things depending on which State one is looking. NASA is studying the subject and its feasibility as demonstrated by an ESAS Appendix being devoted to ISRU. China's white paper contains long-term development targets that include the phrase, "the exploration and utilization of space resources shall meet a wide range of demands"(CNSA, 2000). Japan has a number of scientific missions to assess extra terrestrial resources with Hayabusa that has collected asteroid samples and is returning to earth and the SELENE mission planned to "evaluate [the] possibility of utilizing the Moon." (JAXA, 2005) The European Aurora Programme's Report on "Technologies for Exploration" outlines technological developments for resource utilization (ESA, 2005). The Russian Space Agency's interest in lunar ISRU is for commercial harvesting of He_3 could finance their lunar exploration program.

Corporate interest in extraterrestrial terrestrial resources is growing with companies looking at He_3 like the Russians. Other interests are in water, oxygen and hydrogen utilities services, which could be provided to the national agencies with their resources. Even more interest is in lunar resources for building materials like concrete, titanium, magnesium and other structural materials. The lunar silicon could be utilized for solar panels as well as electronics. As lunar resource utilization becomes more and more attractive, corporations will begin to lobby their governments to provide legal regimes which would enable them to profit from these resources and to cooperate with others on an international level. Cooperation could take place in terms of both national and corporate ventures.

Typically international cooperation between two nations is mandated by government as a political decision or is aimed at obtaining a required competency required for the mission. Politics and cooperation, however, have a price associated with it. This section will investigate and attempt to model some of the costs associated.

6.1.1 International Cooperation

Cooperation between two countries could have many motivations. Some cooperation's are formed through governmental mandate while others are to obtain competencies, which are not nationally available. The most common rational behind cooperation is the reduction in cost. Public cost on a space project is typically a major driving factor behind which projects are selected or how many. Project cost is also affects if an international partner is needed to reduce the cost to the nation. Cooperation, however, typically does not decrease the total cost it creates overhead, supervisors, check mechanisms for a partners work and redundancy. How easily two nations work together is proportional to how much they have worked together in the past and how good their diplomatic relations are. The higher the trust and the better the past experiences the easier it is for two nations to work together with a minimum of overhead costs.

To incorporate the cost increase due to international partnerships, of the ISRU missions being modeled, the relative ease of cooperation must be assessed between all candidate countries. Assigning a value to cooperation is not a simple task as many factors come into play, such as, the history of the countries, the current diplomatic state, the past activities in the sector, and their success-failure ratio. By quantitatively assessing these factors between the two countries it is possible to assign a numeric value, which is relative to the possible cooperation's. This numeric value should represent the difficulty level of the cooperation with which two countries are able to work together. From this factor it is possible to determine a relationship between the countries cooperating and the costs associated with the partnership.

International Cooperation Matrix

The matrix, as seen in Table 6-1, is the relative cooperation values, which are assigned between zero and one (0-1) this table was completed through a survey of ISU faculty. The Faculty were asked to evaluate the ease/willingness of two nations to cooperate on a project within the field of space exploration. This matrix excludes commercial cooperation and cooperation in the field of terrestrial research. The survey was conducted asking the participants to keep in mind a relative scale. The scale begins with a zero, which constitutes two countries who would never consider working together (e.g. USSR and the USA before Apollo-Soyuz or China and Japan today). A value of one is allotted when two countries have an existing infrastructure and can easily work together with few redundancies (e.g. Almost Canada and USA or ESA partner states). The score of 0.5 implies that there have been cooperative efforts some more successful than others; however, due to this history diplomatic channels for cooperation are open and there is an existing infrastructure. An example of a 0.5 is China and ESA with collaborative projects such as Double Star and Chinas desire to participate in Gallileo. For two countries that have never cooperated with each other but nothing preventing them from doing so receive a coefficient of 0.2.

Cooperation Factor

To assess the ease of cooperation, known from this point forward as the cooperation factor (CF), of a multinational cooperation the cooperation values in the matrix must account for all links. Therefore, as the number of cooperating countries increases the number of 2 party relationships increases by the triangular series function (0, 1, 3, 6, 10…) for 4 cooperating parties there are 6 relationships to incorporate. The cooperation factor for a multinational cooperation is the product of all the unique two party relations, within the partnership, raised to the power of the inverse of the number of relationships as described numerically in Equation 6-1.

$$CF = \left(\prod_{i=1}^{n-1} \prod_{j=i+1}^{n} m_{(i,j)} \right)^{\left(1 \Big/ \sum_{k=1}^{n} (n-1) \right)} \qquad \text{Equation 6-1}$$

As an example the ISS is a partnership between Canada, ESA, Japan, Russia and the USA with five partners results in 10 bilateral relationships and a cooperation factor 0.62 according to the average results of a survey of experts. This factor describes the difficulties in organization, decisions making, negotiation and agreement within the project.

Table 6-1: The International Cooperation Matrix

Cooperation in Exploration	**Argentina**	**Australia**	**Brazil**	**Canada**	**China**	**ESA**	**France**	**Germany**	**India**	**Indonesia**	**Israel**	**Italy**	**Japan**	**Philippines**	**Russia**	**Spain**	**Ukraine**	**United Kingdom**	**United States**
Argentina		0.15	0.55	0.45	0.30	0.15	0.40	0.50	0.10	0.05	0.05	0.25	0.35	0.15	0.35	0.50	0.20	0.00	0.60
Australia			0.15	0.45	0.40	0.62	0.45	0.62	0.15	0.30	0.10	0.35	0.65	0.40	0.35	0.25	0.20	0.50	0.85
Brazil				0.15	0.47	0.37	0.57	0.25	0.20	0.05	0.05	0.15	0.25	0.05	0.48	0.25	0.50	0.20	0.70
Canada					0.20	0.90	0.70	0.60	0.35	0.15	0.25	0.25	0.45	0.20	0.35	0.35	0.25	0.75	0.98
China						0.53	0.55	0.30	0.05	0.05	0.05	0.30	0.00	0.00	0.57	0.30	0.20	0.20	0.30
ESA							0.98	0.97	0.45	0.25	0.35	0.87	0.68	0.25	0.80	0.80	0.40	0.70	0.95
France								0.80	0.60	0.20	0.35	0.67	0.55	0.15	0.82	0.80	0.50	0.70	0.85
Germany									0.50	0.15	0.45	0.67	0.60	0.15	0.77	0.55	0.40	0.50	0.80
India										0.40	0.05	0.30	0.20	0.50	0.65	0.50	0.20	0.10	0.55
Indonesia											0.05	0.25	0.25	0.35	0.35	0.15	0.10	0.10	0.35
Israel												0.25	0.10	0.05	0.15	0.10	0.15	0.40	0.85
Italy													0.25	0.15	2.80	0.75	0.25	0.45	0.95
Japan														0.05	0.40	0.30	0.15	0.30	0.70
Philippines															0.20	0.25	0.05	0.15	0.25
Russia																0.70	0.88	0.40	0.45
Spain																	0.40	0.65	0.75
Ukraine																		0.25	0.55
United Kingdom																			0.80
United States																			

Legend
1.0 = Perfect Cooperation
0.5 = Imperfect Cooperation
0.2 = No History of Cooperation
0.0 = Very Unlikely in Cooperation

Cooperation Cost Multiplier

The cost implications on international policy typically are driven by how well the two parties are able to work with one another. If two countries do not trust one another or have never worked together it is inevitable that there are going to be redundancies and duplications in work. As two countries work together and develop a mutual trust as well as a historically based set of procedures a cooperation will being to run smoothly with very few redundancies and a minimum overhead due to the cooperation.

The Transcost model by Dr. Dietrich E. Koelle developed the cost growth factor of (Equation 6-2) which was a marked improvement over the previously noted value of $\sqrt{n}$ (Koelle, 1998). The Transcost model accounts for redundancy through looking at the number of parallel co-contractors (N) within the cooperation. It is noted that for the Transcost model that this is only applicable with parallel subcontractors and not valid where the organization follows a strict prime subcontractor relationship.

$$CCM = n^{0.2} \qquad \text{Equation 6-2}$$

$$CCM = n^{\left(0.4 - \frac{CF}{2.5}\right)} \qquad \text{Equation 6-3}$$

The cooperation costing factor for the FERTILE Moon Model (Equation 6-3) starts with the incorporation of the Transcost model, cost growth factor and a relative scale based on the ability to cooperate. From this a linear scale was created between 0 and 0.4 where a cooperation factor of 0.5 results in the same results as the Transcost Model. This implies that if a cooperation factor is less than 0.5 the costs of negotiation and establishing of protocol will consume resources and create costs. Where as those who have a cooperation factor of greater than 0.5 have an established relationship with channels to begin cooperation, establish criteria and processes. As the value approaches 1, the two nations are very cooperative and have minimal overhead and redundancy within their organizations due to the cooperation and would resemble a prime and subcontractor relationship.

The adopted Cooperation Multiplier for the FERTILE Moon Model (Equation 6-3) is an evolution of the Transcost model, which tends to zero through two methods. If the Cooperation Factor as calculated through Equation 6-1 tends to 1 the Cooperation Multiplier tends to 1. As the number of cooperating countries tends to 1 the Cooperation Multiplier goes to one.

Continuing the example of the ISS given above that has a Cooperation Factor of 0.65 and 5 cooperating nations, the Cooperation Cost Multiplier thus equals 1.33. This assumes equal cooperation between all 5 States, which is not the case.

Model Integration

Within the model you can choose up to 4 nations from a list of 19 nations. For the four cooperating nations the Cooperation Factor is calculated and from this the Cooperation Cost Multiplier is calculated. This model also assumes that all parties are equal partners and that the value received from 1 USD is equal in all countries. The model does not incorporate the cost of cooperation into the total cost but provides an output note giving the Cooperation Cost Multiplier in percent increase.

6.2 Legal Aspects of ISRU

The FERTILE Moon Model compares different ISRU processes and terrestrial supply options for lunar missions in terms of physical parameters and costs. While the model can show the technical and financial benefits of ISRU processes, it does not include the legal ramifications of using these processes. These ramifications could introduce complications and costs to any State that decides to utilize ISRU. Without a discussion of the legal risks of ISRU, a comparison between it and terrestrial supply options is incomplete.

The difficulty in assessing the legal risks of ISRU is that the discussions rarely produce "black or white" analytic answers. This is a grey region because no State has yet performed any extraterrestrial or lunar ISRU, most of the discussions surrounding the legal aspects are still academic with a great amount of vagueness existing in the field. In order to address this, the creation of the FERTILE Moon Model was accompanied by an ISRU legal risk survey that was distributed to the legal community to gauge the current atmosphere surrounding the topic.

6.2.1 Legal Risk Survey

Along with the overall legality of ISRU, there are several specific areas of contention when discussing the legal risks. These areas include property rights, preservation, export control, intellectual property rights, and liability. The survey was meant to gather the opinions of several experts in the space law community in order to highlight which of these issues might be the greatest concern as well as discussing possible mitigation strategies and solutions to these legal roadblocks.

The ISRU legal risk survey consists of 11 questions and was performed through an online survey service. Three rounds of invitations to participate where sent out. The first round was to the mailing list of "ISUTalk", which provided several opinions from space enthusiasts not in the legal field. The second round of invitations was sent to various experts in the legal field. The third round of invitations was distributed with permission to the European Center for Space Law (ECSL).

Those choosing to participate followed an internet link to the survey, which encouraged them to try and examine the issues facing ISRU through a series of yes-or-no questions, which can be seen in Table 6-2; however, legal issues are rarely straightforward and gave way to many interesting comments. These comments have been used to analyze the survey and its related subjects. Many varying opinions were expressed from legal experts from various States. A partial list of the participants to this survey can be seen in the Acknowledgements at the beginning of this Report.

Table 6-2: Table of Questions from the ISRU Legal Risk Survey

Question 1	Do you believe the use of lunar resources for exploration goes against international law?
Question 2	Will a commercial ISRU facility on the Moon be seen as going against current international law?
Question 3	Can the Antarctica Treaty be used as a precedent for determining property rights of extracted lunar resources? If yes, will it have a negative result?
Question 4	Can the Law of the Sea be used as a precedent for assigning property rights to extracted lunar resources? If yes, will it have a negative result?
Question 5	Would the extraction of resources alone be considered as environmental damage that could invoke objections to continued ISRU supported missions?
Question 6	Would you consider ISRU technology as dual-use and therefore limited by export control issues?
Question 7	Do you think the current regimes towards intellectual property rights are sufficient for ISRU missions?
Question 8	Do you believe that the current regimes towards liability are sufficient to cover accidents involving ISRU facilities?
Question 9	Is the Moon Treaty a "dead document"?
Question 10	Regarding a new Moon Treaty, do you believe it is more reasonable to introduce an entirely new treaty or to propose amendments to the existing Moon Treaty?
Question 11	What articles of the Moon Treaty would need to be amended to make the treaty favorable to all space faring states?

6.2.2 Overall Results

The ISRU legal risk survey highlights many of the common concerns of the legal community as well as many areas of contention. While the amount of responses were hampered by the limited time frame of the survey, the analytical responses, tabulated in Figure 6-1, can be used to extrapolate several trends in the present thinking of the legal community:

- There is a strong belief that the implementation of ISRU processes does not go against international law.
- While there was contention whether or not the Antarctica Treaty and Law of the Sea could be used as precedents for defining property rights, most experts who did see it as a precedent do not think it would negatively affect ISRU.
- A majority of the legal community believes that ISRU, in itself, would not be considered as environmental damaging.
- A majority of legal experts see ISRU technologies as dual-use technologies that would be affected by export control.
- There is a strong opinion that the liability and IPR regimes were not sufficient for ISRU processes.
- There is contention about whether or not the Moon Treaty is a "dead document"
- There is contention whether or not it would be better amend the Moon Treaty or to create an entirely new treaty.
- The main section that would need to be changed to make the Moon Treaty acceptable to space-faring nations is Article 11.

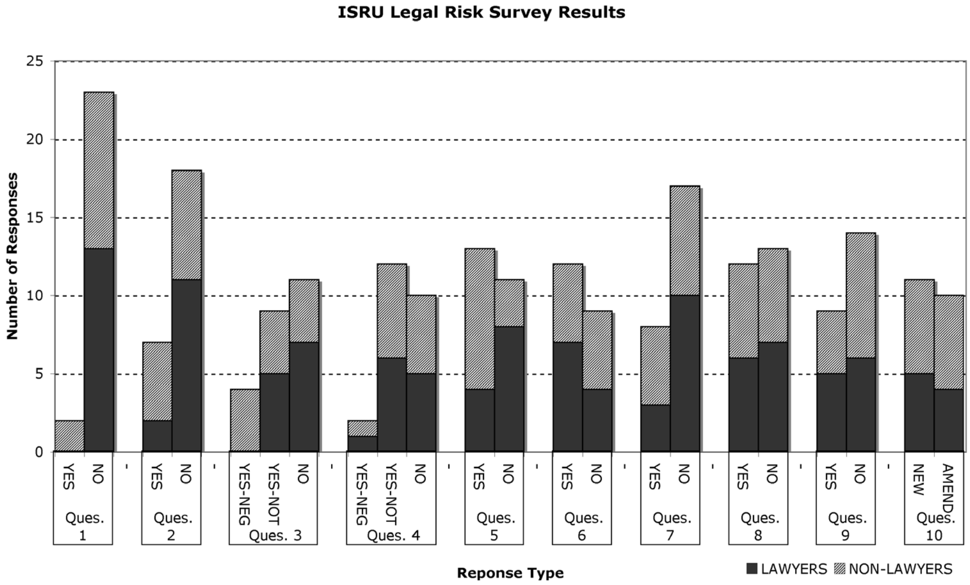


Figure 6-1: Responses from the ISRU Legal Risk Survey

6.2.3 Areas of Contention

Along with the analytical results, the survey produced various opinions from legal experts that highlighted several areas of contention with the future use of in-situ resources and discussing requirements or factors that affected the responses. The survey also presented several thoughts on how to mitigate these risks. The following sections discuss and summarize the thoughts presented in the survey. Direct comments are shown in quotations; however, to protect the anonymity of the thoughts of our experts, the quotations will not be linked to specific persons.

Legality of Missions

The legality of ISRU supported missions is contained in the 1967 Outer Space Treaty (OST) (United Nations, 1967). The freedom to explore outer space for the benefit of all mankind is the treaty's opening principle. Article I declares the openness of space to be the province of all mankind for exploration. ISRU can be seen as embodying this principle through its ability to further mankind's exploration of the solar system.

While Article I of the OST allows the freedom of the use of space resources, there may be conflict with the concept of benefit sharing. The final use of in-situ resources needs to benefit all of humanity. This is due to the fact that space is a commons and there is a first-come first-served mentality; however, since some of the resources are limited and there could be contention to a State that monopolizes the use of resources simply because of the fact that it was the first to arrive. This argument was raised by on expert respondent to the survey, "the exploration of lunar resources is not forbidden, but it is necessary to regulate this exploration. This exploration without regulation is a big risk for the Moon and for the Earth".

Future ISRU missions could involve commercial participation. While there are issues with property rights and ownership of in-situ resources (discussed in the next section), there is the possibility of a commercial company working with a State to supply ISRU capabilities. As one expert states, "no (there is no conflict in international law against a commercial ISRU facility), assuming the activity is authorized and supervised by a state and activity is in compliance with the Outer Space Treaty".

Property Rights

The issue of property rights is covered in both the OST and the Moon Treaty. Property rights are of concern to any state partaking in ISRU because discussion on the use of resources and discussion of ownership go hand in hand. With respect to the OST, Article 1, which refers to the concept of benefit sharing, and Article 2, which refers to the concept of non-appropriation, are of particular interest. When the idea of using commercial companies for ISRU is discussed, Article 6 of the OST, which discusses state responsibility, is also of importance. With regards to the Moon Treaty, the key concept that affects ISRU in terms of property rights is the concept of the "common heritage of mankind" that is described in Article 11.

The three main property right issues that could negatively affect ISRU are the concepts of non-appropriation, benefit sharing, and mixed property. Both the OST and the Moon Treaty specifically say that no State shall be able to appropriate any part of outer space including celestial bodies. Without ownership, the ability for a State to use in-situ resources is called into question. For example, once the oxygen is extracted from the regolith, that resource can only be extracted once. This example also illustrates the second concern with ISRU, which is that space must be used for the benefit of all humanity. This idea of benefit sharing could cause problems because of the difficulties proving that the benefits of ISRU can be provided to all humanity. The final roadblock for ISRU in regards to property rights was highlighted in the comments of Mr. Paul Dembling, the General Counsel to the UNCOPOUS in 1995. Mr. Dembling pointed out that if 20% of a facility was created by using in-situ resources, then 20% of the facility would be subject to the concepts of benefit sharing and non-appropriation.

While several aspects of the OST can be seen as negative to ISRU in regards to property rights, one key idea clearly supports ISRU. This is the idea that space is free for States to explore and use without discrimination (OST Art.1, Moon Treaty Art. 11). With the concept of space being a "commons", there is no legal restrictions to anyone using space and its resources (Zinck, personal communications, 2006) As well the wording of the ideas of non-appropriation is both treaties can be taken to support ISRU. The OST can be seen to apply to ideas such as land claims, while allowing resource utilization whereas the Moon Treaty can be seen to support ISRU by only allowing non-appropriation "in place" which can be seen as allowing use once the resource has been extracted.

Contamination and Preservation

The concept of "harmful contamination" is presented in Article IX of the 1967 Outer Space Treaty with no clear definition. Rather it defines the impact as the detriment to the pursuit of studies in outer space. In 2002, COSPAR defined the impact to space exploration from contamination, with respect to organic constituents and biological life else where in the solar system, in the Planetary Protection Policy. Within these principles the Moon is classified as Category I, which means it is considered not being of direct interest for studying the evolution of life, warranting no planetary protection. Whilst the principles are a political document and adoption is on a voluntary basis, the policy does represent the first attempt by the international community to define the concept of "harmful contamination".

According to this definition of "harmful contamination", ISRU creates no legal objection; however, referring to Article IX of the 1967 Outer Space Treaty: "States Party to the Treaty shall pursue studies of outer space, including the Moon". ISRU can potentially be seen in violation of international law due to the changing of the natural state of the Moon's environment, namely its geological record. This disruption and loss comes into contradiction to the Cosmo-centric ethic considers the Moon having intrinsic value and should be left in its natural state (J. Logsdon et al, 1997). The level of impact described in Section 4.2 represents only 0.001% of the lunar surface per annum, representing limited local loss of scientific knowledge. With respect to waste by-products these can be safely stored for future ISRU processes (Larson & Sanders, personal communication, April 13, 2006). similar to the practices on Earth of mining industries. "We cannot use in the Moon the same logic that we used and still use in the Earth. We need to respect the principle of caution."

Export Control

Export control is handled at the international level by regimes with no legal power but rely upon the political will of the signatory members to implement the principles. It is at the national level where the export control legislation is created and technologies are identified for transfer restrictions. The question relating to the likelihood of ISRU technology being classified as "high technology" was included in the survey to assess the current opinion among the legal community as to the risk perceived by the transfer of ISRU technologies. One expert summarized the reasoning for restricting ISRU technology as to "…the nature of the technology…identity of the transferee…" as the base of the various international regimes. The primary method to determine if a technology will be restricted by export control is to consider if it's origins are military, developed through the utilization of military derived technology or could be included in military components.

Beyond this it is a question of the end user, who they are and for what purpose the technology will be utilized and if it is possible for the technology to be used at the detriment of the licensing nation. This is summarized in this response, "…who the participants are, and whether technology transfer is required to enable the cooperation." As this response suggests, if a space mission can be performed without the unnecessary transfer of technology between participating States then export control issues are non-existent. It is easy to consider that all space technology is of "dual use" and therefore placed under export control legislation; however, in the case of ISRU technology and its connection to exploration may contradict international law through the restriction of the transfers in ISRU technology as noted in this survey response "…this limitation could be seen as going against UN treaties and international principles promoting the cooperation for scientific mission in outer space, in the Moon and other celestial bodies."

IPR and Patents

As ISRU begins on the Moon, it will present an arena for scientific discovery and innovation. With time, the processes of ISRU will be improved and new ideas generated. This brings attention to the need for a legal regime regarding the protection of intellectual property. There are numerous agreements and conventions that form a stable international legal regime, with respect to, IPR on Earth. This regime focuses on the ability of different States to have different IPR laws. This national aspect of IPR is important due to the OST (Art. 8), which gives jurisdiction over any facility in space to its launching state; however, both the OST (Art. 11) and the Moon Treaty (Art. 5) refer to the need to share scientific with the public and the international scientific community.

The two main IPR problems for ISRU are the need to publicly release all scientific discoveries and the lack of jurisdiction on the lunar surface. If all scientific discoveries are required to be public knowledge within the international community, the ability to patent becomes difficult. If an idea is discovered in an area that has no jurisdiction, then there are questions on how to proceed with the patent process.

While the Moon Treaty is restrictive in its need to publish scientific information within 60 days, the OST allows more room for patenting ideas. The OST (Art. 11) includes "to the greatest extent feasible and practicable", which affects when a State must release information and opens it up to interpretation; therefore, it is possible to retain knowledge without breaking international law while the rights to that knowledge are protected. Additionally, since States have jurisdiction over all their equipment, any innovations made on these processes can be seen as within the jurisdiction of that State.

The lack of clarity with regards to IPR can cause difficulties in the development of ISRU and can hinder the ambitions to improve ISRU processes while on the lunar surface. As seen on the ISS, difficulties in jurisdiction can cause contention within between states (Hulsey, 2005). Any State that partakes in ISRU must be aware of these issues in order to deal with the consequences as noted by a legal expert, "There is no current specific regime applicable for the protection of intellectual property rights in space. Moreover, because of the extra-territoriality of outer space, the existing IPR rules can only apply with difficulties."

Liability

The legal regime for liability in space activities consist of the "Convention on International Liability for Damage Caused by Space Objects," which entered force 3 December 1968. This document covers the damage done to other States by a "space object" of another launching state. The phrasing "elsewhere then the surface of the Earth" allows for the belief that this treaty covers operations on the lunar surface. However, as ISRU processes take place, damage may occur from the actions, not just from space objects, for example, the creation of lunar dust or the release of volatiles such as cyanide. These are specific issues with ISRU that must be considered by international law. "The 1972 Liability Convention is a good base to construct a specific regulation of the liability problems related to ISRU activities."

6.2.4 Mitigation Strategies

The discussion of the legal issues facing ISRU highlights the vagueness of international law regimes. There is a need to clearly define several aspects regarding ISRU and other lunar exploration initiatives. At the moment, the discussions have been limited to academic interest. It will not be until ISRU processes are further developed and it becomes more feasible before there will be any urgency to define the related aspects in the legal regimes. "The current legal regime is still open to an interpretation of the laws. In order to move forward, someone must first propose and define these interpretations. The OST was created and agreed upon relatively quickly because of the climate of space exploration during that period."

In order to better define the legal regime towards the use of space resources, analogies can be drawn from similar fields on Earth. As one expert pointed out, "The status of the moon is very much the same as the status of the high seas before the Montego Bay Convention." Two examples of international treaties that could be used as guidelines for future space law development, often referred to, are the Law of the Sea and the Antarctica Treaty. "We have found ways around the problem of res communis with the Law of the Sea. We can do the same with the Moon." The activities taking place both in the Antarctica and in international waters can be directly compared to the use of space resources; however, both the use of the resources from the sea and in Antarctica have distinct differences from those in outer space. "Antarctica and space law regimes bear similarities but also several differences, so the two systems cannot be assimilated."

While States can take these treaties as guidelines or lessons learned for creating a more developed legal regime, the question remains of how to implement the changes to the legal regime?

While the Moon Treaty is in force but not accepted by the major space-faring States, the document is important to the future of space law. The Moon Treaty is binding to those States that have signed it and unless additional States agree upon it, the effectiveness of the document is very limited. A lawyer participant states that (Yes, the Moon Treaty is a "dead document") "But it can be easily be revived, if a reasonable regime based on Article 11 could be worked out."

Amending the Moon Treaty is one option, to modify and develop the law of space but so is creating an entirely new treaty. Other options have different benefits and costs. One limitation in amending the Moon Treaty is that States that are party to the agreement are the only States that may amend it. This means, that space-faring nations cannot propose amendments directly. There is, however, a difficulty in creating a new treaty, which is that it could take up to 20 years before it is in force. "In the current international context, it may be nearly impossible to reach a large consensus among the international community for the elaboration of an entirely new treaty. The adoption of amendments may also be difficult, but at least, a basis exists."

Legal Risk Survey Summary

The ultimate goal of the ISRU Legal Risk Survey is to highlight areas of contention with respect to the legality of ISRU so that they can be incorporated into the FERTILE Moon Model. This way a user of the model can test whether or not ISRU if feasible in terms of the legal framework as well as in terms of technology. The next section will discuss the background and theory behind the implementation of one legal aspect into the current version of the FERTILE Moon Model: export control.

6.2.5 Model Integration - Export Control

The transfer of high technology and items of a military nature are controlled throughout the world by national export control legislation, implemented through licensing. The rationale for imposing export control by the relevant State originates from the protection of their geopolitical, strategic and economic advantages. The space industry is heavily influenced by export control legislation due to the dual use nature of launch vehicles and satellites and the fact that the technology levels are typically very advanced.

Three levels of documentation govern export control. The first level is political documents at the international level, which create the export control regimes. The second level is regional which defines special cases of export control and exemptions within the states partner to the agreement. The third level is the national legislation, which governs licensing.

At the international level, export control regimes are created between participating states. These political documents provide a common basis on which national legislation might be based. These agreements, as political documents, lack any legal enforcement capability; instead implementation is the result of the political will to respect these guidelines. The export controls regimes relevant to space technology are primarily the Missile Technology Control Regime (MTCR) and the Wassenaar Agreement.

In 1996, over 30 Nations of the UN adopted the Wassenaar Arrangement after the previous coordinating committee for multilateral export controls, COCOM, dissolved in 1994. The arrangement comprehensively addresses the issues of export control related to conventional weapons, sensitive dual-use items and associated technologies (WA website). Through advocating for the idea of transparency and responsibility in the interest of improving international security this document was accepted. Part of this transparency involved the creation of the Secretariat of the Wassenaar Agreement in Vienna and a membership who must adopt the principles of the Wassenaar Agreement as well as the principles of other international export regimes, such as the Australia Group. Identified restricted items are collated into the Lists of Dual-Use Goods and Technologies and in the Munitions List. Modifications to the Wassenaar Agreement or its control list must be made through the terms in Article VII of the same agreement.

The MTCR, an earlier attempt to define common export policies amongst its members, is limited in scope, as it has no institutionalized body. The result is that a participating State must only accept the common export list and integrate it into the national legislation. The MTCR is relevant to the space industry due to the inclusion of space launch vehicles in the MTCR Annex under Category I and their related components and support systems in Category II list (MTCR website).

The second level of export control is the regional level where special cases created with respect to the implementation of the international export regimes as seen in the variance of interpretation and implementation (A. Farand et al 2004). The European Community set up an export regime for the control of dual-use technology (Council Regulation (EC) No. 1334/2000); the text covers issues relating to:

- Inclusion of software under the idea of dual-use
- Authorization and application process for licensing at the national level
- Highlighting the problem of re-export and end-use

The uniqueness of this particular legal regime is its allowance of free circulation of technology within the borders of the EU, barring specific sensitive items listed in Article 20. With respect to the exportation outside of the EU authorization is required through the national licensing procedure. For ESA this represents the free transfer of technology amongst 15 of the 17 member states, as Norway and Switzerland are not members of the EU.

An example of incorporation of the international regimes at the national level is Unites States of America. To oversee the transfer of technology the Export Administration Act (EAA) and the Arms Export Control Act (AECA) were created to handle licensing requests. The EAA was created and placed export licensing of non-military hardware under the control of the Department of Commerce. With the control items listed on the Export Administration Regulations (EAR) including items of a dual-use nature. Munitions items are on the International Traffic in Arms Regulations (ITAR); this now includes all satellites and launch vehicles (P. L. Spector et al, 2000). ITAR covers all military hardware and incorporates the MTCR principles and the MTCR Annex (Department of State Guidelines); licensing procedures for items listed in this document are handled by the Department of State.

Presently it is unclear whether the technology required for ISRU will be restricted under export control regimes. Generally space technology is considered either 'high technology' or its origins are of a military nature. The latter is typically an indicator for inclusion in the export control lists whereas the definition of 'high technology' is flexible and can change at the national level. In the US, due to fears of the undue transfer of high technology from satellite export for launch in the People's Republic of China, export licensing for satellites was transferred from the Department of Commerce to the Department of State.

The FERTILE Moon Model has mission scenarios involving international cooperation among a maximum of four States. Based on the ownership of the selected ISRU process it is possible to assess the impact of export issues on the involved States. The five processes in the model, as described in Chapter 4, are currently being studied by institutes and private companies around the world. Assuming the parties currently researching the processes will be the owners of the intellectual property in the ISRU missions modeled. Table 6-3 lists the States in which these processes are being researched and correspondingly under what national export control legislation applies.

Table 6-3: Registered Nation of Researching Entities

ISRU Process	Institute/Private Company	State of Registry
Hydrogen Reduction of Ilmenite	Carbotek	USA
Carbothermal Reduction	Aerojet	USA
Molten Silicate Electrolysis	Washington University, St. Louis	USA
Hydrogen Extraction	Arkansas College, AK	USA
Water Extraction	Colorado School of Mines	USA

Due to the complexity of national export control regimes and specific relationships between nations creating an export control output with an impact on the model outputs would be impossible to incorporate into the model. Rather the output will be a qualitative assessment between the mission scenario partner countries and the identified countries owning the intellectual property rights. The function in the model is to check the partner countries against the listed countries shown in Table 6-1. When the state controlling a technology is not involved directly in the mission scenario the output will order the technologies into two lists those with an export control issue and those without.

It is important to note that this output does not represent a barrier to technology exchange as that is dependent on the respective nation's legislation. Rather, the output draws attention to a real issue that can impact on the cost and the possibility of a mission where export authorization may delay the mission beyond deadlines (D. Lihani, 1999). These issues must then be discussed and considered in the evaluation of all model outputs; however, if the technology is controlled by a State participating in the mission the transfer of technology is facilitated by the licensing agency of the State thus removing these limitations.

Legal Summary

The previous section focused on the legal factors in determining the feasibility of ISRU. These concepts are important to consider to ensure that the analysis of ISRU tests for the total feasibility, not just based on technological aspects. The ISRU Legal Risk Survey was a major accompaniment to the FERTILE Moon Model that was used to gather legal opinions on various issues, including export control, which has been implemented in the model. There is yet another field of study that could affect the feasibility of ISRU and that needs to be addressed. The next section discusses the ethical ramifications of pursuing ISRU.

6.3 Ethics

The utilization of Moon's resources is a specific case of a much broader issue: the relationship between humans and their natural environment. This relationship is guided by the study of ethics. This branch of philosophy attempts to understand the nature of morality and to discriminate what is right from what is wrong.

Ethics concern the study of every possible consequence and implication for the environment of any mission, its scientific purpose put aside. Social and moral implications need to be taken into consideration (Arnould, 2006). The World Commission on the Ethics of Scientific Knowledge and Technology (COMEST, 2000) created in 1997 as an advisory body of UNESCO is already addressing an ethical approach for the progression of science and technology and could therefore be the starting point for a worldwide discussion on ISRU and ethics. This would prepare the ground for the adoption of an international declaration reflecting essential human principles, such as human rights, preservation of natural patrimony, and the present responsibility of mankind regarding the future generation.

Jacques Arnould and Andre Brack (personal communication, 2006) proposed the creation of an international body that would be in charge of managing the Moon's resources in the scope of their utilization. This body could be founded on a legal framework similar to the Antarctica Treaty System. Antarctica's scientific value can be accessed with no discrimination; nevertheless its patrimony is protected against massive commercialization (McKay, 1996). According to this treaty, no economic benefit can drive Antarctica's exploration. It emphasizes on providing scientific benefits to all of humanity. In the scope of ISRU, awareness of the consequences of the commercial exploitation of the Moon's resources is necessary, as the drive for profit may jeopardize efforts of preservation.

Space agencies present the Moon exploration and ISRU operations as highly risky enterprises (McKay, personal communication, 2006). McKay has been involved for 25 years with the Antarctica missions and stresses the point that a ratio of 1 casualty per year should be unfortunately expected during the pioneering phase. This has never threatened the Antarctica's program; neither should it for space exploration.

In the traditional monotheist's religions, Man differs from other beings and has a moral duty to wisely manage the environment. ISRU is nowhere prohibited as long as it is performed for the good of mankind (El-Baz, personal communication 2006). It is therefore morally justified for human to explore and utilize Moon's resources.

The study of environmental ethics could provide answers to questions related to Man's responsibility towards future generations. Does humanity have the right to inalterably modify the Moon for ISRU activities? A pessimistic approach would be to remind ourselves of the damaging of the Earth's environment and imagine a similar unwise and unsuccessful attempt to exploit the Moon. Classifying the Moon as World Heritage or establishing national parks on the Moon with restrictions and rules may be one solution (Cockell & Horneck, 2004)

Humans have to adapt to the new scientific achievements and responsibilities that come with the exploration of space. Identifying guidelines which are sensitive to moral, ethical and cultural issues will prove essential to answer questions such as "What should we do" and "How should we live", keeping in mind that future generations will have no choice but to cope with what we leave for them.

6.4 Summary

International cooperation costs money the more parties involved, the more troubled their inter-relationships and the more problematic cooperation may become. The more effective a cooperation between the parties of a cooperation, the fewer the overhead costs associated with the project will be. Within a working cooperation the relationships appear more like a contractor subcontractor relationship in which organizational costs are minimized.

The legal ramifications of pursuing ISRU processes cannot be ignored. Any State that is considering the benefits of ISRU must also include the costs of addressing the lack of defined legal regimes surrounding the results. While discussions in the legal community are limited to academic interest at the current time it makes consensus very difficult to achieve. As the use of ISRU becomes more feasible, as is a possibility in the following years, the sense of urgency will encourage the process of developing international law to deal with all the issues addressed above.

Export control at the international level focuses on promoting the idea of non-proliferation of arms and maintaining international security. Whereas, current regimes are voluntary and have no legal power over its members other than through political will, the principles are transferred to the national level. At the national level the interpretation of the export control regimes differ between States. In the Model, export control highlights when a problem is more likely to occur for required technology and encourages analysis be conducted, for the mission scenarios, on the possible export issues.

Just as political and legal aspects affect the feasibility of ISRU, ethical issues will be raised as the processes become more of a reality. The Moon has a special place in many religions and cultures and there are varying opinions on whether or not it is humanity's place to use the resources of the Moon. Any person or State looking at including ISRU in their mission architectures must be prepared to deal with objections presented from an ethical point of view, just as there will be legal and political objections as well.

With the conclusion of this chapter, the first part of the Report has been completed. The previous chapters have introduced the FERTILE Moon Model and described all the factors that make up the model's architecture. Not only were the factors mentioned, but the reasoning behind their choices and assumptions were discussed as well. With the knowledge gained in the previous chapters, the reader is ready to move onto the second part of the Report, which will focus on describing the useful outcomes of the FERTILE Moon Model.

7 ANALYSIS

Previous chapters have dealt with the architecture of the model, the demand for resources, their supply from Earth as well as from in-situ lunar resources, and the interdisciplinary aspects involved. Equipped with an understanding of the drivers that set the demand and the capacity to deliver supplies, it is now relevant to explore the trade-offs between lunar missions which are fully terrestrially supplied and those which make use of ISRU. Such trade-offs for assessing the feasibility and effectiveness of different supply options are discussed in this chapter. This helps to evaluate the most effective set of options that would lead to a sustained human presence on the moon.

The different cases that can be applied to the model and resulting discussions are the focus of the present section. Section 7.1 discusses the credibility of the model in how it compares to similar studies, the accuracy of the sources of data, as well as the model limitations. Section 7.2 discusses the various operational phases and then shows how the model analyses these development stages. This allows the key parameters that affect the capabilities of ISRU to be identified. Section 7.2.3 considers what technologies would help carry out effective and efficient ISRU in an environment that is very different to that of Earth. Section 7.2.5 looks at the sensitivity of ISRU provision to changes in the input parameters and assumptions. The chapter concludes with a discussion on the commercial viability of ISRU supply of resources in the context of a developing cis-lunar economy.

7.1 Validating the Model

Modeling work in the form of analyzing the demand, supply and logistics of space resources has been carried out in the past, but by a relatively small subset of the space science and exploration advocates. Also, a large amount of the modeling work carried out so far has been concentrated to lunar base requirements. This is largely representative of the view that a return to the Moon would be for the prime motive of setting up a ‘permanent habitat’. Although these studies provided valuable guidance and inspiration for the present analysis, the design methodology in the FERTILE Moon Model is different. Feasible uses of in-situ resources largely depend on the base maturity assumed. The mixture of supplies imported from Earth and those that can be provided in-situ will change constantly. Hence, it is essential to simulate many different scenarios in order to understand where the results of the model are best suited. This section compares the design methodology and validity of the FERTILE Moon Model to previous modeling studies. This section also attempts to assess the accuracy of the model, and identify the major model limitations.

7.1.1 Comparison of Various Models & Similarities

Different models have been used during this study for guidance and verification of the assumptions and choice of key parameters. These references include studies that are dedicated to lunar exploration as well as studies from the broader space community. This shall help put into perspective the considerations for market, risks and economic viability, taken into account by potential stakeholders in a lunar base development Table 7-1 summarizes components of other studies and disciplinary models used for this study.

Table 7-1: Summary of Different Modeling & Econometric Analysis Studies

Model Author, Yr	Lunar Base Development	Economic Analysis	Used Only For Validation	Other Features	Comments
Eagle Engineering Inc, 1998	X			Includes scalability of ISRU facilities and processes	A comprehensive study on lunar oxygen extraction with consderations for pilot plant and sizing of equipment
Echart, 1996			X		
Koelle, LUBSIM - 3.0, 2000			X	Large scale lunar development	Simulation for a lunar base
Koelle, TRANSCOST 6.0, 1995		X			Cost engineering for the development of transportation segment of Earth-lunar exploration.
Blair et al., 2002. Lunar ice mining	X	X			Focused at the private sector willing to engage in an ice mining venture for propellent production. First integrated study for a detailed NPV analysis.
ELISSA	X			LSS specific	Incorporated for LSS options and demand modeling
Cyr, AMCM 2005		X		AMCM is a system level cost model.	Parametric costing based on AMCM is included in FERTILE Moon Model. It is more appropriate for large scale programs.
Cyr, SOCM 1999		X			Incorporated for operations and labor cost functions and assumptions.

7.1.2 Model Accuracy Assessment

Since there have been few models created in the past dealing with similar issues, there is a limited amount of information available. The result is that the model makes many assumptions concerning the input data, the functions, and the relationship between parameters. The following sub-sections summarize areas where it is difficult to find historical data, and attempts to explain how the numbers used in the model were chosen. The accuracy of these values is important as they entail major considerations for the model outputs, thus affecting the overall accuracy of the model.

Life Support Parameters & Inaccuracies

The values for the model for the LSS demand are given in Table 7-2. As they are relative to physiological parameters that depend on circumstances and individuals, they are subject to strong variations. For example, the value for individual oxygen consumption is relative to the level of activity. Thus the value used in the model is an average between values for complete inactivity and intense effort. Similarly, as discussed in Chapter 4 (Supply) the values used for potable water, airlock and habitat volumes are strongly dependant on the mission duration.

Table 7-2: Life Support Input Values

Model Input	Model Value	Min Value	Max Value
Oxygen (kg/person/day)	0.84	0.9	0.78
Potable water	2.8	2.5	3.1
Hygiene Water (Short Term)	2	1	3
Hygiene Water (Long Term)	10	2	18
Airlock volume	4.25	1.25	5
EVA water	4	3.6	5.4
Habitat Volume (Short Term)	5	-	-
Habitat Volume (Medium Term)	58	-	-
Habitat Volume (Long Term)	93	-	-

Transportation – The Moon to Earth

The parameters selected for transportation from the Moon back to Earth are shown in Table 7-3. The Delta-V for the Earth return is 5900 m/s. SR is the structural coefficient with a range from 0 and 1, 10% (0.1) is a typical value. Specific impulse depends on the type of engine, range is from 0 to thousands, and an I_{sp} of 450 is the typical value for chemical engines that use LOX and LH as oxidizer and propellant. AR is aero-braking, and is a ratio of total aero-braking possible over the delta-v required for Earth Orbit Injection. This is described further in the Future Work section. K is a safety margin that can be applied to delta-V that also accounts for extra trajectory requirements.

Table 7-3: Transportation Demand Parameters

Inputs	Model Value	Min	Max
Delta-V	5900	0	-
SR	0.1	0	1
Isp	450	0	-
AR	0	0	1
k	0.1	0	-

ISRU Processes

All of the processes used for resource extraction are accounted for in the model with three values: efficiency, specific power and specific mass. (Table 7-4) The values used are an average of values found in different references. Due to limited literature, for some processes and certain values, no average values were calculated, and the only available ones were used.

Table 7-4: Parameters of ISRU Processes

Process and Parameters	Average	Min Value	Max Value
Hydrogen Reduction of Ilmenite			
Efficiency (%)	1.41	0.33	2.5
Specific power (kW/(t_{O_2}/year))	9.15	2.3	16
Specific mass ($t_{equipment}$/t_{O_2})	0.57	0.15	1
Carbothermal Reduction of Silicate			
Efficiency (%)	25.9	-	-
Specific power (kW/(t_{O_2}/year))	23	-	-
Specific mass ($t_{equipment}$/t_{O_2})	0.1	-	-
Molten Silicate Electrolysis			
Efficiency (%)	21.4	21.4	-
Specific power (kW/(t_{O_2}/year))	1.48	1.48	-
Specific mass ($t_{equipment}$/t_{O_2})	0.0065	0.01	0.003
Hydrogen Extraction			
Efficiency H_2 (%)	0.0044	0.004	0.0047
Specific power (kW/(t_{O_2}/year))	732	124	1340
Specific mass ($t_{equipment}$/t_{O_2})	5	4.3	6.7
Water production			
Efficiency (%)	1	-	-
Specific power (kW/(t_{O_2}/year))	16.38	-	-
Specific mass ($t_{equipment}$/t_{O_2})	0.038	-	-

It is important to identify areas where the model contains uncertainties, due to lack of knowledge about the lunar environment or the specific aspects of the various ISRU technologies. Once identified, these areas can be highlighted, providing the context in which to understand the results from the model, as well as earmarking areas that require further refinement. As can be seen, much of the data critical to the understanding of ISRU on the Moon is based on limited present day knowledge. Over the next 10 years, improved global mapping of the moon, including mineralogy characterization, will help reduce the uncertainty in our understanding of lunar geology. Robotic precursor missions to the moon could also be used to demonstrate promising ISRU processes in their operational environment, in advance of sending human missions.

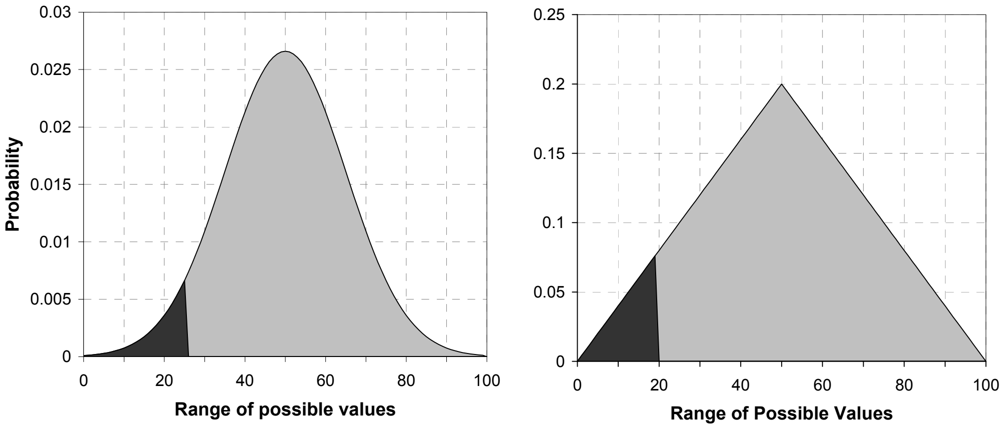
Monte Carlo Simulation Iterations

In the FERTILE Moon Model, the iteration number represents the number of times the simulation runs with randomly inputted parameters. In particular for a Gaussian distribution the

NormInv function is supplied with the mean and the standard deviation of the normal distribution plus a random number between 0 and 1 which represents an area under the curve, shown in Figure 7-1(a). In this way the random input parameter is weighted in accordance to a Gaussian distribution, so a value close to the mean value (50 in the example) will be relatively more probable than a value far from this value.

In addition to the randomly "weight generated" input parameter, it was necessary to add some controls in order to avoid implausible results in the output. It was necessary to cut the Gaussian distribution at 1/10 and 10 times the mean value. This approach affects the symmetry of the curve, and therefore can produce a displacement of the mean value and a modification of the standard deviation. Taking this into account, the Gaussian distribution has been allowed only in the specific cases in which such effects are not significant.

Due the particular characteristics of the simulated input parameters having a comparable mean and standard deviation, the Gaussian distribution is in general a bad choice. Therefore such parameters are simulated by resorting to a Triangular distribution, shown in Figure 7-1(b).



(a) (b)

Figure 7-1: Controlled Gaussian Distribution and Triangular Distribution

A series of empirical tests were used to determine the optimal number of iterations required to achieve stability in the results. The model was run for a series of selected significant cases (usually scenarios characterized by average values for all the input parameters) over a wide range of iterations from 0 to 10,000. The displacement of every point with respect to the reference point (the 10,000 iterations point) was evaluated in terms of mean value displacement and of standard deviation variation for each of the output parameters. As a result, three different level of confidence can be defined, indicating the number of iterations required to meet a certain level of confidence, these are shown in Table 7-5.

Table 7-5: Simulations Levels of Confidence

Level of Confidence	Minimum Number of Iterations
Within 5% from the reference	2000
Within 10% from the reference	400
Within 25% from the reference	40

The stability at increasing number of iterations can be seen in an example (Figure 7-2) of a typical graph produced by the model (e.g. final demand of water for the hydrogen extraction process). It is evident how the variability of both the mean and the standard deviation values tends to stabilize after a few hundreds of iterations.

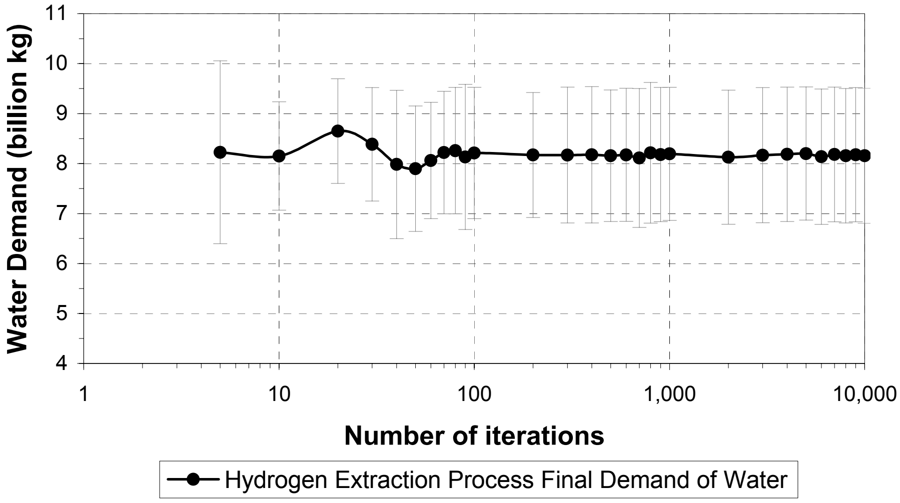


Figure 7-2: Hydrogen Extraction Final Water Demand vs. Number of Iterations

Therefore the modeling analysis performed by the FERTILE Moon Model equips the user with a variety of tools with which valid trade-offs and decisions can be made within given ranges where the model is designed to work. These ranges can also be thought of in terms of mission and exploration architecture attributes such as timescale of implementation, mission crew members, duration and operational cycles of facilities. Further analysis is run to simulate different levels of ISRU required. These relate to the pace and level of exploration that is undertaken in the next lunar missions. Here the roadmap architecture snapshots are discussed in more detail as phases of lunar development.

7.1.3 Model Limitations

The design approach taken in the FERTILE Moon Model is just one of several which could be adopted. The FERTILE Moon Model focuses solely on the demand for hydrogen, oxygen, and water for life support, propellants (for moon-Earth transport), and process reagents wheras lunar resources can be used for a variety of other useful functions. For example, lunar regolith can be used as a cheap and effective habitat radiation and thermal shield. In addition, a plethora of visionary authors have proposed methods of producing components such as solar panels, cement, glass, and even metals that could be used in a lunar base. Development of other lunar products such as helium-3 which could be used on Earth are often termed as 'bootstrapping' technologies that could also be used as an incentive to lunar development. Therefore, the model is limited in terms of the overall resources that can be utilized in-situ.

Listed below are some other main limitations contained in the current FERTILE Moon Model

- Since the actual technologies do not yet exist, facility mass is calculated based on the demand, therefore the model will always meet the requested demand and scale the facility and cost accordingly.
- The model does not calculate how many missions are needed to set up the required infrastructure; it just states the infrastructure mass and power requirements.
- The model can not produce 3 dimensional plots. For this reason varying more than one parameter at a time is not recommended, unless manual plotting is performed.
- The model does not calculate the hydrogen, oxygen and water demand for lunar equipment. It should be noted that these numbers can have a significant effect on the results.
- The user cannot specify the power source. Depending on the power demand for the chosen mission scenario, solar power or nuclear fission is automatically selected.
- The model does not specify the required infrastructure in any detail (number of vehicles, type and number of mining plants, habitat size or type, number of re-supply missions). It simply outlines the demand in terms of mass, power and cost.
- The model does not calculate the consumption rate of resources. Therefore the rate at which resources need to be produced cannot be derived from the model.
- It is not possible to define the ISRU process parameters as a range of values.
- The model does not highlight any synergies between Moon and Mars exploration. Technology developments that can be used on both Moon and Mars would be useful.
- Choice of economic outputs (the model currently only specifies the overall cost). It would be useful to have a detailed financial breakdown including NPV based on DCF items.
- It would be useful to have a visualization of the plant type and size required to meet demand.

7.2 Analysis

The analysis of the various scenarios begins with a discussion of the water electrolysis option in section 7.2.1 for all mission scenarios, whether it be supply from earth or from the Moon. Then, the different phases in lunar development are discussed in section 7.2.2 and the results of the various scenario analyses of these phases are discussed in section 7.2.3. Section 7.2.4 examines the relationships between key parameters and how the effects shall manifest in future technologies and architectures. Section 7.2.5 looks at the sensitivity of ISRU provision to changes in the input parameters and assumptions. The section concludes with a discussion on the application of the model and how the results of this early version can be useful.

7.2.1 Electrolysis of Water on the Moon

One of the options for terrestrial supply of hydrogen and oxygen to the Moon it is to deliver water and then use electrolysis to separate it in to the required oxygen and hydrogen. This approach has the advantage of providing an easy to manage medium that doesn't require cryogenic storage. In contrast, it does require a large amount of power to separate water in to its constituent elements. However in the case of meeting the hydrogen demand, using the electrolysis of water on the Moon, would require a significant increase (almost an order of magnitude) of the launching mass.

7.2.2 Phases of Lunar Development

The Vision for Space Exploration (NASA, 2004) announced by US President Bush in January 2004 establishes the goal of returning humans to the Moon by 2020, as the first step in extending a human presence across the solar system. The vision contains key principles such as the desire to open the venture to international partners as well as commercial interests. The Moon has often been regarded as a natural stepping stone for human space exploration - located just beyond the gravity well of Earth and blessed with an abundance of oxygen for use as propellant - it makes a valuable space port. Establishing a base on the Moon will be of strategic importance for the long term sustainable exploration of the solar system.

Numerous studies have been produced on lunar bases and their development. Cappellari (1972) and Duke (1985) have grouped lunar development in to four major phases, with associated activities in each phase. (Table 7-6)

Table 7-6: Lunar Development Phases (Adapted from Eckart, 1996a)

Development Phase	Elements	Activities
Precursor	• Orbiters • Landers • Surface Rovers	• Global topographic mapping • Global mineralogy assessment • Gravity/Seismic mapping • Subsurface data collection • Robotic surface investigation • Instrument/Experiment demonstration
Pioneering "Sortie" or Human short stay missions	• Human Landers • Basic Habitats • Surface Transport Rovers	• Lunar base site preparation • Science instrument placements • Short range exploration • Lunar oxygen pilot plant
Outpost “Consolidation”	• Extensive Base • Permanent Occupancy • Far Side Observatory	• Extended science facilities • Extended mining facilities • Lunar oxygen production plant • Longer range surface transport • Lunar navcom constellation
Settlement	• Fully operational bases	• Large scale oxygen production/export • Advanced laboratories • Lunar Manufacturing • Expanding population base

These phases of lunar development offer a backdrop upon which various lunar exploration mission scenarios can be considered. For example, in the pioneering phase, missions will be conducted by small numbers of astronauts working together on the lunar surface for less than a month, whereas in the settlement phase, it is expected that the lunar base is well established. The level of in-situ resource utilization in each phase is a matter for debate, however it is expected that in the early stages the base will be highly dependant on re-supply of resources from Earth, slowly becoming more self-sufficient in specific resources as time progresses (Figure 7-3). The value of ISRU in the early precursor and pioneering phases is not well established, and it is one of the objectives of this report to offer some analysis on the subject.

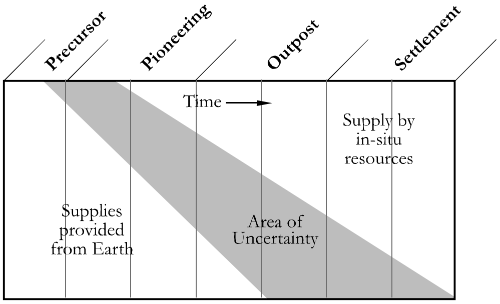


Figure 7-3: Areas of Uncertainty for Different Base Maturities (adapted from LSI/LPI)

Various scenarios in each of the four lunar development phases are considered, and the FERTILE Moon Model is used to evaluate the feasibility of using ISRU in each phase. The model can be used to estimate the demand for each resource, as well as key parameters including the regolith feedstock required, size of facility required, process specific costs, and saving (if any) over terrestrial supply. The scenarios considered in each phase are described in Table 7-7.

Table 7-7: Scenarios of ISRU Development

Development Phase	Scenario Description
Precursor	This phase will focus on resource assessment, prioritization and ISRU technology demonstration. The example considered is of using ISRU in preparation for pioneering missions, with an emphasis on meeting life support and propellant demand.
Pioneering	In the pioneering phase the value of ISRU depends on the relative cost of re-supply, as well as the level of activity and the mission duration. For this scenario the following parameters are used: Crew Size: 4 - 6 people Mission Duration: 0 - 28 days LSS Closure: 20% Activity: 5 EVA's per person per week
Outpost	In the outpost phase, resource demand increases, requiring more infrastructures and increased re-supply missions. By-products of resources become more important. For this scenario the following parameters are used: Crew Size: 6 - 12 people Mission Duration: 30 - 180 days LSS Closure: 60% Activity: 5 EVA's per person per week
Settlement	The lunar base must become self-sustainable in terms of energy and resources, so life support loop closure is high. The commercial viability of lunar oxygen export is possible. In this scenario the following parameters are considered: Crew Size: 12 - 30 people Mission Duration: 180 - 364 days LSS Closure: 80% Activity: 5 EVA's per person per week

It must be noted that the scenario values shown in this section contain a discrepancy with section 3.2.1 on life support loop closure. The reasoning behind this is that the life support system is taken from existing technologies and other models in the life support field, whereas the data in table 7-7 is taken from existing research in the area of mission architectures and lunar base planning. For the purposes of this analysis, the values in Table 7-7 were used; however, the loop level closure is a user input and can be varied if necessary.

7.2.3 Scenario Results & Discussion

The various phases of development defined previously in Table 7-7 were analyzed using the FERTILE Moon Model. The results are discussed in terms of key parameters that affect the feasibility and merit of each phase.

Precursor Phase

As discussed before, the first phase of the ISRU mission architecture will most likely be in the form of precursor missions not involving humans. There are several goals to these missions:

- Robotic missions to search for appropriate landing sites.
- Robotic missions to characterize the regolith composition and internal structure.
- Small ISRU facilities to test the technology readiness for ISRU processes.
- Human preparatory missions. These would set up facilities in advance of human landings.

In the case of preparatory missions, one scenario would be to produce resources from tele-operated ISRU facilities and store the products awaiting human arrival. Testing this technology would be useful in the context of lunar exploration, and also have relevance in the context of missions to Mars. The demand for oxygen and hydrogen for use as propellant far outweighs the demand for these resources from life support. Therefore the analyses considered here focuses on producing the propellant demands of the mission.

Figure 7-4 shows the mass of the facility required for different levels of oxygen production. Unless the ISRU facilities can be launched in segments and automatically assembled on the surface of the Moon, the facilities will be constrained by the mass that can be delivered to the lunar surface. The upper limit today is with the Delta4 heavy lift launcher at approximately 3100 kg for payload mass.

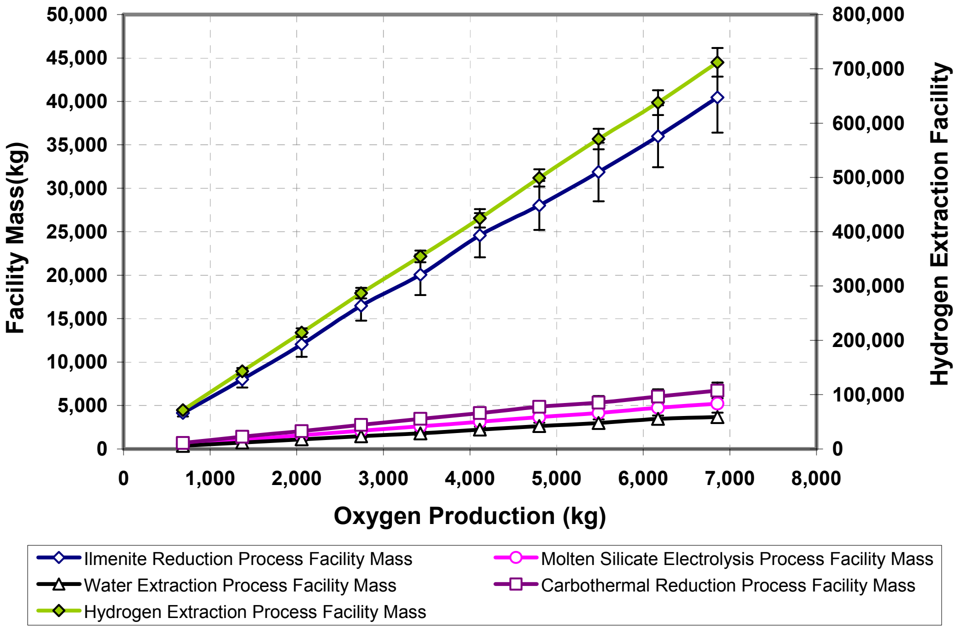


Figure 7-4: Graph of Oxygen Demand vs. Facility Mass

Figure 7-4 illustrates that the molten silicate and carbothermal electrolysis processes have a reasonably low facility masses for oxygen production levels on the order of 2,000 kg. Even up to oxygen production of 6,000 kg the facility masses are not extremely high. The competing processes of hydrogen extraction, hydrogen reduction of ilmenite and water extraction have facility masses which increase in proportion to the output demand. On this graph, Hydrogen extraction has a secondary scale on the right side of the plot since it has a different order of magnitude higher than the other processes. This implies that hydrogen extraction values are in un-feasible compared to the other processes, this is the case for the remainder of the precursor phase and thus hydrogen extraction, if plotted, will have its own scale on the right side. The facility mass for these processes exceeds the current launcher deliverable mass even at relatively low levels of oxygen production (between 1,000 and 2,000 kg). Water extraction can give a facility mass of less than 3,000 kg for up to 2,000 kg of oxygen; therefore can be chosen in some cases. The facility mass of the power system is not shown, but ranges from 100 to 700 kg for between 2000 and 6000 kg of oxygen.

Automated precursor missions will not be able to travel vast distances in order to excavate for regolith. Therefore the excavated mining area is also a factor to consider. Figure 7-5 shows the mining area that needs to be excavated for a certain amount of oxygen.

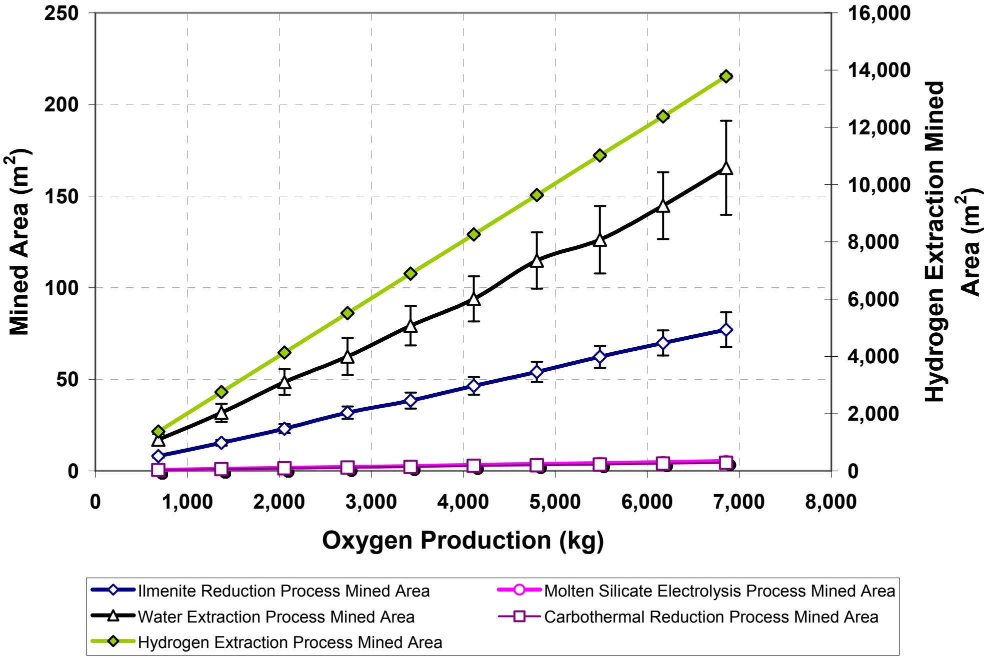


Figure 7-5: Graph of Required Mining Area vs. Amount of Oxygen

Figure 7-5 shows that the molten silicate and carbothermal processes do not need vast amounts of regolith (due to their high efficiency) whilst hydrogen reduction of ilmenite and water extraction require close to 10 times more mined area to produce a similar oxygen output. Hydrogen extraction is again plotted with respect to a secondary axis.

The operating or production run time required for these automated robotic facilities to work before the crew missions arrive is important. It is known that continuous running machines will have malfunctions and problems and require maintenance. The speed of running parts can lead to wear and tear and the optimum speed and time of operating machines in the space environment must be determined. Figure 7-6 shows the process cost with the rising running time and the terrestrial option.

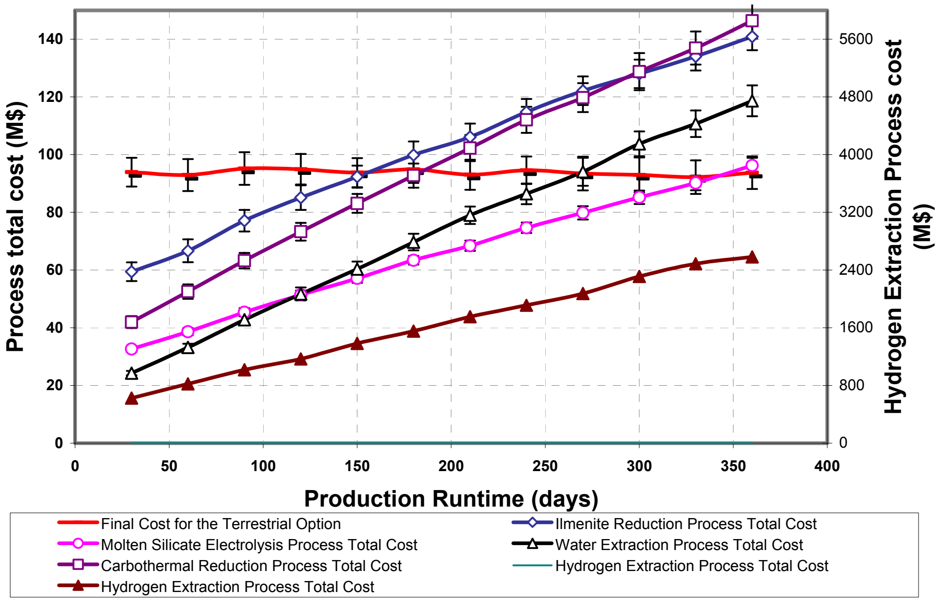


Figure 7-6: Graph of Production Runtime vs. Process Cost

As can be seen the process total cost rises in time but at different rates. The time frame of 1 to 3 months indicates reasonable cost, however, the 4 other processes are still under the terrestrial option total cost (launching the oxygen and hydrogen from Earth). Hydrogen reduction is the first, excluding hydrogen extraction, to cross over the terrestrial option, at 160 days. Carbothermal reduction and water extraction cross over at a range of 180 to 280 days, while molten silicate electrolysis only crosses over at 360 days. This implies that producing the resources on the lunar surface will be more economical for missions of short and medium durations. However, these processes are not well suited for long duration mission or use in mass production facilities. Therefore demonstration missions and propellant production and storage can be interesting for early precursor missions.

Pioneer Phase

The Pioneer phase of lunar development focuses on the return of man to the Moon, and the initial exploration missions. These will primarily be conducted of crews of 4-6 astronauts on the surface for 7 to 28 days. This mission phases will be dominated by high surface activity, lunar base site preparation, and testing of various lunar technologies including ISRU facilities.

Using the FERTILE Moon Model, we can estimate the hydrogen, oxygen and water demand requirements for crews of up to 6 people working on the lunar surface for up to 28 days. Initial missions at this stage are expected to have a low level of Life Support System (LSS) closure, therefore two cases are considered, one featuring 0% LSS loop closure and the other featuring 20% LSS loop closure. These life support requirements, together with a transport requirement of one lunar surface to low lunar orbit ascent are supplied as inputs to the model. The resource demands are shown in Figure 7-7.

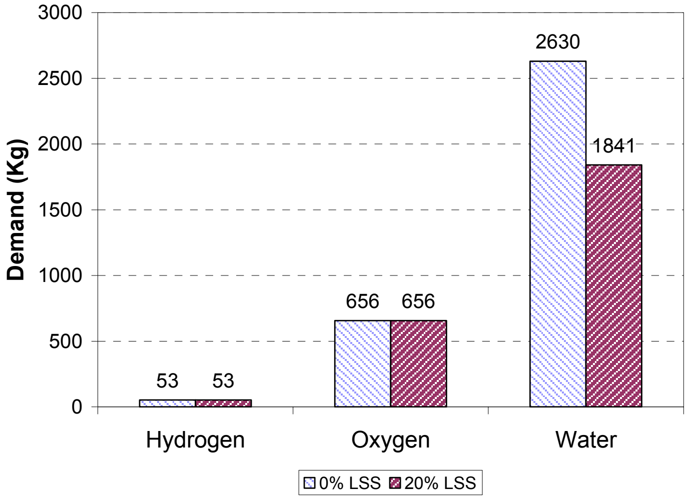


Figure 7-7: Resource Demand for the Pioneer Phase

It can be seen that the mass drivers for this scenario are the demand for 656 kg of oxygen (312 kg for life support, 344 kg for propellant) and between 1.8 and 2.6 tons of water (0% and 20% loop closure respectively). Also, it is visible that the loop closure, for pioneering phase missions, really only has affect on the amount of water needed. Running the model for 1000 iterations using a triangular Monte Carlo simulation gives an estimate of the 3 ISRU processes that can meet the oxygen demand; the results of these simulations are shown in Table 7-8.

Table 7-8: Parameters for ISRU Provision of Oxygen

ISRU Process	Hydrogen Reduction of Ilmenite	Carbothermal Reduction with Methane	Molten Silicate Electrolysis
Oxygen Demand (kg)	656	656	656
Feedstock (kg)	54,372	3,149	3,775
Mining Area (m^2)	7	1	1
Process Specific Cost (USD/kg)	800	3,599	4,383
Process Facility Mass	3891	653	498
ISRU Supply Cost (USD)	23,020,878	17,252,904	15,004,060
Equiv. Terrestrial Cost (USD)	29,709,613	29,709,613	29,709,613
% Saving over Terrestrial Supply	22 %	42 %	49 %

The relatively low demand for oxygen means that only a small amount of regolith feedstock is required to meet the demand. Assuming a regolith extraction depth of 3 meters and a regolith density of 2450 kg per cubic meter, the lunar regolith required as feedstock to the molten silicate and carbothermal processes is accessible within very modest area of 1 meter squared. However in all ISRU process cases, the facility mass required to produce this demand of oxygen is comparable to the mass of the resource itself. It is therefore questionable whether it is not more prudent just to transport the required resources, rather than the ISRU facility to produce them. Of course, once established, a lunar oxygen producing facility could be used for subsequent missions.

Of the three oxygen producing processes, the molten silicate process appears to offer the greatest saving over terrestrial supply combined with the lowest facility mass (498 kg) required to be delivered to the Moon.

By plotting the ISRU supply cost versus the terrestrial supply cost for the same mass of resource, the breakeven points for ISRU supply become evident (Figure 7-8). This shows that for the production of oxygen, the hydrogen reduction of ilmenite process only becomes cost effective if it can be used for over 70% of the oxygen demand provision. The molten silicate process fairs better and becomes cost effective at around 50% demand provision.

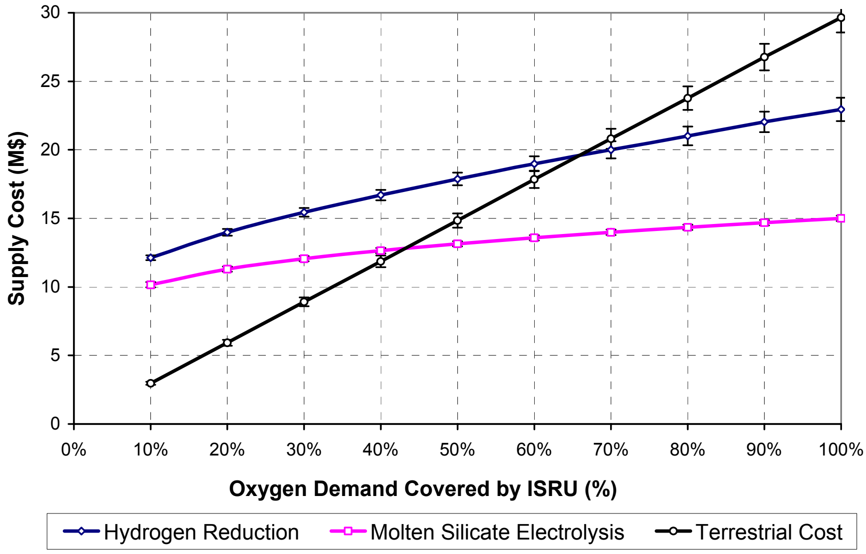


Figure 7-8: Graph of the Break-Even Points of ISRU Processes

Unlike the precursor phases of lunar development, pioneering only becomes feasible with increasing demand. This seems to be due to the fact that early human scenarios only required a small amount of resources for life support and only one return mission, whereas the precursor phases analyzed the possibility of stockpiling propellant for several return journeys. Thus the resource demands are very different. Another factor that may affect the results is that no provisions were made for lunar surface equipment. On these early human missions, these numbers may have an affect. For further discussions on the model limitations, refer to section 7.1.3 on the model limitations.

Outpost Phase with the FERTILE Moon Model

Once the early missions of the precursor and pioneering phases are complete, astronauts will travel to the Moon and stay for longer periods time. These phases are essential in proving the importance of ISRU for lunar development. Outpost phase missions also have different objectives than precursor and pioneering phase missions, they are outlined below:

- Infrastructural development and Construction on lunar surface
- Semi-permanent human presence on the Moon
- Lunar missions become routine (similar to ISS missions today)
- Semi self-sufficient lunar base (in terms of energy, life support system, propellant, etc)
- Possible economic viability for private companies (e.g. Utility companies, ^{3}He mining, etc)

Different mission parameters must be varied in order to determine the feasibility of utilizing lunar resources during the outpost phase. Feasibility can be analyzed in terms of cost, mass, and power budgets through simulations in the model. Table 7-9 describes the demands for resources for the maximum limits for outpost phase missions with 100% ISRU (i.e. 12 crew members, 182 day mission, 5 EVAs/week, 60% loop closure, and three trips to lunar orbit for re-supply).

Table 7-9: Outpost Phase Resource Demands

ISRU Process	Hydrogen Reduction of Ilmenite	Carbothermal Reduction with Methane	Molten Silicate Electrolysis	Hydrogen Extraction	Water Extraction
Hydrogen Demand (kg)	318	318	318	318	318
Water Demand (kg)	9,909	9,909	9,909	9,909	9,909
Oxygen Demand (kg)	4,074	4,074	4,074	4,074	4,074
Feedstock (kg)	334, 196	19, 880	23, 609	60, 151, 857	577, 182
Mining Area (m^2)	45	3	3	8, 184	79
Output Oxygen(kg)	4,074	4,074	4,074	4,074	4,074
Output Hydrogen(kg)	0	0	0	2, 604	509
Output Water(kg)	0	0	0	0	9, 909
Facility Mass (kg)	2, 007	338	258	35, 212	149
Facility Power (kW)	31, 849	76, 703	4, 934	3, 832, 491	61, 106

Based on simple demand and requirement calculations performed by the scenario illustrated in Table 7-9, some analysis can be performed. Oxygen and water seem to have the highest priority for outpost-phase missions, whereas hydrogen has a much lower demand. This can also be visualized in Figure 7-9 where hydrogen does not increase much with crew size, while water and oxygen demand increase much more. Another conclusion presented in Table 7-9 is that the hydrogen reduction process is a poor choice for producing the oxygen and hydrogen needed due to the vast mining site necessary, size of the plant, and power needed for operation. Based on this fact, the hydrogen reduction process will not be analyzed in the remainder of the outpost phase analysis due its impracticality.

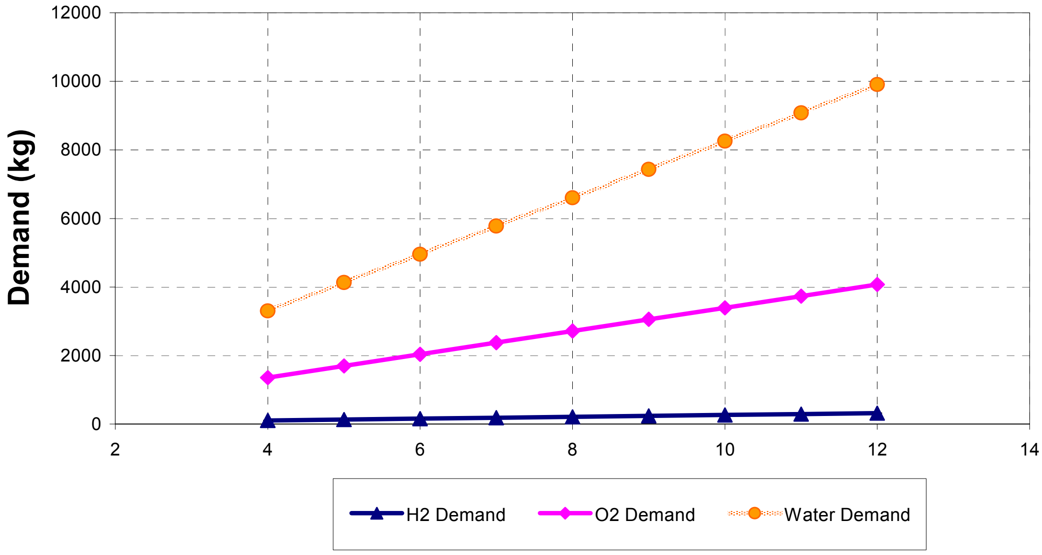


Figure 7-9: Graph of Resource Demand vs. Crew Size

Although the hydrogen reduction of ilmenite, molten-silicate electrolysis, and carbothermal reduction processes can only produce oxygen, these processes efficient in terms of mining area, regolith needed, power requirements, and plant mass. According to Table 7-9, the water extraction process requires a larger surface area than the three oxygen producing processes and more power than hydrogen reduction and molten silicate electrolysis; however it has the advantage of a small plant mass (due to the simple chemical process involved) and of producing water, oxygen, and hydrogen, using a simple chemical process.

Using these four processes remaining for producing 100% of the oxygen necessary to accommodate the crew, ISRU becomes economical over 182 day mission at approximately 6.5 crew members for molten silicate electrolysis, and 9.5 crew members for water extraction, whereas ilemnite reduction and carbothermal reduction do not become economically justified for this scenario (see Figure 7-10). The trends of the curves described how as the amount of resources needed depend greatly on the crew size, so as the crew size increase, so does the feasibility of using ISRU. This is due to the amount of oxygen needed for life support since the habitable volume will be much greater, and the propellant required increases due to increasing mass of the crew.

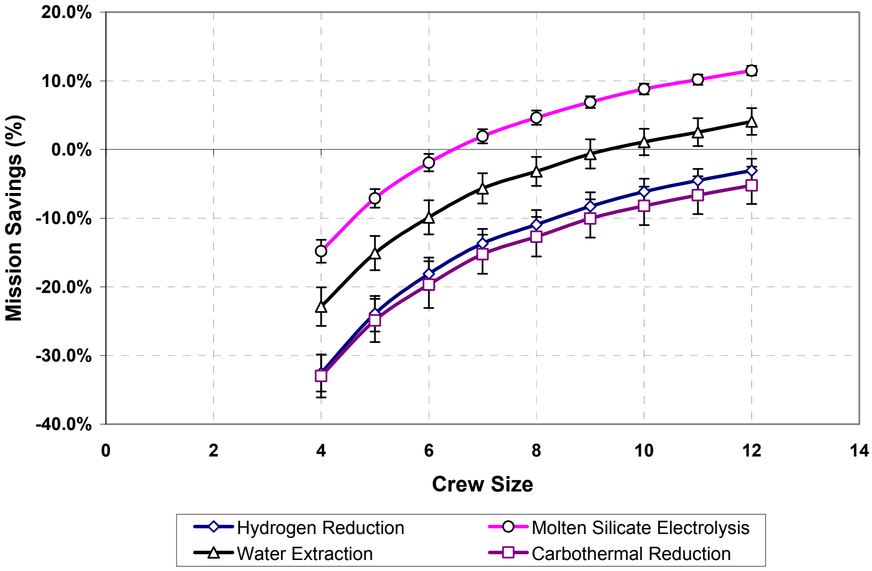


Figure 7-10: Graph of Crew Size vs. Percentage Savings
(4-12 crew, 182days, 5EVA's/week, 60% LSS, 100% oxygen)

When varying the mission duration, the model determines the mission length at which the processes become economical to produce 100% of the required oxygen. Figure 7-11 demonstrates this case.

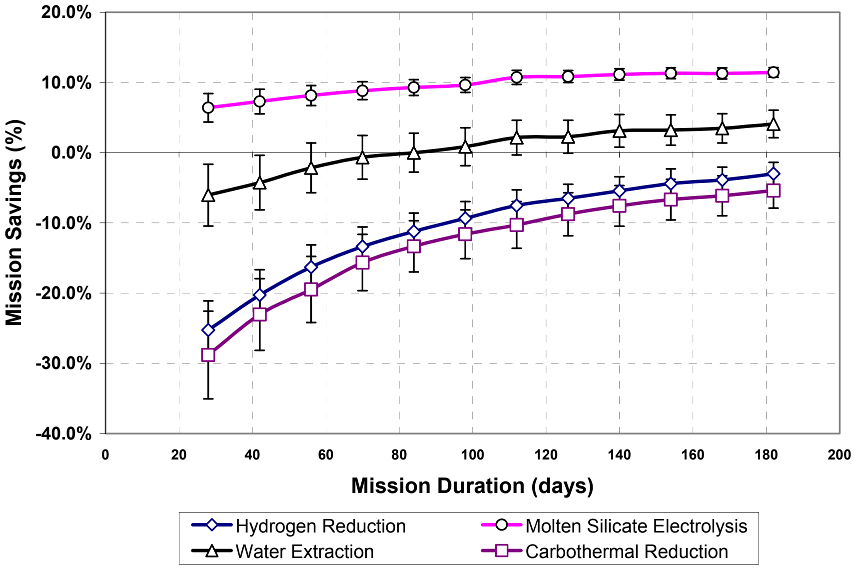


Figure 7-11: Graph of Mission Duration vs. Percentage Savings (12 crew, 28-182days, 5EVA's/week, 60% LSS100% oxygen)

In this plot molten silicate electrolysis is once again economically the most efficient process where it is always economically justifiable for this scenario. Water extraction becomes attractive just around 84 days into the mission. Hydrogen reduction of ilmenite and carbothermal reduction do not become advantageous over transporting resources from Earth, reaching just below the breakeven point at the end of the mission. This is due to the high development costs of the processes. It can also be seen that this processes have a higher slope than water extraction and hydrogen reduction (i.e. the curves approach the breakeven point quicker), implying that the operational costs are lower. This hypothesis will be tested in the settlement phase section next following the outpost phase missions. Comparing figure 7-12 and 7-13 shows how the demand varies much more with crew size than with mission duration. This is due the fact that the propellant requirements do not change with time, unless there are more re-supply missions, but it will change with increasing crew size (i.e. mass). In terms of life support, the habitable volume must be filled at the beginning of the mission and with the combination of the high level of loop closure for this system and the negligible leakage, there is little change over time.

Although the previous plots justify the use of ISRU technologies vs. transporting resources from earth for two of the five processes, a major assumption was made in which 100% of necessary resources were assumed to be produced by ISRU. In the outpost phase of lunar development, depending on the current infrastructure present, there may not be a production rate sufficient to supply 100% of the resource needs through ISRU. The following Figure 7-12 shows how the cost compares to varying levels of ISRU oxygen production, with a mission of 182 days and 12 crew members. This plot shows that molten silicate electrolysis becomes economically feasible at 55% production rate, water extraction at 75% production rate and carbo-thermal and ilmenite are never reach the break-even point once again.

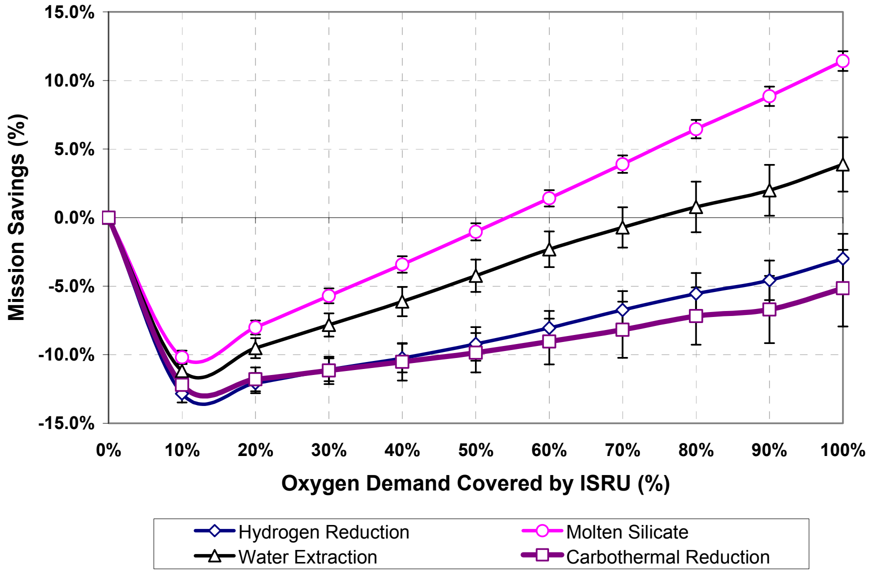


Figure 7-12: Graph of Cost vs. Percentage of Oxygen Produced
(12 crew, 182days, 5EVA's/week, 60% LSS, 0-100%Oxygen)

Figure 7-12 also shows the trend of the high cost for the implementation of the processes, and the progressively lower costs as production increases, causing hydrogen reduction and carbothermal reduction to reach an economically viable solution if the oxygen produced surpasses the required demand for the mission.

Although oxygen is essential in the aforementioned missions, hydrogen and water will also be necessary. As stated previously, hydrogen extraction seems to be an inefficient process to produce hydrogen and oxygen, which leaves water extraction as the only means to produce these resources. The graph representing the point at which producing water and hydrogen on the lunar surface through water extraction becomes feasible was also created but is not presented here, the breakeven point was found at 35% for maximal mission duration, crew size, and loop closure. It is important to remember that water extraction highly depends on the quantity, if any, of lunar ice in permanently shadowed craters on the lunar poles.

Therefore, according to the FERTILE Moon Model for an outpost phase of lunar development, the minimum parameters for an economically feasible ISRU mission are presented in Table 7-10.

Table 7-10: Mission Minimum Requirements

Process	Crew Size	Mission Duration (days)	% ISRU for Oxygen	% ISRU for Water
Hydrogen Reduction of Ilmenite	>12	>182	>100	N/A
Carbothermal Reduction	>12	>182	>100	N/A
Molten Silicate Electrolysis	>6.5	>28	>55	N/A
Hydrogen Extraction	Never	Never	Never	N/A
Water Extraction	>9.5	>84	>75	>35

There is no one solution to the question of is ISRU feasible. Depending on the mission characteristics of each phase, some processes yield economically feasible results that are listed in Table 7-10. The table economically justifies the use of molten silicate electrolysis, then followed by water extraction. Water extraction is also the only justifiable solution to producing hydrogen and water on the lunar surface, however the assumed content of 1% of ice water in the lunar soil may has a huge affect on the choice of this process. Hydrogen reduction of ilmenite and carbothermal reduction are not economically viable for this phase of lunar development, but do come close to the necessary values and should reach the necessary levels in the outpost phase missions where production levels and resource requirements increase. These factors will cause the operational costs and development costs to be redistributed making the processes feasible. Hydrogen, as mentioned earlier, presents enormous costs and impractical mass and power requirements making it an unfeasible solution. A discussion of the validity of these results were presented earlier in this chapter and recommendations are described based on these results are discussed in the following sections. Cost will not only be the only criteria for selecting a process, as versatility to produce several resources and by-products from the same process offer great advantages. For example, hydrogen reduction of ilmenite produces iron that could be used in materials for construction and molten silicate produces silicon for solar panels. Also, infrastructural elements such as power sources and complicated engineering designs for complex chemical processes must be reduced to provide the safest and most reliable solution, such as the simpler chemical process proposed for water extraction. It is essential to remember that the goal of ISRU is not only to save money on mission design, but to create self-sustaining and adaptable colonies starting on the moon and traveling beyond.

Settlement Phase

The settlement phase of a lunar base is defined as a permanent human presence. It is a continuation of the outpost phase into an almost fully self-sufficient colony and possibly economically viable venture. Therefore the mission requirements of this phase of lunar development differ greatly from the aforementioned scenarios. Similarly to the outpost phase, in order to determine the feasibility of ISRU, several parameters must be varied to obtain significant figures in terms of cost, mass, and power for each process. The following table outlines the results of the model for the upper limit of the variables outlined above for settlement phase missions (i.e. 30 people, 1 year, 80% loop closure, etc) (Table 7-11).

Table 7-11: Upper Limit Requirements for the Settlement Phase

ISRU Process	Hydrogen Reduction	Molten Silicate Electrolysis	Hydrogen Extraction	Water Extraction	Carbothermal Reduction
Hydrogen Demand (kg)	1,588	1,588	1,588	1,588	1,588
Water Demand (kg)	31,200	31,200	31,200	31,200	31,200
Oxygen Demand (kg)	15,929	15,929	15,929	15,929	15,929
Feedstock (kg)	1,303, 394	93, 395	235,166,798	2,229,426	75,060
Mining Area (m^2)	177	13	31,995	303	10
Output Oxygen(kg)	15,929	15,929	15,929	15,929	15,929
Output Hydrogen(kg)	0	0	10,184	1,991	0
Output Water(kg)	0	0	0	31,200	0
Facility Mass (kg)	7, 766	1, 010	137, 720	574	1, 330
Facility Power (kW)	123,640	19, 615	15, 037,462	241, 845	303, 630

The table above allows the user to outline some conclusions without plotting any results. As with the outpost phase, hydrogen extraction seems to be an engineering challenge due to its large requirements for mining area, facility mass, and facility power. The other processes are several orders of magnitude smaller in these areas. In terms of oxygen production, molten silicate electrolysis has the lowest power requirements, second smallest facility mass after water extraction, and a small mining area (second after carbothermal reduction). These factors in turn produce a need for few infrastructural elements, lower mass to transport to the lunar surface, and more efficient power usage. Therefore, molten silicate electrolysis will be once again one of the most efficient processes. However, since water and hydrogen will also be needed on the lunar surface, water extraction is the only feasible way to produce it in-situ. Water extraction also has a very low facility mass, due to the simplicity of the chemical process, thus will have a low cost as well. In order to determine the economical feasibility and to answer the question of when does it become worthwhile to produce resources on the moon rather than transport them from Earth, a more complex analysis is provided below.

With a varying crew size, in-situ oxygen production is economical for all processes (excluding hydrogen reduction) at the minimum crew size. As it was the case for outpost phase missions, molten silicate electrolysis and water extraction have a higher savings percentage in comparison to the terrestrially supplied option. In Figure 7-13, the trend indicates that as crew size increases, so does the feasibility of ISRU for oxygen production.

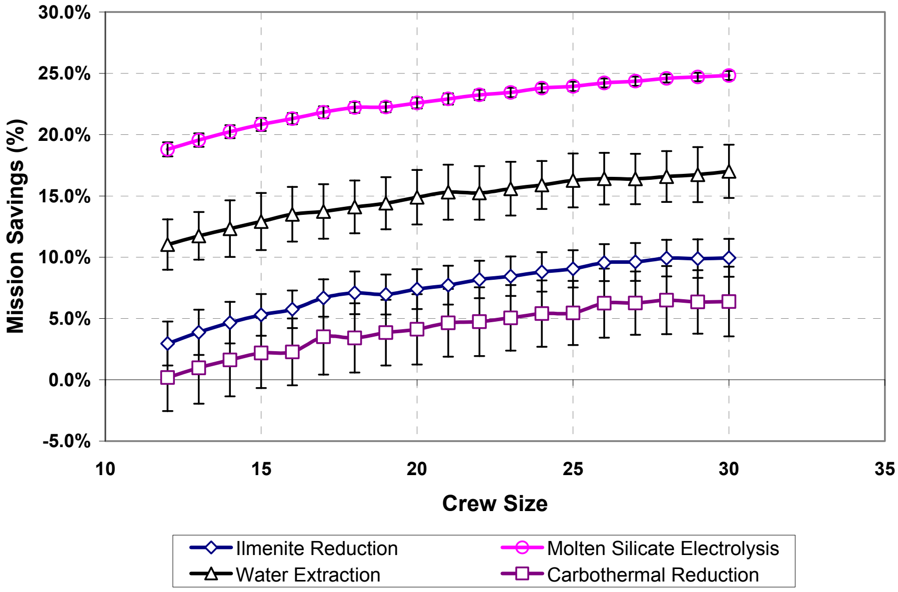


Figure 7-13: Graph of Crew Members vs. Percentage Savings (12-30 crew, 364days, 80%LSS, 100% oxygen)

The following figure (Figure 7-14) shows the effects on varying mission duration on the savings compared to the terrestrial option, again for the production of oxygen. In this plot, hydrogen reduction, molten silicate electrolysis, water extraction, and carbothermal reduction are all economically feasible for all mission durations (with maximum mission parameters). The interesting trend on this plot is how savings decrease as mission duration increase for molten silicate electrolysis and water extraction. This is because the initial savings for this scenario are quite high due to the high resource and production requirements (for 30 astronauts) and these resources do not increase much with increasing mission duration. Therefore, the operational costs will still increase over time and overcome some of the savings due to a smaller increase in demand, causing the savings to decrease slightly.

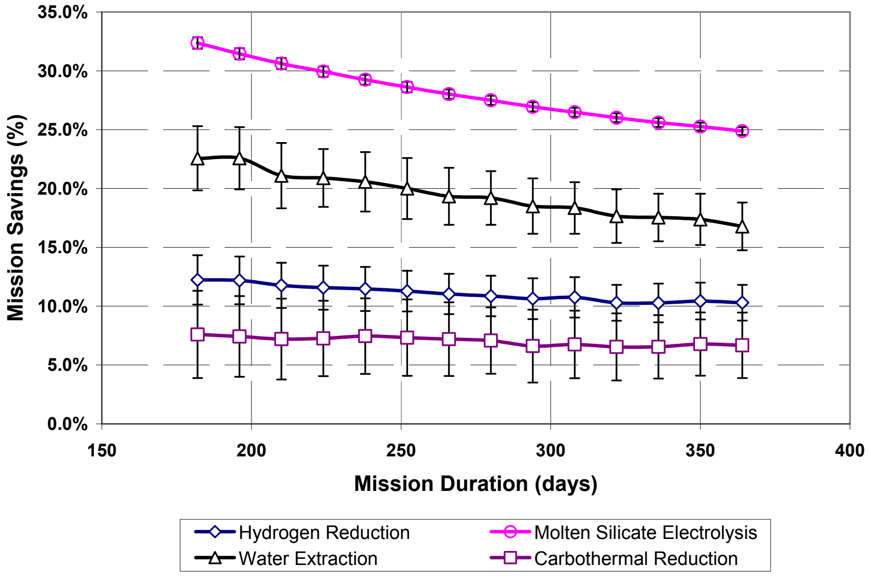


Figure 7-14: Graph of Mission Duration vs. Percentage Savings (30 crew, 182-364days, 80%LSS, 100% oxygen)

The previous missions stated above assumes a level of 100% ISRU production, another interesting analysis is to vary the level of oxygen production to determine the minimum level of ISRU needed to breakeven. Figure 7-15 shows how molten silicate electrolysis becomes feasible at 15% oxygen production, water extraction at 20%, hydrogen reduction of ilmenite at 67%, and carbothermal at 87%. This plot shows how the economic feasibility of ISRU depends greatly on the amount of resources produced. Therefore, as long as higher levels of oxygen demand are needed, ISRU will remain feasible for all four aforementioned processes. In terms of water production, water extraction must have a production rate of approximately 10% is necessary with a crew of 30 people and a mission duration of 1 year.

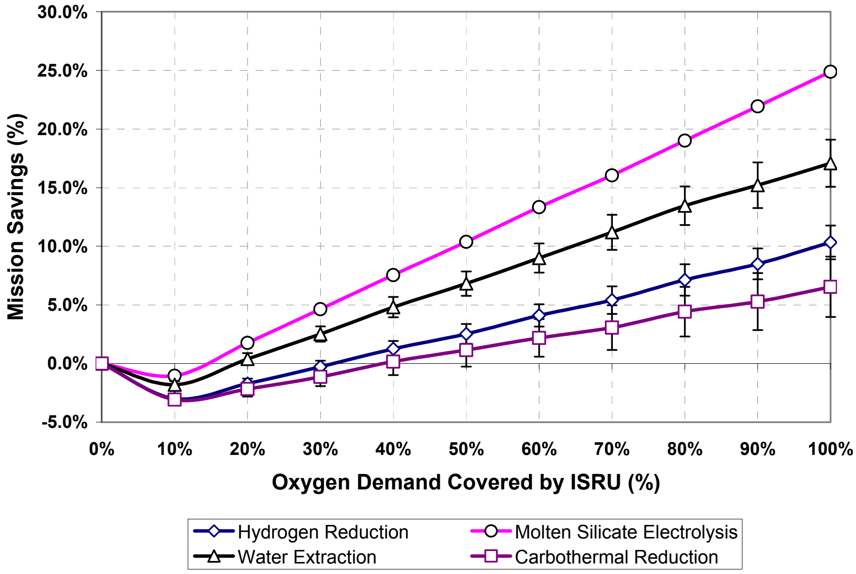


Figure 7-15: Percentage Oxygen Production vs. Percentage Savings (30 crew, 364days, 80%LSS, 0-100% oxygen)

After running the above scenarios in the FERTILE Moon Model, the minimum parameters for an economically feasible settlement phase can be found these outlined in the Table 7-12.

Table 7-12: ISRU Mission Minimum Requirements

Process	Crew Size	Mission Duration	% ISRU for Oxygen	% ISRU for Water
Hydrogen Reduction of Ilmenite	>12	>128days	>67%	N/A
Carbothermal reduction	>12	>128days	>87%	N/A
Molten Silicate Electrolysis	>12	>128days	>15%	N/A
Hydrogen Extraction	Never	Never	Never	N/A
Water Extraction	>12	>128days	>20%	>10%

In this phase of lunar development, according to the FERTILE model, all processes (excluding hydrogen production) are always economically feasible, which gives way to a multitude of process options and combinations. This implies that for longer term missions with higher requirements increase the feasibility of ISRU in all aspects. In addition this scenario did not take in to account hydrogen, oxygen, and water demands for lunar surface equipment (rovers, facilities etc) which are assumed to be part of a settlement phase on the Moon. The inclusion of this extra demand would have a significant affect on the outputs, however would only make the results appear better for ISRU. Therefore, the next step in mission planning would be to begin developing the technologies necessary for creating the chemical processes, and selecting, based on real data, the more efficient process best suited for development.

Summary

The analysis performed illustrates the resources which are feasible and useful to produce on the Moon. Hydrogen Extraction is found to be impractical due to the enormous amounts of feedstock that would need to be mined to produce even a modest amount of the resource. It should be noted however that the costs shown for the Hydrogen extraction process presented here are believed to be over-estimations, sometimes significant as the specific mass of the facility has been assumed to be as low as 4% of the mass of the products.

Oxygen production is the most promising and realistic near term resource that can be produced by ISRU on the Moon. Schrunk et al (1999) summarize the trade studies carried out and infer that although the primary reason for lunar mining of oxygen was to help lower the transportation cost of propellant to LEO,

> “the economic incentive for mining the Moon improves rather than worsens … because no matter how inexpensive it becomes to lift materials, supplies and propellants from Earth to the Moon, it will always be proportionately cheaper to set up a lunar production facility and obtain the required supplies from the Moon.” (Schrunk et al, 1999)

The water extraction process is highly dependent on the assumed percentage of water content in the regolith, however with an estimate of 1%, this processes is feasible for most cases. The effect of varying the assumed water content is looked at closely in the sensitivity section.

7.2.4 Future Architectures and Technology Development

The scenarios presented above provide a general economical feasibility of oxygen, hydrogen and water production based on cost, mass and power. Mass and power are physical terms that define the facility and the technologies it utilizes and both attributes can change over a course of time in order to enhance the system. Here, the feasibility of ISRU capability is examined from technical and evolutionary perspectives, with the intent to understand the technology changes and developments necessary for extension of these technologies to future exploration for Mars or other planetary bodies. For example, although lunar water ice extraction may not be the best chemical process, the technology of drilling for sub-surface water would become an important test plant for Mars exploration. To assess the technical feasibility, it is necessary to examine current terrestrial technologies that could be adapted for use in future exploration strategies.

Systems that need to be developed for Lunar ISRU are not dependent on exotic or breakthrough technologies, such as in the case of Helium-3. Hence, lunar oxygen, hydrogen and water extraction would include adapting appropriate candidate technologies that exist on Earth. Existing technology from the underground mining, chemical and construction industries can be modified in order operate efficiently in the lunar conditions and operational cycles. Table 7-13 summarizes the effects of different technologies and assigns a value of importance to the parameter.

Table 7-13: Impact of Key Technologies on Major Cost Variables

	□ Low Impact ▦ Moderate Impact ■ Heavy Impact	Net lunar oxygen delivered to LEO	Earth-to-Moon transportation cost	Power required	Number of lunar base resupply missions/yr	Unit mass of lunar base modules	Cost of power	Ground support labour	Processing/storage facility cost	Power system mass	Number of types of lunar base modules	Ground support overhead factor	Processing storage facility cost	Cost of modifying existing space modules	Mass of processing /storage facility	Unit cost of lunar base modules
Transport	Performance and cost of CLV or other launch vehicle	■	■	□	■	■	□	□	□	□	▦	□	□	□	□	■
	Performance and cost of transfer vehicle (if available)	■	□	□	■	■	□	□	□	□	□	□	□	□	□	□
	Autonomous landing and command & control	□	□	□	■	■	□	▦	□	□	■	□	□	□	□	□
	Availability of aerobrake for LO_2 delivery	■	□	□	□	□	□	□	□	□	□	□	□	□	□	□
Power	Lunar base power source	□	□	□	□	▦	□	□	□	■	□	□	□	□	□	□
	Scalability of small (< 100 kW) power systems	□	□	□	□	□	■	□	□	■	□	□	□	□	▦	▦
	Power consumption of processing technique(s)	□	□	■	□	□	■	□	■	■	□	□	■	□	■	■
	Complexity of power system installation	□	□	□	□	□	■	▦	□	▦	□	▦	□	□	□	□
	High Density or Alternate energy storage	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	Maintainability of power system	□	□	□	□	□	□	□	■	□	□	□	□	□	□	□
Precursors	Robotic sensors	□	□	□	□	□	□	▦	□	□	□	▦	□	□	□	□
	Robotic mining systems - preliminary/pilot plants	▦	□	□	□	▦	□	▦	□	▦	□	□	□	▦	□	□
	Ka Band or Higher communication systems	□	□	▦	□	▦	□	▦	□	□	□	▦	□	□	□	□
	Machine Human interface	□	□	□	□	□	□	□	■	□	□	■	□	□	□	■
	Data Compression Information Processing	□	□	▦	□	□	□	▦	□	□	□	□	▦	□	□	□
	Large scale data management systems	□	□	□	□	□	□	□	□	□	□	□	□	□	□	□
	Availability of Lunar H	■	□	□	■	■	□	□	■	■	□	□	■	□	■	■
Pioneering/ outpost	Advanced robotic mining systems	■	□	■	■	□	□	▦	■	□	□	□	■	□	■	■
	Automated processing technology	□	□	■	□	■	□	□	■	■	■	■	■	□	■	■
	Alternative, regenerable energy economies	□	■	▦	■	□	■	□	□	□	□	□	□	□	□	□
	Dust protection, seals, abrasive resistant materials	□	□	□	■	■	□	□	■	□	■	□	□	□	■	■
	Lightweight Hi-Reliability life support	□	□	□	■	■	□	□	□	□	■	□	□	▦	□	■
	Surface mobility equipment	□	□	■	□	□	□	▦	□	□	▦	□	□	▦	□	□
	Tribology	□	□	□	■	▦	□	□	▦	□	▦	□	▦	▦	□	▦
	Small, efficient, portable, thermal control systems	□	□	□	▦	▦	□	▦	▦	□	□	□	▦	□	▦	▦
	System health evaluation systems	□	□	□	■	□	□	▦	▦	□	□	▦	▦	□	▦	▦
Settlement	Advanced life support systems	□	□	□	■	■	□	□	■	□	■	□	□	□	■	■
	Adavanced lunar base shielding	□	□	□	□	▦	□	□	▦	□	▦	□	□	▦	▦	□
	Duration of lunar crew shifts	■	■	□	■	□	□	□	■	□	■	□	□	■	□	■
	Degree of closure in the life suppor system	▦	□	□	■	▦	□	▦	□	□	□	□	□	□	□	□
	Size of the lunar base	■	□	□	■	■	■	□	□	□	■	□	■	■	■	■
	Commonality between LO_2 storage facility and depot.	■	■	■	■	□	□	■	■	□	■	□	□	■	□	▦

Large uncertainties exist in the current knowledge of the lunar environment and its suitability as an operating environment. The user must treat these uncertainties whilst evaluating practical options. The chemical processes may work efficiently, but the greater challenge is to dig, extract, collect, pound to the required size and transport the feedstock to the chemical plant. Here lunar mining equipment is discussed in terms of evolving the technologies for lunar exploration.

Designing Lunar Equipment based on Earth Operations

Although much of the technology is available on earth, it would need to be tailored to lunar conditions. Here we review the constraints on design criteria and selection and what the feasible options are:

- Designs on earth for mining and construction are designed to be robust with little significance to making structures light weight.
- Dale Boucher (Taylor, 2004) proposed a VAMPS process (refer to section 4.2.9)

Environmental constraints

As discussed in Chapter 4, most of the resource extraction methods are limited to being chemical processes. Various data available from simulators, Apollo samples, and other evidence suggest that lunar conditions would be a harsh environment to operate in.

- Systems down selected for our mining of the resources are all tailored for operation on Earth are bulky and huge – these would need to be developed into light weight structures with similar payload ratios. This is expressed simply in section 7.2.3 where mining areas are in the range from 1 to 10m^2 with a depth of no more than 3m for the more efficient processes, large bulky equipment would therefore be detrimental to the extraction process. Mechanisms optimized for lunar surface would utilize slender joints and members and would need to incorporate parts that are replaceable, specially treated (Sherwood and Woodcock, in Lewis), long lived and incorporating recent advances in lunar tribology for more effect production operations.
- Moving parts are subjected to amounts of dust that can be abrasive. No atmosphere and no air convection (which causes problems with lunar dust erosion and friction effects on parts exposed to this). This is also dependent on the chemical process used. For example, for oxygen production with ilmenite, the regolith needs to be a size of 1 micrometer; therefore over a mine of 20m^2, there is a significant impact on dust cloud built ups.
- Effects due to sunlight, gravity and diurnal cycles and radiation phenomena would need to be accounted for
- Previous Apollo mission data on the lunar drilling and coring suggest that removal of cuttings from boreholes is difficult, shoveling material for transport is easier but not a good option in terms of energy (Burke, personal communication, 2006)
- The reduced gravity environment would cause the bulldozers and other excavating machines to exert much less downward forces and therefore shallower excavations would be beneficial. (Schrunk et al,1999)
- It is also uncertain if bedrock exists, but it is believed from the experience gathered during Apollo missions that lunar rocks are more friable than earth surface boulders.

Transportation Constraints

- Launch capability is closely linked with the question of oxygen, hydrogen and water and how to procure them.
- Surface mobility – many systems use hydrogen as fuel in order to transverse surface on the moon. Requirements of surface mobility depend on the demand, the sizing of the facility and increasing of base size. Surface mobility in terms of conveyors for hauling of extracted regolith may either add initial demand or would need to be improved as facility mass increases.

Adopt, Adapt and Improve

Such technologies can help build important synergies between processes on Earth with those on the Moon and beyond. These synergies would transfer the best part of the technology and equipment design processes to be adapted to extraterrestrial conditions to derive cost and energy effective solutions. These technologies draw attention to key parameters that need to be considered in order to invest in such ventures. Hence, a sensitivity analysis was carried out in order to see how the relationships are affected.

7.2.5 Sensitivity Analysis

A sensitivity analysis of the FERTILE Moon Model allows the user to understand the relationships and sensitivity to varying parameters. The sensitivity analysis highlighted some relationships that were not necessarily obvious when the model was created. The following section describes these relationships.

Demand Sensitivity

While comparing the demand of resources for different missions, it was found that varying crew size has a much greater affect than varying mission duration on the requirements of oxygen and hydrogen, whereas water has a similar rate of change for both. This is discussed in further detail with a comparison of the plots in the analysis of results section 7.2.3.

Supply Sensitivity

The analysis for the water extraction process was found to be highly dependant on the assumptions regarding the process efficiency. Due to the large uncertainty surrounding the content and characterization of water-ice in the lunar regolith at the south pole, simulations were conducted to gauge the effect of varying extraction process efficiencies. Figure 7-16 illustrates the cost of water production as a factor of production runtime, with efficiencies for Water Extraction of 0.5%, 1.0% and 2.0%.

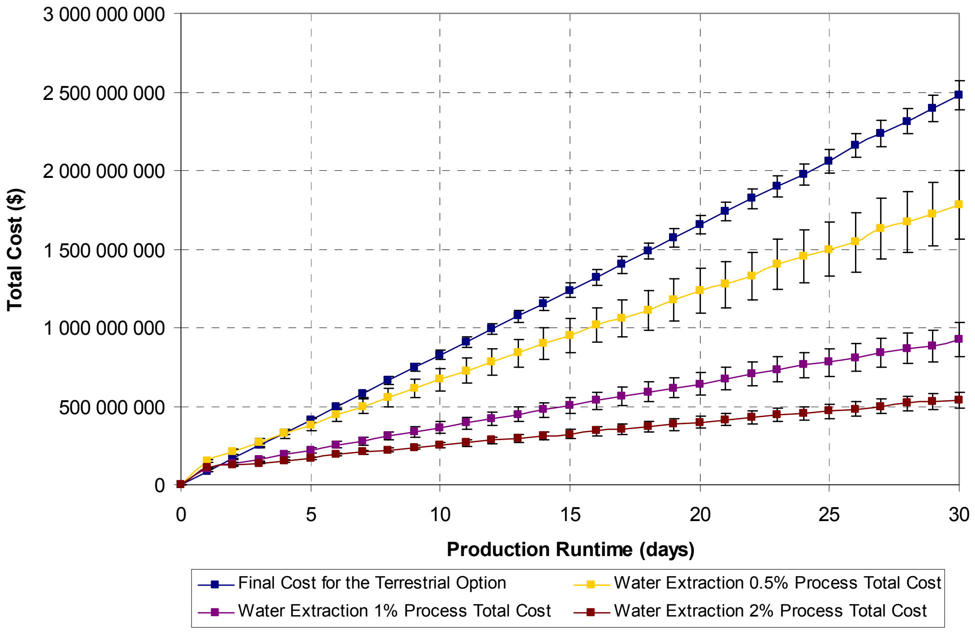


Figure 7-16: Graph of Production Runtime vs. Cost for Water Extraction

Cost Parameters

The mining equipment and facility amortization period sensitivity analysis is elaborated here. The model assumes a 10 year amortization period for all ISRU facilities. This assumption is not particularly suited to small pilot plants or demonstration facilities which are designed for shorter operational lifetimes. Hence a sensitivity analyses is performed, and the results of one precursor mission are presented here in Table 7-14.

Table 7-14: Amortization Sensitivity Analysis Fixed Parameters

Parameter	Value	Rationale
Crew size	1 - 10	Method to vary lunar equipment: higher crew sizes generate approximately 7 tons of oxygen which is likely the maximum needed for precursor missions
Hydrogen ISRU	100%	Precursor mission
Oxygen ISRU	100%	Precursor mission
Simulation type	Triangular	Reasonable accuracy
Production Runtime	30 days	Reasonable mission duration
Iterations	100	Reasonable accuracy to processing time ratio

The results of the mining equipment and facility amortization sensitivity analysis are illustrated in Table 7-14. It is important to note that the percentage differences indicated in Figure 7-17 are from the Fertile Moon Model default value of 10 years.

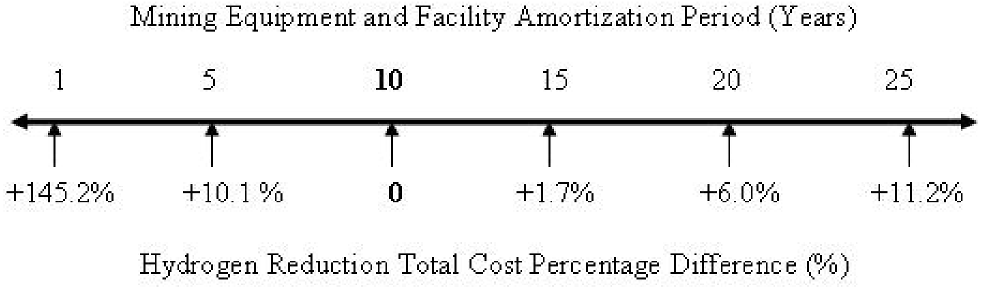


Figure 7-17: Amortization Sensitivity Results

The results shown in Figure 7-17 clearly indicate that for amortization periods of 10 years or less, the hydrogen reduction total cost increases significantly, up to over 145% for 1 year. In the case of amortization periods of over 10 years, the hydrogen reduction total cost increases modestly to account for the extended use of the mining equipment and facility.

Process Efficiencies

A long mission was used to make this analysis, using the input parameters shown in Table 7-15. Note: these parameters were kept constant; none of them were used as a range of values.

Table 7-15: Mission Parameters

Parameter	Value
Crew size	30
Mission duration	364
Number of EVA	7
LSS closure	70
Number of Trips	6
% Hydrogen	100
% Oxygen	100
% Water	100
Production runtime	390

Using the scenario described above, some ISRU process parameters were varied in each simulation: Process Specific Mass, Process Specific Power and Process Mining Specific Cost. Figure 7-18 shows how the ISRU Supply Cost varies with different values of Process Specific Mass. A linear trend line with its equation and correlation are also shown.

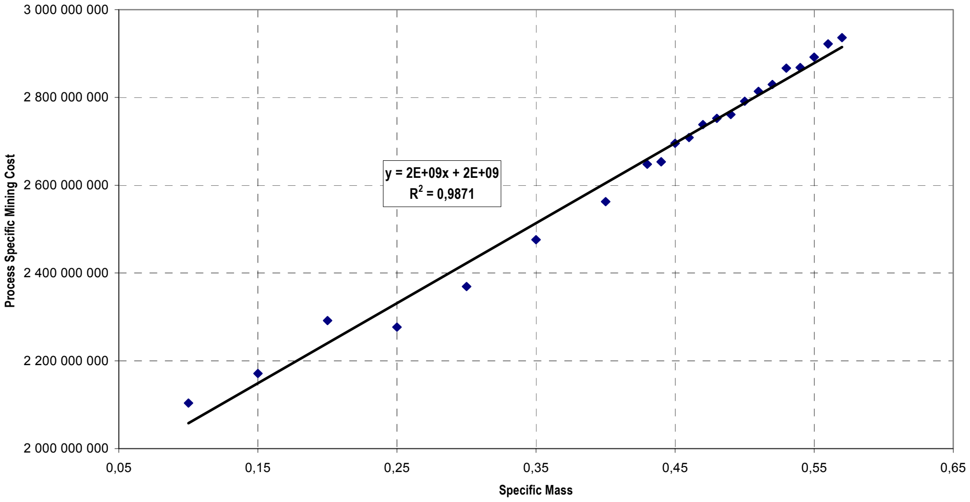


Figure 7-18: Graph of Mining Cost vs Specific Mass

The same procedure was repeated for each of the three parameters and for all the five processes. Table 7-16 summarizes their respective values of slope and correlation. The highlighted values are the ones that have higher values of slope and better correlation. This means that in process 1 (hydrogen reduction of ilmenite), for example, the Process Cost is more sensitive on the Specific Mass than on the Specific Power or the Specific Mining Cost.

It is also noted that some processes do not correlate with certain parameters. For example, process 4 (water extraction) does not correlate to Mining Specific Costs (0.0089 correlation).

Table 7-16: Correlation of Parameters

Process	Specific Mass		Specific Power		Mining Costs	
	Slope	Correlation	Slope	Correlation	Slope	Correlation
1	2.00E+09	0.9871	2.00E+08	0.9988	1.00E+07	0.8467
2	-4.00E+09	0.9091	2.00E+08	0.9969	655378	0.9642
3	3.00E+09	0.9623	3.00E+08	0.9985	9.00E+08	0.0391
4	5.00E+11	0.9965	4.00E+08	0.9854	-1.00E+07	0.0089
5	-5.00E+09	0.3655	3.00E+07	0.996	4.84E+05	0.8356

The different cost values were also compared to the earth supply option, in order to know the break even points. From the mission described above, only Hydrogen Extraction and Water Extraction are more expensive than the earth supply option. The break even point for the hydrogen extraction process is reached by reducing the Process Specific Power from 732 to 115 W/kg. The break even point for the water extraction process is reached by reducing the Process Specific Mass from 0.04 to 0.029 kg/kg.

7.3 Private Sector Involvement

Space activities beyond Earth orbit have so far been exclusively conducted by national governments through their space programs. However there is a growing recognition of the importance of opening the space frontier to commercial activity. Wertz (1999) recognizes that 'the fundamental limitation to expansion into the solar system is not technological, but economic'. In most studies, experts relate the high cost of lunar space commerce to the high costs of the ground to moon transportation systems and their development. Two widely accepted views are to engage in high-return schemes or to increase the number of players in order to spread the risk. Section 6.4.2 and 6.4.3 discuss the technology development and policy formulation in order to assess ISRU supply by the commercial sector is possible.

7.3.1 Feasibility & Strategies

Most literature review private sector interests in lunar exploration in the context of utilizing space energy resources (such as helium-3) or space "real estate utilization" (Davis, 2006) where access to the lunar surface and reduced gravity environment would lead to development of various human endeavors for development. It is true that most documented interests in lunar exploration that are termed 'commercial' involve products of resource utilizations that would lead to a higher rate of return or tremendously large profits that can offset the huge upfront investment and risks (commodities).

Who Would Like To Do ISRU?

As stated earlier, the initial uses of ISRU would be the economically less attractive uses such as use of oxygen and other supplies to assist life support systems and possibly transport back to earth for crew. Hence, in our case, the term 'commercial' entails the status of an enterprise that would be providing extraction of oxygen, hydrogen and water as services to government customers. This is analogous to services provided for basic utilities on Earth. For example, water is a resource available for free and in abundance to all mankind. However, it requires collection, desalination and appropriate treatment and storage before it can be transported and subsequently consumed. Such a service is provided by a private for-profit enterprise. Hence, taking the above analysis of the FERTILE Moon Model further, one can explore the feasibility of the lunar resource utility service.

A certain insight needs to be given to what such a company would be like. It is likely that the first contenders for interest in ISRU operational capabilities would be companies that are not traditionally associated with space exploration. A commercial company interested in enabling a 'utility' provision for ISRU derived oxygen, hydrogen and water would require expertise in mining, chemical processes as well as transportation and storage of materials and gases on Earth. It would be a company that would help meet most demand via collaboration with the Earth-to-Moon transportation segment.

The company would certainly have to possess valid reasons for such a venture that would be expensive to set up, such as spin-offs of technologies and processes on Earth. Companies such as Caterpillar Inc., who manufacture heavy mining and infrastructure equipments, are already expressed interest in lunar mining activities (Stratton, personal communications, 2006; Reiners, personal communication, 2006). Other candidate companies that may find the ISRU utility service of interest could be other heavy equipment companies such as Schlumberger, oil and energy companies such as Shell or Texaco or aerospace companies such as Raytheon. Such participation would be made possible by having adequate rights for further use granted during the demonstration and development phases.

The current model assumes a certain level of assay developments before a permanent ISRU facility is established on the moon. These include prospectors, leveling of the ground for set-up as well as establishment of a power source. The first scout missions, which would be key in reinstating the confidence of a company, would be mobile facilities that would have scaled down sub-systems for mining, beneficiating as well as chemical treatment and dump/slag recovery. These facilities would have to move autonomously or via tele-operation from one place to another in order to find the optimal site for the process. As production rates and demands increase, scaled up versions of such facilities can be set-up as static facilities and larger scale transportation from a mining site further afield via surface vehicles or conveyers can be carried out.

Company attributes and commercialization/business plans of a company looking at the ISRU Utility service can be as shown in Figure 7-19. Kazakidis and Scoble (2003) state that the efficiency of the production schedule and cost estimates in a mining plan (on Earth) depend on its ability to account for the variations in the geological characteristics of the ore body and on the operating team. Although these uncertainties are in the context of activities carried out on Earth, the uncertainties are double on the moon.

Depending on funding of initial prospecting missions, many of the uncertainties may be reduced and clear scenarios for interested parties to choose strategies to invest in a risk avert manner. One of the risks that is identified is the lack of customers. It is assumed that for the purpose of discussion pertaining to the service utility option, the government or governments have established the lunar base and hence represent a customer for the utility services. Whether this forms a sufficient market depends on the lunar base size and on the space transportation requirements. Figure 7-19 shows the commercial options that are available for a successful venture. This composite figure also addresses the programmatic risks that a company may face later.

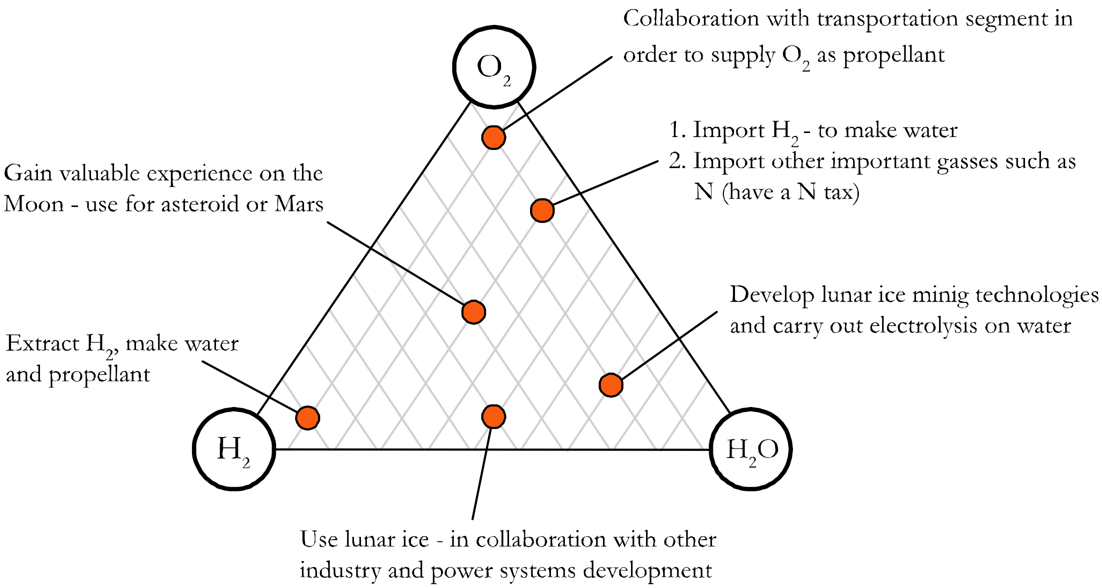


Figure 7-19: Commercial Options for ISRU

Depending on funding of initial prospecting missions, many of the uncertainties may be reduced and clear scenarios for interested parties to choose strategies to invest in a risk avert manner. One of the risks that is identified is the lack of customers. It is assumed that for the purpose of discussion pertaining to the service utility option, the government or governments have established the lunar base and hence represent a customer for the utility services. Whether this forms a sufficient market depends on the lunar base size and on the space transportation requirements. Figure 7-19 shows the commercial options that are available for a successful venture. This composite figure also addresses the programmatic risks that a company may face later.

7.3.2 Economic Viability

The Vision for Space Exploration announced by President Bush in 2004 (NASA, 2004), clearly states the desire to include commercial actors in exploring near Earth space. This position was reiterated by White House Science Advisor, Dr. John Marburger in his speech of 15 March 2006, where he outlined the position of the US administration to expand the sphere of human economic activities beyond Earth orbit. The White House and NASA recognize the simple fact that a permanent human presence beyond Earth orbit cannot be sustained indefinitely by a national space program. The best way to guarantee the expansion of humanity beyond LEO is to establish the infrastructure upon which a cis-lunar economy can develop.

The advantages of promoting exploration activities to the private sector include promoting greater innovation, diversifying risk and increasing the number of actors who can provide a certain capability (for example cargo delivery to LEO). This level of redundancy is traditionally lacking in existing space programs, where a critical failure in one program (for example the Shuttle) can jeopardize other programs (for example, the ISS).

Private sector involvement in the initial stages of lunar exploration could include the provision of utility services such as power and fuel. Initial customers would be the national space agencies, but would expand as more players enter the market. Any company which can provide such a service would achieve 100% market capture, and would be strategically places as a key player in the development of the cis-lunar economy.

There are possibilities for other economically viable ventures on lunar surface and orbit such as entertainment and tourism, competitive sports, educational and research, near earth asteroid tracking, advanced sensor electronics, etc. However, it is believed by the authors that these are only possible in timescales longer than are anticipated by the modeling analysis considered here. The question still remains, 'how' is it going to be possible to create such a venture? Benaroya (2001) proposed a framework to substructure the projects into smaller independent and profitable units. These units are subsequently managed by a Lunar Development Corporation (LDC), a company of engineers, scientists, financial and legal teams that would act as venture capitalists to coordinate and attract investments for the independent company units.

7.3.3 Policy Formation

With a review of programmatic issues and opportunities available to today's entrepreneurs interested in participating in financially viable ventures, it is possible to mitigate the risks of space ventures. Government spending at least for the United States, Russia and Europe is significantly different than it was in the 1960s. Now the paradigm is to encourage as much private sector participation as possible so that the investment and expenditure in space activities can be justified in terms of geographical return via awarding of contracts, employment and research.

It is important for the public sector to prioritize technologies into a critical path technology demonstration roadmap. Each technology would hence provide a solution to the smaller effective means of doing exploration in a cost effective manner whilst adapting strategies to compensate for uncertainties. Many space enthusiasts and advocates have already taken a step in this direction. In the US, NASA is currently working with the Santa Monica, California-based X Prize Foundation to conduct 'Centennial Challenges'. One such challenge is the Lunar Lander Analog Challenge which aims to demonstrate the capability of carrying humans and cargo back and forth between the lunar surface and orbit (NASA, 2006). Another initiative between the Florida Space Research Institute and NASA's Centennial Challenges program is a 'first to demonstrate' competition of th**e** MoonROx Challenge to advance the state-of-the-art of oxygen production from lunar regolith. This competition will feature a USD 250,000 cash prize for a team that demonstrates a capability to extract 2.5 kilograms of oxygen from a regolith simulant (JSC-1a) within a four hour period (FSRI, 2006).

7.4 Summary

In this report, Chapter 3 (Demand) and Chapter 4 (Supply) familiarized the reader with the requirements and options for supply of resources on the Moon. Chapter 5 and 6 then presents the cost and legal aspects of the study. The analysis section presented aims to view, calibrate and test the results of the model. Lunar ISRU developments would develop in tandem with the different phases of lunar development. Scenarios for each phase from precursor to pioneering to outpost and settlement were presented, using the model to elucidate the factors which affect ISRU provision. This suggests that the model is flexible and can be applied to a variety of cases to evaluate the feasibility of ISRU in different phases of lunar development.

With regards to the results of particular scenarios; it appears that hydrogen extraction is the most impractical method for resource utilization due to the large volumes of regolith required for even a modest supply. The process of water extraction is highly dependent on the assumption of the percentage of water-ice present in the regolith at the lunar South Pole; however, with the current estimate at 1%, water extraction represents an economically and technically viable solution. The most abundant and easiest resource to acquire is oxygen, which is shown to be cheaper to produce using ISRU in most cases, and different processes are appropriate for different phases of lunar development.

The reader is encouraged to take the solutions of the model and put them through a pragmatic test in order to see what additional trade-offs can be performed. A discussion of trade-offs between simple and modified earth technology results in understanding what systems are better suited to the lunar conditions. After having discussed 'how' to use resources in-situ, it is important to understand who is going to be performing these activities. Government and private sector partnerships are discussed in the context of a private enterprise carrying out Lunar ISRU 'utility' provision. This highlights the constraints and programmatic risks as well as the policy for such ventures.

The model was designed in order to be an adaptable and flexible tool, thus this report does not encompass all possible avenues for its use. Presented in this section were various scenarios and phases in lunar base development; however the real advantage in the use of this model is that it may accommodate all types of scenarios. The following chapter discusses all types of future work that is possible for the model that was not previously discussed, whether it be of its utilization, modification of design, or validation of data, the goal is to allow the FERTILE Moon Model to be useful in the future for real decision making purposes.

8 CONCLUSIONS AND RECOMMENDATIONS

The previous eight chapters have described the FERTILE Moon Model and its role in studying and analyzing ISRU's feasibility. This chapter will summarize the main points and conclusions that have been drawn throughout this report and will also discuss the future work that needs to be done with respect to the improvement of the FERTILE Moon Model as a whole. It is necessary to first reiterate the rational for analyzing ISRU and for developing such a tool.

8.1 Why Was the FERTILE Moon Project Undertaken?

Humanity is at the beginning of a new era where humans will be sent beyond Earth orbit for the purpose of establishing a permanent and sustainable presence in space in general and on other celestial bodies in particular. This wave of exploration may involve state of the art technologies and concepts, but the strategies that will make it successful will be the same as the ones used by humans hundreds of years ago as they expanded across the planet. The key to successful exploration and expansion lies in the ability to "live off the land" which is why space agencies are examining the implementation of ISRU strategies. Each frontier that exists for exploration has certain resources available to those who are able to locate and extract them. The Moon, which appears as a barren wasteland to some, actually has a wealth of resources available. For example, the regolith on the surface of the Moon has amounts of oxygen and hydrogen as well as numerous metals and glass that can be used to sustain humans. There is also the possibility of the presence of water, which, if verified, can be a great asset for anyone who can extract it.

Although all these potential resources are of great benefit to any lunar explorer or settler, none of them have ever been successfully used for the benefit of mankind yet. While numerous concepts of ISRU processes have been theorized, none have ever been successfully tested in-situ. There is very little certainty available on the benefits and reliability that ISRU offers. Because of this lack of certainty, mission planners are hesitant to include it in their future plans. There is not enough information on whether or not ISRU should be developed and that is why it is necessary to examine its feasibility.

Many different approaches exist to study the feasibility of an idea. The most common one consists in defining experiments to test different aspects of the idea as well as to analyze which factors impact the experiments. For the concept of ISRU, such an approach is not realistic as it is highly unlikely that policy makers and mission planners will be willing to invest the huge amounts of money required. Another way to study the feasibility of a concept is to model it here on Earth. Though physical modeling is often costly and time demanding, computational modeling, on the other hand, appears extremely effective when it comes to analyze the feasibility of such a concept as ISRU.

The FERTILE Moon project aims to create a versatile and robust computational model as a tool to test the feasibility of ISRU. The model is based on all the current information available on the concept of ISRU and uses an interdisciplinary approach to examine the economic benefits of ISRU compared to the more traditional terrestrially-supplied approach of space exploration. The FERTILE Moon Model focuses on three resources that will be key in the early development of a human presence on the lunar surface: hydrogen, oxygen, and water.

8.2 FERTILE Moon Report Summary

The body of this report was broken down into two major parts. The first part, which encompasses Chapter 2 to Chapter 6, describes how the FERTILE Moon Model works and the theory and reasoning behind the variables used. The second part, Chapter 7, shows how the model can be used and draws some conclusions on the feasibility of ISRU.

8.2.1 Part One – The FERTILE Moon Model

This part of the report was broken down into five chapters:

- Modeling
- Demand
- Supply
- Costing
- Political, Legal, and Ethical Aspects

Each chapter will be summarized with a discussion of its relevant conclusions in this section.

Modeling

The FERTILE Moon Model was created using Microsoft EXCEL with Visual Basic. This option was chosen over other possible modeling solutions based on its simplicity of use, versatility, and its ability to allow the model to be easily upgraded. The model uses a graphical user interface to allow the user to set various inputs in order to create desired graphs based on what information they require for their analysis. The structure of the model was broken down into three layers as shown in **Figure 8-1**.

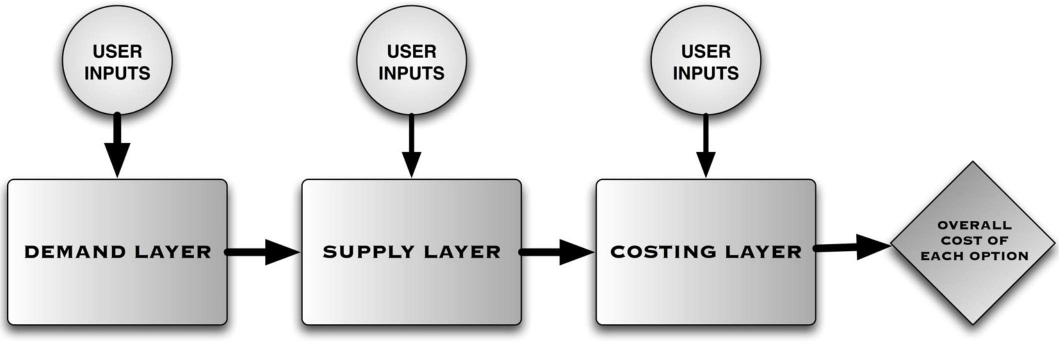


Figure 8-1: An Overview of the Layers of the FERTILE Moon Model

The Demand Layer focuses on two key areas that will affect the demands of lunar missions: the necessity for propellant and the requirements of the life support systems. These areas of focus were chosen because they will be important in early lunar development and have been identified as areas that could benefit greatly from ISRU. The model allows the user to input various mission parameters such as crew size and payload sizes, which are used to calculate the total required hydrogen, oxygen, and water for the specified mission.

The outputs from the Demand Layer are combined in the Supply Layer with several user inputs that define the desired method of supply. The model allows the user to choose a value between 100% terrestrial supply and 100% ISRU supply for each individual resource. This function was included to improve the versatility of the model by making it possible to calculate costs for numerous supply methods. This is important since there have been no definitions created on how many in-situ resources will be used in future missions.

Each parameter outputted from the Supply Layer is used in the Costing Layer to calculate the cost of supplying the mission with each of the five ISRU processes included in the model. Because there is no definite answer concerning the process the most likely to be used, all five processes are evaluated, making the FERTILE Moon Model a valuable tool for mission planners. The model also provides the user with the overhead cost due to integrating international partnerships into the mission plans, as well as information concerning the impact of export control issues on the mission cost.

Demand

The Demand Layer, which was described in Chapter 3, shows how life support systems and transportation requirements affect the amounts of hydrogen, oxygen, and water needed for a particular mission. Life support systems have been included because of their impact on mission architecture. In-situ propellant production was also considered because its implementation should result in significant mass savings.

The transportation section of the Demand chapter focuses on the needs for returning payloads from the Moon to Earth with the possibility of stopping in LLO. Different mission scenarios were thus defined so that mission architectures that include Earth- or Moon-orbiting space stations could be considered and evaluated.

The life support section of the Demand chapter focuses on examining the amount of water and oxygen needed to ensure crew survival, create sufficient habitable space, and support EVAs. Environmental control and life support systems vary greatly depending on the length and size of a mission. Thus the FERTILE Moon Model incorporated the results of ELISSA to create three classes of systems and allowed the user to consider different mission durations and crew sizes.

Supply

The Supply Layer focuses on two main options for supplying the desired mission. The first option is the traditional approach of bringing everything from Earth. To make the model more robust, two sub-options were taken into consideration: bringing all the resources in liquid form from Earth or bringing water to the lunar surface and using electrolysis to create the required hydrogen and oxygen. Since the terrestrially supply approach was employed in all previous exploration missions, it is considered as the baseline for the model's comparisons.

The second option available is to use resources available on the Moon. The FERTILE Moon Model allows the user to select the percentage of the demand for each specific resource that must be met through ISRU processes. The current form of the model compares five distinct processes for meeting the demands in hydrogen, oxygen, and water.

Table 8-1: Unified Table of ISRU Processes

ISRU Process	**Feedstock**	**Output**	**Specific Mass**	**Specific Power**	**Efficiency**
			$\frac{Mass\ facility[Mt]}{Mass\ Output[Mt]}$	$\frac{Plant\ Power[kW]}{\Pr oduction\ Rate[Mt/year]}$	$\frac{Mass\ Output[Mt]}{Mass\ feedstock\ [Mt]}$
HRI	Mare soil Basalt rock	O_2	0.15	1.93	0.40%
CRS	Lunar soil (Olivine)	O_2	0.1	23	26%
MSE	Lunar soil	O_2	$6.5*10^{-2}$	1.5	21.4%
HE	Lunar soil	H_2	3.4	124	0.004%
		O_2			0.007%
WE	Lunar soil	H_2O	$3.9*10^{-2}$	16.4	1%

[1] HRI : Hydrogen reduction of Illmenite; [2] CRS : Carbothermal reduction of silicate; [3] MSE : Molten silicate electrolysis; [4] HE : Hydrogen extraction; [5] WE : Water extraction

The goal of the Supply Layer is to calculate all the relevant parameters for supplying the resources for each of the supply options.

Costing

The Costing Layer connects the total amounts of hydrogen, oxygen, and water that were calculated in the Demand Layer with the parameters created in the Supply Layer. The calculations deal with the launch costs involved in terrestrial supply options as well as the capital and recurring costs involved in ISRU production. The output from the Costing Layer allows for the comparison of each ISRU process in the model with a baseline of a 100% terrestrially supplied mission. This layer also incorporates the interdisciplinary aspects of ISRU and shows the user the difference, in terms of mission costs, between an international cooperation-based mission and a mission conducted by a single country.

Political, Legal, and Ethical Aspects

One of the strengths of the FERTILE Moon Model is its focus on using an interdisciplinary approach to modeling ISRU options. Legal, political, and ethical issues can change a mission plan that is economically feasible based on its engineering to being unfeasible in the real world. This version of the model focuses on including a tool to help analyze the usefulness and effects of including international cooperation. For the legal aspects, however, equations were not implemented into the report because of the complexity of turning legal concerns into equations. Furthermore, there is a lack of consensus on how important certain legal concerns are to the involvement of ISRU in future space exploration plans. In an attempt to capture the overall atmosphere and differing opinions that surround the legal regime of ISRU, the FERTILE Moon Model comes with the ISRU Legal Risk Survey. This survey presented numerous legal experts with a series of yes/no questions to answer regarding ISRU as well as room to comment on the complexity of each issue. Several key areas of contention discussed include property rights, preservation concerns, export control, intellectual property rights, and liability. The overarching feeling in the legal community appears to be that there needs to be more definition in some or all of these areas to ensure that the legality of ISRU is firmly in place. As for strategies to implement this further definition of the legal regimes, there is just as many varying opinions as there were on the issues involved. There is also a feeling in the legal community that no one will be willing to set out specific interpretations of the current legal regime until it is necessary. That is, until ISRU is fully developed and firmly intertwined with the space exploration policies' of various nations, the discussion of the legal risks to ISRU will remain only of academic interest.

Just as legal concerns can hamper the involvement of ISRU processes into future planning, so does the ethical implication surrounding ISRU. There are many debates currently underway that include looking at the use of resources from a secular view to looking at their use from a religious viewpoint.

8.2.2 Part Two – Analysis

The second part of the report focused on showing how the model can be used and presents some conclusions regarding ISRU that can be drawn from the use of the current FERTILE Moon Model.

The design philosophy of the model is based on two important factors, the procurement of supplies from ISRU technologies and the costs associated to it. Cost engineering for space applications remains sparsely understood for the greater part. The cost of equipment and facilities for lunar missions are particularly difficult to evaluate as only a handful of reference missions actually took place during the Apollo program. The problem is of greater importance when assessing the efficiency and cost of ISRU technologies. Based on the available literature, the three key factors describing ISRU processes, namely the efficiency, specific power and specific mass, show 10 to 80% variations with respect to the average value considered in this study. Moreover, the efficiency considered refers to the chemical efficiency of the reaction rather than the actual process efficiency. The main causes for this high level of inaccuracy come mainly from the lack of knowledge of the lunar environment and its resources, as well as the low level of development of ISRU technologies. In order to cope with this level of uncertainty, a Monte Carlo simulation was implemented for these parameters, taking in account their respective average and standard deviations.

A total of five ISRU processes were considered based on the completeness of the information available for them. The Molten Silicate Electrolysis Process (MSEP), the Ilmenite Reduction Process (IRP) and the Carbothermal Reduction Process (CRP) are all producing oxygen from regolith. A fourth process was considered for hydrogen extraction, and a fifth one for water extraction. While the efficiency of the former is very limited by the hydrogen abundance in the lunar soil, the efficiency of the later all depends on the assumed presence of water-ice in the permanently shadowed crater of the lunar poles. Although not confirmed yet by previous missions, the water-ice concentration was assumed to be 1% according to simulations performed in specialized studies. The feasibility of the water extraction process may change dramatically if higher concentrations are indeed measured in-situ.

In its current state, the model accounts only for the use of hydrogen, oxygen and water for life support systems and propellant for return trips to LEO. The total demand of H-O-W resources excludes aspects such as surface transportation. On the other hand, the supply side of the model does not take in account other uses that can be made of regolith and its potential byproducts. Using the regolith as cheap and effective radiation and thermal shield, or processing it into raw material such as glass, titanium or cement, may prove to be decisive in the use of ISRU for future mission. Although the model can be seen as a complementary study rather than a comprehensive assessment of ISRU, it is still limited in its capacity to evaluate the feasibility of such technology. It remains very general in its description of the infrastructure required to support ISRU processes, and cannot evaluate the number of trips required to bring all of the equipment to the Moon. The estimation of the demand on the LSS side remains strongly dependent on the mission duration, the environmental conditions to which humans are exposed, as well as their level of physical activity, resulting in a potential error of 10% to 20 % for the amount of consumables required by normal activity and EVA's. The evaluation of the demand on the transportation side also remains very general, resulting in a potential error of 10% to 20% in propellant consumption depending on the type of mission considered.

The evolution of ISRU capabilities on the Moon is assumed to go through four stages in the next 30 years. The early *precursor* stage will be highly dependent on re-supply of resources from Earth, and is assumed to consist mainly in robotic missions aiming to map the Moon and demonstrate the readiness of certain technologies. The *pioneer* stage corresponds to the next phase characterized by manned mission of less than 28 days with a crew limited to 6 astronauts. The subsequent outpost phase would aim to consolidate the human presence on the Moon by sending small crew of less than 12 people for duration limited to 180 days. The final stage would consist in a complete settlement of less than 30 people for a stay of less than a year.

Dominated by the demand in propellant to return from the Moon, simulations performed for precursor missions show that all ISRU processes become more cost effective than the Earth option for production runtime of 200 days and over, the MSEP process being the first one to cross the breakeven point at 100 days. Results for the pioneer phase show that the mass of the facility required to meet the demand of oxygen is comparable to the mass of the resource itself. Deploying an ISRU facility just for the sake of covering the needs of pioneering activities may thus be questionable. However, it may become fully justified when considering long term missions. Indeed, considering that the ISRU facility and related equipment would be used for 10 to 25 years after installation results in an increase of only 11% of the standard cost considered in the FERTILE MOON model. In comparison, using the facility for only one year after installation would result to an increase of 145% of that same cost.

The subsequent outpost and settlement phases show similar trends when simulated with the model. In both cases, the crew size has a much greater effect on hydrogen & oxygen demand than the mission duration, both factors having an equal impact on the water demand. The financial breakeven point for the outpost phase is crossed for all processes for crews larger than 9 people, missions longer than 60 days, and a minimum of 70% of oxygen and 35% of water supplied from ISRU. The breakeven point for the settlement phase is reached by the IRP, MSEP, and CRP for crews above 28 people, mission duration greater than 128 days, and a minimum of 80% of oxygen supplied from ISRU. The IRP, MSEP, and CRP are ranked based on their economical feasibility as first, second and third respectively. The hydrogen and water extraction processes are less appealing in terms of savings for the outpost phase, and appear to be completely unfeasible for the settlement phase. Based on a sensitivity analysis, the hydrogen extraction and water-extraction processes may become feasible if the specific power is reduced from 732 to 115 W/kg for the former, and the specific mass from 0.04 to 0.029 kg/kg of feedstock for the latter.

For all simulations, two alternatives have been considered for the terrestrial option which is used across the report as the baseline for all analysis (i.e. bringing all resources from Earth). The first alternative consisted in bringing hydrogen and oxygen in their liquid form, while the second one consisted in importing water from Earth and using electrolysis to produce hydrogen and oxygen. In all cases, the option based on the electrolysis option resulted in significant increase of the launching cost, making it more expensive.

8.3 Future Work for the FERTILE Moon Model

The FERTILE Moon Model introduced in this study is a preliminary model. Significant future work will be necessary to improve the overall accuracy of the results provided but also to ensure that the FERTILE Moon Model remains a comprehensive and critical tool for the analysis of ISRU. All the aspects of this model, engineering, scientific, financial, political and legal should be considered for further improvements and development.

Modeling

The FERTILE Moon Model uses a unique structure to examine the economic feasibility of using ISRU technologies to support various types of mission to the Moon. This unique structure allows the user to see how engineering, scientific, financial, legal and political inputs affect various mission parameters. The recommended future improvements to the model will only take into account aspects specific to the design and operation of the model.

The recommended future work with respect to the model is as follows:

- Allow the user to choose from a number of probability distributions to fit the variables for which the Monte Carlo was implemented.
- Define an appropriate method or technique to estimate uncertainty and data values,
- Define model parameters that are currently constants, such as the specific mass and specific cost of the power technology, as a function of one or more of model inputs.
- Improve the performance of the FERTILE Moon Model by implementing Visual Basic scripts rather than using Excel functions.
- Improve the output plots to use various 'marker' styles for ease of interpretation of data.
- Integrate the political and legal aspects by considering the cooperation overhead in the final cost.
- Add input parameters for costing, such as amortization period and interest rate.
- Develop a second model using different software and compare both model outputs by conducting statistical analysis.

Demand

The total demand in hydrogen, oxygen and water depends only on the inputted mission parameters. The Demand Layer is the first step in the FERTILE Moon Model. The calculations in the subsequent Supply Layer are highly dependent on the results of the first step. In other words, ensuring the accuracy of the Demand Layer parameters is extremely important to ensure the accuracy of the entire model. Recommendations for future work in the Demand Layer will be first assessed for the transportation demand and then the life support system demand.

The recommended future work for the transportation demand is as follows:

- The model should include various transfer options, the current version only offering one Hohmann transfer trajectory. Anything ranging from the traditional Apollo-type transfer to more novel approaches with reduced energy should be proposed.
- The user should be allowed to choose from a number of destinations. For example, determining the propellant required to go from the lunar surface to the libration point L1. The libration point L1 is potentially an important stepping stone for refueling purposes.

The recommended future work for the life support systems demands is as follows:

- Consider integrating a LSS design tool, such as ELISSA to the FERTILE Moon Model, to increase the calculation accuracy, simplicity and overall flexibility.
- Focus on including technology cost, power and mass budgets for LSS.
- Include a better evaluation of the cost of EVA per hour for a lunar mission. Currently the cost of EVA per hour is based on data from the ISS.
- Constants, such as crew member mass, should be inputted parameters rather than constants as they can significantly affect the LSS requirements.

Supply

The Supply Layer of the FERTILE Moon Model utilizes both the user inputs and outputs of the Demand Layer to calculate the required equipment to supply a lunar mission with the necessary resources. In turn, the outputs of the Supply Layer are fed into the Costing Layer. The calculations conducted in the Supply Layer must thus be as accurate and up-to-date as possible. The future work suggested for the Supply Layer is intended in answering this need.

Future work focusing on the supply from Earth is as follow:

- Analyze the future trends of launchers and their payload capabilities to the lunar surface, launchers such as the CEV, HLV, etc. should be included in this work.
- Implement a third Earth supply option allowing to bring only hydrogen and oxygen to the lunar surface and relying on fuel cells to create water.
- Define, in the model, the specific mass of electrolysis systems as a function of the oxygen consumption.

Future work focusing on ISRU is as follow:

- Consider the regolith composition as an input for the model to allow for a better understanding of how various processes are affected by the nature of the lunar soil.
- Gain a better understanding of the components that are included into the mass calculations or power generation.
- Obtain more data points regarding specific mass, power, efficiency etc.
- Incorporate spin-off and spin-in of technologies for ISRU (eg: high temperature materials, tele-operations for mining) and their benefits or cost savings into analysis.
- Define a better way to estimate spare requirements for different equipment.
- Incorporate an option to choose advanced calculations for the depth of regolith mined according to the chemical process used. For example, ilmenite reduction with hydrogen requires digging to the subsurface of about 3-5m depth, which is not necessary for the carbothermal and molten silicate method.

- Allow the model to take into account the efficiency of the various ISRU processes. Currently efficiency parameters are only based on the feedstock intake and requirement of product. This is a linear relationship, which would lead to conservative values for mined area.

Costing

The Costing Layer provides the user with the costs associated to the two different types of supply options, allowing for further trade-off analysis, comparison and discussion.

Future work focusing on costing is as follow:

- Validate the costing equations with the Price costing model.
- Allow for the launch cost per kg to be a user input or have the launch cost related to a specific launch vehicle, currently launching costs are only based on historical data weighted proportionally to the number of launches and payload capability.
- Conduct more in depth study on how terrestrial equipment and facilities, such as chemical plants, cement plants, mining beneficiation and general large facilities that would be utilized in an ISRU program, could be scaled to lunar ISRU facilities.
- Define mining costs for each different process as each process may have different requirements in terms of mining equipment.
- Include scientific payback into the cost benefit analysis of ISRU processes.
- Help private sector companies in assessing the economic viability of ventures involving lunar resource utilization by including more specific financial modeling such as NPV and DCF calculations in the model.

Policy

National policies impact upon everything within the space sector. The state of international policy is a dynamic environment in which change may be rapid. It is thus essential for the FERTILE Moon Model to be kept up-to-date with inputs from experts in order to remain accurate.

Future work focusing on policy is as follow:

- Expand the country selection to include all nations active in space.
- Expand the number of possible cooperating parties.
- Incorporate fractional cooperation such that all parties are not calculated as equal partners.
- Incorporate Purchase Power Parity as each nations purchase power varies with respect to its neighbor.
- Create national lists of competencies to aid in the selection of cooperating states based on a set of mission requirements.
- Continually update the cooperation table with respect to exploration in order to keep it as accurate as possible.
- Create a cooperation matrix based upon research for future development to be implemented in the model.
- Implement, in the model, a cooperation matrix based on commercial cooperation for the ability to purchase competencies.

- Continue the development of the table listing all cooperative activities between nations. The suggested method is to distribute the table to all external relations departments at the agencies asking them to provide a comprehensive list.

Legal

The existence of the legal ramification of using ISRU can introduce complications and costs to any State that decides to go forward with ISRU. Legal aspects thus need to be taken and legal risks assessed.

Future work focusing on legal aspects is as follow:

- Extend the export control checklist to account for other ISRU related technologies as they are developed, such as the mining equipment and beneficiation facilities,
- Expand on simple Go/No-Go output to assess participating nations' relations to each other with respect to export agreements.
- Introduce limitations on launcher selection due to the identified member states.
- Examine the results of the ISRU Legal Risk Survey and attempt to further integrate the results in the FERTILE Moon Model.

8.4 Concluding Remarks

The model exists as a preliminary version and requires significant future work to remain up-to-date and be able to accurately reproduce the many complex interactions between demand, supply, and costing of lunar missions. The current form FERTILE Moon Model provides several improvements over past lunar models including its versatility, its ability to adapt, and its interdisciplinary approach. This report was meant to show the reader the thinking that went into the development of the model and present its potential usefulness. Strategies such as ISRU will be an integral part of the new phase of human space exploration. The first step is to discover the true benefits and costs of ISRU and the FERTILE Moon Model is here to help.

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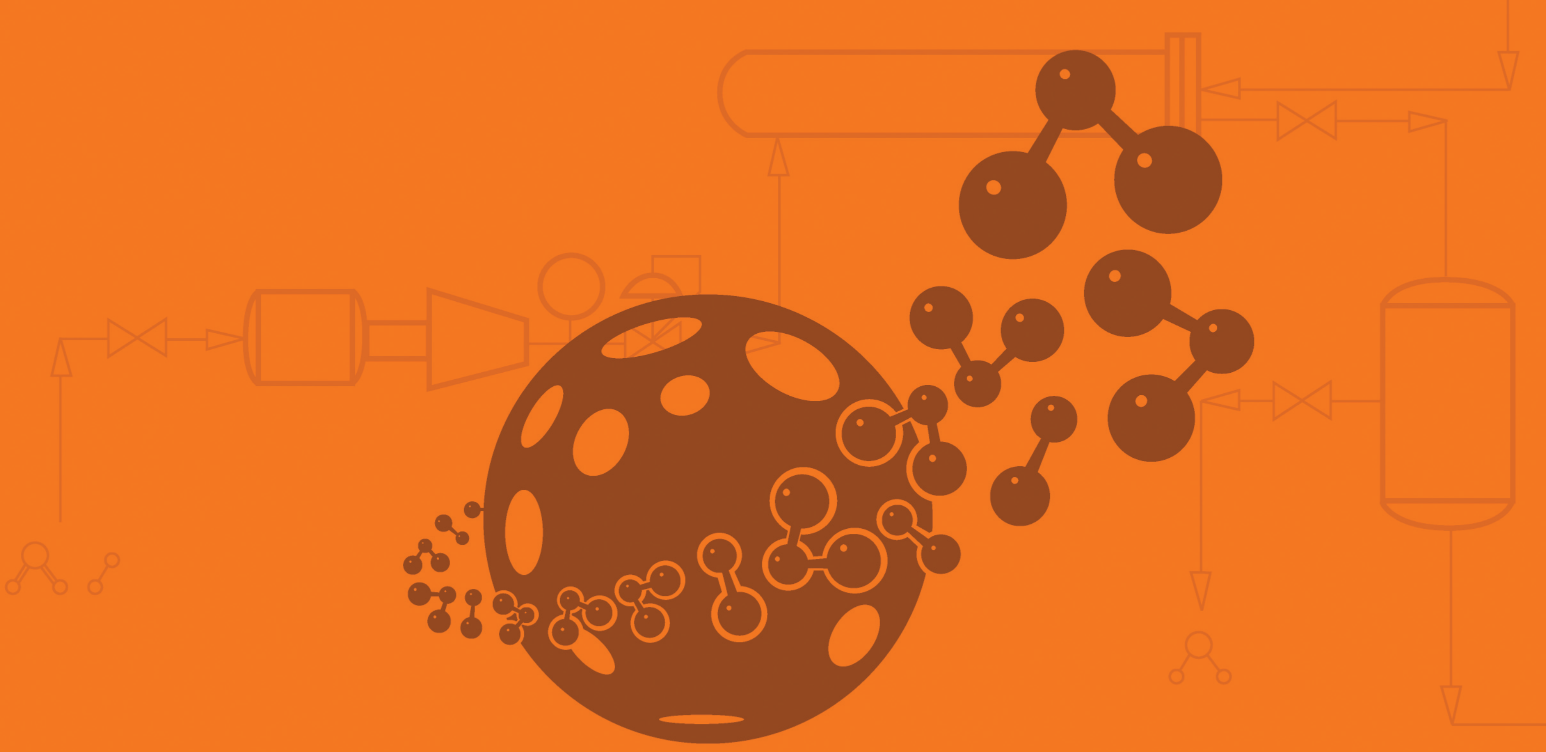
To evaluate the economic feasibility of lunar In-Situ Resource Utilization (ISRU) technologies for hydrogen, oxygen, and water production by creating a model from an interdisciplinary perspective. This study compares the supply of resources produced in-situ on the Moon with those supplied from Earth and makes recommendations based on various scenarios.



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