Detailed Design Report for the
2004-05 ISRU University Design Competition
from the
MIT LunarDREEM Team

Lunar Demonstration of Resource Extraction
from Extraterrestrial Material
Detailed Design Report Cover Page for the
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(Lunar Demonstration of Resource Extraction from Extraterrestrial Material)

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# TABLE OF CONTENTS

Cover Page .................................................................................................................. 2  
Contents ....................................................................................................................... 3  
List of Figures ............................................................................................................... 5  
List of Tables ............................................................................................................... 6  
DDR Summary ........................................................................................................... 7  
Detailed Preliminary Design Report ................................................................. 8  

1. Compilation of Assumptions ........................................................................... 8  
2. In-situ Oxygen Production System ......................................................... 10  
   2.1 Overview of ISOPS Architecture ....................................................... 10  
   2.2 Design of Furnace Subsystem .............................................................. 12  
      2.2.1 Furnace Subsystem Concept of Operations .......................... 12  
      2.2.2 Furnace Heating Options ....................................................... 12  
      2.2.3 Furnace Power Analysis and Requirements ....................... 13  
      2.2.4 Furnace Geometry ............................................................... 17  
      2.2.5 Furnace Interfaces ............................................................... 19  
      2.2.6 Furnace Subsystem Mass ..................................................... 19  
   2.3 Design of the Radiator ........................................................................ 20  
      2.3.1 Thermal Calculations ............................................................ 20  
      2.3.2 Radiator Mass and Power Requirements ............................ 22  
   2.4 Design of the Electrolysis Subsystem ............................................... 22  
      2.4.1 Electrolysis Subsystem Concept of Operations .............. 22  
      2.4.2 Design of Electrolyzer .......................................................... 23  
      2.4.3 Electrolysis Subsystem Power Requirements .................. 25  
      2.4.4 Electrolysis Subsystem Mass .............................................. 26  
   2.5 Design of the Hydrogen Recycling System ...................................... 27  
      2.5.1 Overview of Hydrogen Flow through ISOPS .................. 27  
      2.5.2 Verifying Adequate Hydrogen Flow through Furnace ........ 28  
      2.5.3 Hydrogen Recycling Trade Study ...................................... 28  
      2.5.4 Hydrogen Recycling Subsystem Mass and Power Requirements 28  
   2.6 Design of the Oxygen Storage Tank .................................................... 29  
      2.6.1 Oxygen Tank Design ............................................................ 29  
      2.6.2 Oxygen Storage Tank Mass and Power Requirements .......... 30  
   2.7 Summary of ISOPS mass and Power Requirements ........................ 32  
   2.8 Controls and Process Efficiency Measurements ................................ 32  
      2.8.1 Controls and Regulation ...................................................... 32  
      2.8.2 Process Efficiency Measurements .................................... 33  
   2.9 Process Demonstration Experiments ................................................. 33  
      2.9.1 Brief Literature Review ....................................................... 33  
      2.9.2 Description of Laboratory Apparatus ............................... 35  
      2.9.3 Description of Demonstration Experiments and Results .... 35  
      2.9.4 Flow Rate Experiment ....................................................... 37  
3. Regolith Excavation, Collection, and Delivery System .............................. 39  
   3.1 Design of the Excavation System ......................................................... 39  
      3.1.1 Excavation Concept of Operations ..................................... 39  
      3.1.2 Mass of the Excavation System ......................................... 40  
      3.1.3 Excavation System Power Requirements ......................... 44  
      3.1.4 Laboratory Experimentation .............................................. 47  
      3.1.5 Summary of Excavator System Mass and Power Requirements 51
LIST OF FIGURES

Figure 2.1: Schematic of In-Situ Oxygen Production System (ISOPS)..................................................11
Figure 2.2: Dual-Chamber Mass-measuring Instrument.................................................................22
Figure 2.3: Diagram of a Two-cell PEM Stack.................................................................24
Figure 2.4: Diagram of PEM Electrolyzer Processing.................................................................25
Figure 2.5: Hydrogen Flow through the Oxygen Production System............................................27
Figure 2.6: Diagram of Oxygen Storage Tank..................................................................30
Figure 2.7: ISOPS Laboratory Set-up.................................................................................35
Figure 2.8: Process Demonstration Experiment Results.........................................................36
Figure 2.9: Set-up for the Vertical Flow Rate Experiment......................................................37
Figure 3.1: Diagram of Auger Concept...........................................................................40
Figure 3.2: Auger Cross-section..................................................................................41
Figure 3.3: Diagram of Collection Bin..........................................................................43
Figure 3.4: Mass of Excavation System as a function of Auger Diameter .........................44
Figure 3.5: Number of Holes as a function of Auger Diameter .............................................44
Figure 3.6: Auger Free-body Diagram and Governing Equations...........................................45
Figure 3.7: Power Required to Vertically Translate Auger.....................................................47
Figure 3.8: Excavation Experiment Apparatus........................................................................48
Figure 3.9: Excavation Experiment Data Table ..........................................................................49
Figure 3.10: Excavation Time as a function of Auger Diameter.............................................50
Figure 3.11: Graphical Comparison between Experimental and Theoretical Torque.........................51
Figure 3.12: Regolith Delivery System..............................................................................52
Figure 3.13: CADD Model of Compression Chamber............................................................54
LIST OF TABLES

Table 2.1: Comparison of Oxygen Extraction Methods ................................................................. 10
Table 2.2: Summary of Furnace Heat Loss to Environment ............................................................. 16
Table 2.3: Summary of Furnace Power Requirements ..................................................................... 17
Table 2.4: Summary of Results of Flow Rate Experiment ................................................................. 18
Table 2.5: Furnace Geometry ............................................................................................................ 18
Table 2.6: Furnace Interfaces ............................................................................................................ 19
Table 2.7: Furnace Mass Budget ...................................................................................................... 20
Table 2.8: Radiator Mass and Power Requirements ......................................................................... 22
Table 2.9: Summary of Electrolysis Subsystem Power Requirements ............................................. 26
Table 2.10: Electrolysis Subsystem Mass Budget ............................................................................ 27
Table 2.11: Hydrogen Mass Required for Processing 10kg Batch Size ........................................... 28
Table 2.12: Summary of Hydrogen Recycling Subsystem Mass and Power Requirements ............. 29
Table 2.13: Oxygen Tank Material Study .......................................................................................... 31
Table 2.14: Radius and Width of Oxygen Tank Wall ........................................................................ 31
Table 2.15: Summary of Oxygen Storage Tank Mass and Power Requirements .............................. 32
Table 2.16: Summary of ISOPS Mass .............................................................................................. 32
Table 2.17: Summary of ISOPS Power Requirements ...................................................................... 32
Table 2.18: Observations from Vertical Flow Rate Experiment ....................................................... 38
Table 3.1: Torque and RPM as a function of Auger Diameter ............................................................ 46
Table 3.2: Excavation Experiment Data Table .................................................................................. 49
Table 3.3: Tabular Comparison between Experimental and Theoretical Torque .............................. 49
Table 3.4: Summary of Excavation System Mass and Power Requirements ..................................... 51
**DDR SUMMARY**

The Detailed Design Report (CDR) details the design for two subsystems of a robotic lander exploring the South Polar region of the moon: an integrated system for both the production of oxygen and extraction of water from lunar regolith and a system for the excavation and transfer of lunar regolith to experiment test chambers.

First, qualitative and quantitative assumptions necessary to carry out the functions of these subsystems are listed. Then, we present designs for the major subsystems of the In-situ Oxygen Production System (ISOPS). These include the furnace, radiator, electrolysis system, hydrogen recycling system, and oxygen storage tank. We describe ISOPS controls and process efficiency measurements, and we present results of process demonstration experiments. We then present the design for the Excavation, Collection, and Delivery System and results of related laboratory work. This includes the design and results of laboratory experimentation for an Excavation Subsystem to collect regolith, a Bulk Physical Characteristics Test Chamber, and Regolith Delivery Mechanism to transfer regolith from the Excavation System to other test chambers. We then present a mission concept of operations for the Excavation, Collection, and Delivery System and the In-Situ Oxygen Production System.

Finally, we provide an Outreach Report detailing the outreach activities of the team over the 2004-2005 academic year.
DETAILED DESIGN REPORT

1. COMPILED OF ASSUMPTIONS

1.1 Environmental Assumptions

1.1.1 Given as part of the competition guidelines

- Robotic lander is delivered to the South Polar region of the moon (>75° S)
- Robotic lander rover either lands in or moves into a permanently shadowed crater where water ice is present within a meter of the surface.
- The excavator subsystem will collect at least 100kg of regolith, and the oxygen production/water extraction subsystem must process all of this 100kg within a one-month mission.

1.1.2 Additional assumptions made by LunarDREEM team

- Temperature in the permanently shadowed crater is constant at ~40K.
- Ambient pressure is a hard vacuum.
- Solar radiation has no appreciable effect on subsystems.
- The floor of the permanently shadowed crater is flat ground, with powdery dust to at least 1 meter.
- The regolith in the permanently shadowed crater has no more than 1% ice-water by weight. (Based on data from the Clementine and Lunar Prospector probes, [Feldman, 2000])
- No more than 2% wt. oxygen will be extracted from the iron-oxides in the polar lunar regolith. (Data shows ~4% could be extracted from lunar mare, and ~1.2% from lunar highland material. The lunar south pole is an intermediate region, and we assume ~2%).) [Allen, 1996]
- The average density of the lunar regolith prior to excavation is 3100 kg/m$^3$ [Heiken, 1991]. The average density of the lunar regolith after excavation is 1500 kg/m$^3$.

1.2 Mobility/Rover Assumptions

1.2.1 Given as part of the competition guidelines

- A rover the size of the Mars Exploration Rovers will carry the design team’s experiment package.
- The lander has ample volume available to meet the experiment requirements.
- Experiment packages should attempt to meet mass (50 kg) and power (100 W) constraints.

1.2.2 Additional assumptions made by LunarDREEM team

- “Experiment package” includes excavator subsystem, oxygen production/water extraction subsystem, bulk physical characteristics test chamber, and process efficiency measurements
- Experiment package is mounted on the rover; the rover provides mobility for all the subsystems (including excavation subsystem); rover mobility is dictated solely by mobility requirements for the Experiment Package.
- Rover can deliver the entire 100W continuous power to the Experiment Package when required.
- Rover can “plant itself” to provide sufficient reaction force to counter excavation forces.
- No constraints on subsystem-rover interfacing; subsystems can be placed anywhere on the rover.
- The rover has adequate computing and communications capability for the Experiment Package.

1.3 Control Assumptions

1.3.1 Given as part of the competition guidelines
- Real-time communications will be available on a continuous basis between the rover and Earth.

1.3.2 Additional assumptions made by LunarDREEM team
- Earth-based user control will not be limited by bandwidth availability.
- Earth-based control/oversight is available 24 hours a day throughout the entire mission.

1.4 Other Assumptions

Other assumptions specific to subsystem technologies are detailed separately in the following sections.
2. IN-SITU OXYGEN PRODUCTION SYSTEM
In-situ Oxygen Production System (ISOPS) – an integrated subsystem for both the production of oxygen and extraction of water from lunar regolith.

2.1 Overview of ISOPS Architecture

Choosing the Process for an Oxygen Production Plant
The purpose of ISOPS is to demonstrate oxygen production from lunar regolith and validate that the processes operate for the entire mission duration as expected based on predictions from terrestrial laboratory experiments. This technology demonstration will provide a precedent for using in-situ resources to enable production of consumables and propellant for future lunar exploration and settlement, with eventual application to the exploration of Mars and other destinations in the solar system. Over twenty processes for the extraction of oxygen from lunar soil have been proposed [Taylor, 1993], varying greatly in their level of development; some have already undergone extensive lab testing on lunar soil simulants, while others are still theoretical. Four classes are of particular interest for large-scale production of oxygen: hydrothermal reduction, carbothermal reduction, molten silicate electrolysis, and vapor phase reduction [Taylor, 1993]. The processing temperature, approximate yield, and relative complexity are summarized in Table 2.1 below. Taylor scores relative complexity on a scale of 1 to 10; a score of “1” indicates the process has many steps, while a score of “10” indicates the process has one step.

Table 2.1: Comparison of Oxygen Extraction Methods [data from Taylor, 1993]

<table>
<thead>
<tr>
<th>Processing Method</th>
<th>Processing Temperature (deg. C)</th>
<th>Approximate Oxygen Yield</th>
<th>Relative Complexity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrothermal Reduction</td>
<td>900</td>
<td>&lt;4%</td>
<td>9</td>
</tr>
<tr>
<td>Carbothermal Reduction</td>
<td>1600</td>
<td>20%</td>
<td>3</td>
</tr>
<tr>
<td>Molten Silicate Electrolysis</td>
<td>1300</td>
<td>20%</td>
<td>8</td>
</tr>
<tr>
<td>Vapor Phase Reduction</td>
<td>2200</td>
<td>20%</td>
<td>8</td>
</tr>
</tbody>
</table>

Oxygen requirements for a lunar base are estimated to be 0.83 kg per person per day. A hydrothermal reduction process, with a ~4% oxygen yield, would require processing approximately 50 – 100 kilograms of regolith per person per day, or 0.016- 0.032 m$^3$ to meet this requirement. The other three methods shown in the table are more efficient than hydrothermal reduction, so it might be assumed that one of them would be chosen for large-scale production of oxygen. However, there are three compelling reasons to use hydrothermal reduction processing for a small-scale robotic demonstration mission. First, hydrothermal reduction is the simplest process, and the lower processing temperature associated with hydrothermal reduction particularly lends itself to a small, power-constrained, robotic mission. Second, there is currently an extensive dataset of laboratory experiments analyzing the hydrothermal reduction process on lunar regolith [Chambers, 1995; McKay, 1996; Allen, 1996; Ogiwara, 2000], providing a sound basis for process validation in the lunar environment. Third, lunar regolith sinters (melts) at temperatures above 1050 deg C. Any process involving temperatures higher than this must include special mechanisms to ensure
that sintered regolith does not adhere to the apparatus and obstruct processing mechanisms. For the initial demonstration mission, the additional complication of sintering is best avoided. In summary, the choice of a process for a human-scale oxygen extraction plant can be left for the future. Even if the ultimate choice is a process other than hydrothermal, we believe that a hydrothermal-based demonstration mission makes sense. The detailed chemistry of the actual extraction process is only part of the mission, which will also demonstrate excavation, collection and handling of lunar regolith, collection and electrolysis of water from the high-temperature processing chamber, and collection and storage of oxygen.

By concentrating on hydrothermal reduction, we have effectively selected task 4 as our area of specialization. However, a hydrothermal reduction processing system can also be used to extract water ice from lunar regolith, fulfilling the requirements of task 5. Nominally, hydrothermal reduction involves heating regolith to 900 deg C and then flowing hydrogen over the sample to react the oxygen in the regolith into water, which escapes as vapor and is collected for eventual electrolysis. However, heating regolith to 900 deg C also serves to evaporate any water-ice which is present in the sample, which will be collected along with the water released as part of the hydrothermal processing. Thus, a hydrothermal reduction processing system can be used in two modes. First, regolith is heated to drive off any existing water, and the water-ice content of a sample is measured. Second, regolith is reduced using hydrogen, and hydrothermal process efficiency is measured. The major elements of an oxygen production/water extraction system using hydrothermal reduction processing are shown in Figure 2.1 below.

Figure 2.1: Schematic of In-Situ Oxygen Production System (ISOPS)

The system process begins with loading lunar regolith into the furnace. The lunar regolith is heated up to 900°C, or 1173K, at one atmosphere of pressure. Hydrogen then flows through the furnace and reduces the regolith in the furnace by reacting with the oxygen in the regolith, releasing water vapor. The water vapor is condensed as it flows through the radiator and weighed using the mass chamber and balance to obtain one measure of the process efficiency. The water is then electrolyzed to form oxygen gas and hydrogen gas. The oxygen gas is pumped to the oxygen collection tank, where it is compressed and stored and the hydrogen is recycled back to the furnace.

The following sections present designs for the major subsystems of the In-situ Oxygen Production System (ISOPS). These include the furnace, radiator, electrolysis system, hydrogen recycling system, and oxygen storage tank. We describe ISOPS controls and process efficiency measurements, and we present results from process demonstration experiments.
2.2 Design of the Furnace Subsystem

In this section we present the design of the ISOP furnace subsystem. We begin by describing furnace operations. We then detail the power requirements for furnace operations. We describe the geometry of the furnace, interfaces with the other ISOPS subsystems, and materials. Finally, we present a first order mass estimate for the furnace subsystem.

2.2.1 Furnace Subsystem Concept of Operations

The objective of the furnace is to heat regolith to sublimate water ice bound in the regolith, and provide an environment in which flowing hydrogen reduces the regolith. The furnace subsystem must also measure the amount of water ice bound in the regolith and the amount of oxygen released from the regolith.

First, regolith is loaded into the furnace. Through the loading process, the furnace volume is evacuated to near vacuum. The furnace heating elements then raise the temperature of the regolith through radiative heat transfer to approximately 400 K. At this temperature and near vacuum, and water vapor in the regolith will sublimate within the furnace chamber [Chaplin, 2005]. This water vapor is then evacuated to the lunar environment through a vent that is heated to avoid the formation of ice blockages. The change in mass of the regolith before and after the water vapor is evacuated gives one measure of the regolith water ice content. The furnace, again at near vacuum, is heated to 1173K (900 deg C). Hydrogen gas then flows through the system to reduce the regolith and carry the released oxygen out of the furnace in the form of water vapor. The change in mass of the regolith before and after processing gives one measure of the oxygen released from the regolith.

2.2.2 Furnace Heating Options

The furnace requires power to heat the regolith from 40 K to 400K for sublimation of ice water, and to heat the regolith from 400K to 1173 K for the reduction process, as well as maintain temperature during the hydrogen reduction process. These power calculations are dependent on the type of heating technology implemented.

We considered three furnace heating technologies: electrical, microwave, and radioisotope heating units (RHU). Electrical heating furnaces are common and have been used for many decades in Earth operation. The microwave furnace is a relatively new technology which has recently experienced a diversification of applications. RHUs have seen limited use in selected space applications; however, there is no precedent for using RHUs to heat a furnace. These three technologies are discussed below in more detail.

There are two types of electrical heating furnaces: arc and resistance. In addition, electrical furnaces can be designed for operation in air or in a vacuum. The purpose of the furnace in the ISOPS system is to heat the regolith to the desired temperature, and maintain this temperature for three hours (i.e. the processing time). An electrical resistance furnace provides this capability by passing current through the heating elements, which get warm and radiate heat.
Microwave heating efficiency depends on the materials used and the frequency of the microwaves. The penetration depth into a material depends on the dielectric properties of the material. The microwaves penetrate objects, thus enabling a very rapid and high-intensity heat transfer throughout an item. This leads to a volumetric heating capability, which is ideal for materials with a large volume to surface area ratio.

Radioisotope Heating Units (RHU) naturally provide thermal heat from the decay of a radioisotope. Thus, a furnace using RHUs would need no electrical power input for heating operations. Each RHU weighs 40 grams and continuously outputs approximately 1 W of heat; and, for use in a furnace-type application, RHUs would be distributed around the heating area. The continuous heat output of RHUs complicates their use in a furnace; once the regolith is heated to the desired temperature, the RHUs will continue to add heat to the system. One way to accommodate the continuous heat input would be to flow additional cooling gas around inside the furnace but around the chamber containing the regolith; this flow is separate from the reducing hydrogen flow inside of the furnace, but can be recycled along with it. Moreover, the rate of the cooling gas flow could be used to modulate the temperature within the furnace; for example, if the regolith temperature begins to decrease, the rate of the cooling gas flow can be decreased. The electrical power required for operation of the furnace system would be the power required for the feedback of temperature and control of the cooling gas flow rate. However, this is not an efficient thermal control mechanism.

Though the RHU furnace would eliminate the need for electrical power to heat the furnace, the technology is difficult to use. Since RHUs are a nuclear based technology, they are governed by a complicated regulatory procedure, and, they can only be employed when it has been demonstrated that no other satisfactory alternative exists.

Due to a lack of available information on regolith material properties and microwave heating, and the complicated regulatory procedure associated with RHUs we have chosen electric resistance heating to proceed with a detailed design.

2.2.3 Furnace Power Analysis and Requirements

Assuming an electrical resistance heating mechanism, the furnace power analysis must include the power required to raise the temperature of regolith, radiative heat loss to the environment, and heat loss due to hydrogen gas flow through the furnace.

2.2.3.1 Power to Heat Regolith

The power required to raise the temperature of the regolith is calculated assuming a constant specific heat \( C_p \) for the regolith of 840 J/kg-K \[Long, 1982; Acero, 2003\]. The power required can then be calculated using,

\[
P_{\text{regolith}} = \frac{C_p \, \Delta T \, m_{\text{batch}}}{t_{\text{heating, batch}}},
\]

(Eq. 2.1)
where $\Delta T$ is the desired temperature increase in Kelvin, $m_{\text{batch}}$ is the mass of the regolith heated in each batch in kg and $t_{\text{heating,batch}}$ is the heating time.

The total time that must be devoted to ISOPS also depends on the heating time of one batch, the processing time, and the time require to load and unload regolith from the furnace. Assuming it takes 15 minutes to load and unload the furnace, and we process each batch for 1 hour, the total time that must be devoted to ISOPS is given by,

$$t_{\text{ISOPS}} = (t_{\text{heating,batch}} + 1.25)N,$$  \hspace{1cm} (Eq. 2.2)

where $N$ is the number of batches, which is also a function of batch size since a total of 100kg of regolith will be processed.

We examined the impact of the batch size and the heating time on ISOPS and the mission timeline: an iterative process. Batch sizes of 1kg, 2.5kg, 5kg, 10kg, 20kg, 25kg, 50kg and 100kg were used and the heating time was varied such that the power required and the total heating time were constrained. The optimal batch size chosen for our design is 10kg with a batch heating time of 49hrs; this combination of parameters resulted in 502.5 hrs (~3 weeks) and 54.0W required for heating the regolith to 1173K.

Although this is the theoretical power required to heat regolith to the appropriate temperatures, there are inefficiencies due to radiative heat losses and hydrogen gas flow through the furnace.

2.2.3.2 Heat Loss To Environment

To calculate radiative heat losses through insulation we assume that our furnace is at a temperature of 1173 K. This will give us an accurate estimate of heat losses during hydrogen reduction. However, since radiative heat losses are a function of the difference in temperature between the furnace and its environment, the radiative heat losses will not be constant during the heating process. We decompose the furnace heating into two heating phases (723K and 1173K) to more accurately determine the amount of power available to the electrolysis subsystem. This is discussed further in Section 2.4. Assuming a constant furnace temperature of 723 K will provide a conservative upper bound on radiative losses during heating up to 723 K. Likewise, assuming a constant furnace temperature of 1173 K will provide a conservative upper bound on the radiative losses during furnace heating from 723 K to 1173 K.

To calculate radiative losses, we assume that our furnace is insulated with high-temperature multi-layer insulation (MLI). During processing at 1173 K the effective conductivity (K) of high-temperature MLI is approximately 0.0083 W/m$^2$K [Daryabeigi, 1999]. Since the conductivity of this material increases with temperature, this value provides a conservative estimate for losses during heating as well. We assume that the surface of the MLI radiates to space as a thin polished metal with a surface emissivity, $E_{\text{surf}}$, of approximately 1 [Eckhart, 1999]. We also assume that approximately half the furnace surface area is radiating out to space, and half the furnace surface area is radiating towards the lunar surface. Since the
conduction through the MLI must be equal to the radiation out to space, the heat per unit area, $q_{\text{surf}}$, rejected towards the surface is given by,

$$ q_{\text{surf}} = BE_{\text{surf}} \left( T_{\text{wall, surf}}^4 - T_{\text{sink, surf}}^4 \right), \quad \text{(Eq. 2.3)} $$

where $B$ is the Boltzmann constant. $T_{\text{wall, surf}}$ is the temperature of the MLI outer wall towards the lunar surface and is given by,

$$ \frac{K(T_{\text{furnace}} - T_{\text{wall, surf}})}{t_{\text{MLI}}} = BE_{\text{surf}} \left( T_{\text{wall, surf}}^4 - T_{\text{sink, surf}}^4 \right), \quad \text{(Eq. 2.4)} $$

where $T_{\text{furnace}}$ is either 723 K or 1173 K. $t_{\text{MLI}}$ is the thickness of the high temperature MLI and is chosen to be 0.35 m. It is important to note that the effective conductivity of high temperature MLI cited in [Daryabeigi, 1999] and used in this report was experimentally determined using material 0.013 m in thickness. We make the assumption that this effective conductivity is constant through thicknesses up to 0.32 m.

$T_{\text{sink, surf}}$, the sink temperature towards the lunar surface, is given by,

$$ T_{\text{sink, surf}} = E_{\text{reg}} T_{\text{crater}}^4, \quad \text{(Eq. 2.5)} $$

where $E_{\text{reg}}$ is the emissivity of lunar regolith of 0.935 and $T_{\text{crater}}$ is the temperature in the crater of 40K.

The heat rejected per unit area rejected towards space, $q_{\text{space}}$, is given by similar equations using a sink temperature of space of 2.7 K to derive the temperature of the furnace wall towards space.

The total radiative heat losses is then given by,

$$ Q_{\text{reg}} = q_{\text{surf}} \frac{A_{\text{surf}}}{2} + q_{\text{space}} \frac{A_{\text{surf}}}{2}, \quad \text{(Eq. 2.6)} $$

where $A_{\text{surf}}$ is the surface area of the furnace.

Using the surface area of the furnace calculated in Section 2.2.4, the radiative heat losses through the high temperature MLI during heating and processing are summarized in the Table 2.2.

There are additional radiative heat losses when the water vapor is evacuated to lunar environment because during this time the vent is not insulated with MLI. Assuming the vent area, $A_{\text{vent}}$, is $\frac{1}{2}$ square millimeter and is pointed towards the lunar surface, the additional radiative loss during venting is given by,
\[ Q_{\text{vent}} = A_{\text{vent}} B E_{\text{surf}} (T_{\text{furnace}}^4 - T_{\text{surf}}^4), \]  
\hspace{1cm} (\text{Eq. 2.7})

where \( T_{\text{furnace}} \) is 400 K. This results in an additional radiative loss of 7.1 W.

The amount of time we must provide this additional 7.1 W to furnace operations is approximately equal to the amount of time requires for the water vapor in the furnace to effuse through the vent to the lunar environment. This is calculated with the equation below.

\[ P = P_0 e^{-Ct}, \text{ where } C = \frac{A \left( \frac{RT}{2\pi M} \right)^{\frac{1}{2}}}{V}, \]  
\hspace{1cm} (\text{Eq. 2.8})

where \( t \) is time for effusion, \( P \) is the ambient pressure of the lunar environment (vacuum) and \( P_0 \) is the pressure in the furnace due to the water vapor. This is calculated using the ideal gas law. \( A \) is the area of the vent, \( V \) is the volume of the furnace, \( R \) is the universal gas constant, \( T \) is the temperature in the furnace of 400 K, and \( M \) is the mass of water vapor in moles. Solving for effusion time, we calculate that approximately 91 seconds are required to evacuate the water vapor from furnace.

In the table below we summarize heat loss to the environment for the furnace subsystem.

<table>
<thead>
<tr>
<th>Table 2.2: Summary of Furnace Heat Loss to the Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat Loss through MLI (W)</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>Heat Loss through Vent (W)</td>
</tr>
<tr>
<td>Total Heat Loss to Environment (W)</td>
</tr>
</tbody>
</table>

2.2.3.3 Heat Loss To Hydrogen Flow

As the hydrogen flows through the furnace, heat from the furnace heating elements and from the regolith will transfer into the cooler hydrogen gas, which enters the furnace at 298K. Since the furnace is in steady state with a constant hydrogen flow rate, the heat transfer into the hydrogen gas must equal the additional power provided to the system. Thus, given a change in the enthalpy of the hydrogen, the power input can be calculated using the steady flow energy equation applied to the furnace, which in this case is written

\[ \dot{W} = \dot{Q} - m_{H_2} (h_{H_2,\text{out}} - h_{H_2,\text{in}}), \]  
\hspace{1cm} (\text{Eq. 2.9})

where \( \dot{Q} \) is the furnace heat losses (assumed to be 50W for these calculations), \( m_{H_2} \) is the hydrogen mass flow rate (0.002 kg/s) and \( h_{H_2} \) is the enthalpy of the hydrogen. The enthalpy
is a function of temperature and pressure and can be found on standard tables for $\text{H}_2$. During processing the internal furnace pressure will be 1 atmosphere; the hydrogen temperature at the inlet of the furnace will be 298K; however the hydrogen temperature at the exit of the furnace is unknown. The hydrogen exit temperature can be calculated from the heat input to the hydrogen flow (or the additional power required) using,

$$\Delta T = \frac{Wt}{c_p m_{\text{H}_2}},$$  

(Eq. 2.10)

where $t$ is the time the hydrogen spends in the furnace (0.8 sec), $m_{\text{H}_2}$ is the mass of the hydrogen in the furnace, and $c_p$ is the specific heating of hydrogen (assumed to be constant at 14209 J/kg-K or 14.2091 J/mol-K).

Thus, iteration using these two equations will converge upon a hydrogen exit temperature and heat lost to the hydrogen flow. We found that the hydrogen temperature gradient across the furnace is less than 1K and that the heat lost to heating the hydrogen is 25W.

### 2.2.3.4 Summary of Furnace Power Requirements

<table>
<thead>
<tr>
<th></th>
<th>Heating from 40 K to 723 K</th>
<th>Heating from 723K to 1173 K</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regolith Heating (W)</strong></td>
<td>54.0</td>
<td>54.0</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Total Heat Loss to Environment (W)</strong></td>
<td>17.3 (+ 7.1 W for 91 seconds)</td>
<td>24.2</td>
<td>24.2</td>
</tr>
<tr>
<td><strong>Heat Loss to Hydrogen Flow (W)</strong></td>
<td>0.0</td>
<td>0.0</td>
<td>25.0</td>
</tr>
<tr>
<td><strong>Total (W)</strong></td>
<td>71.3 (+ 7.1 W for 91 seconds)</td>
<td>78.2</td>
<td>49.2</td>
</tr>
</tbody>
</table>

### 2.2.4 Furnace Geometry

The cross-sectional area of the furnace which hydrogen gas flows through during processing is constrained by two factors. First, we require the linear flow rate of hydrogen through the furnace to be greater than 1 cm/s to optimize our oxygen yield [Allen, 1996]. However, we do not want to flow hydrogen gas through the furnace at a rate that picks up and blows around significant amounts of regolith.

In Section 2.9.4 we describe our experiment to determine maximum flow rate through the furnace. The results of this experiment are reproduced in the table below.
Table 2.4: Summary of Results of Flow Rate Experiment

<table>
<thead>
<tr>
<th>Approximate Flow Velocity (cm/s)</th>
<th>Qualitative Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>90</td>
<td>very small pieces beginning to pick up</td>
</tr>
<tr>
<td>130</td>
<td>small pieces picked up to a maximum of 1/2&quot;</td>
</tr>
<tr>
<td>148</td>
<td>small pieces are blown around 1-1.5&quot;</td>
</tr>
<tr>
<td>192</td>
<td>small pieces are blown around 1.5-2&quot;, medium pieces are blown around 1-1.5&quot;</td>
</tr>
<tr>
<td>216</td>
<td>medium pieces are more turbulent, 1.5-2&quot;</td>
</tr>
<tr>
<td></td>
<td>small pieces are blown up to 7&quot;</td>
</tr>
</tbody>
</table>

Based on these results, we choose 192 cm/s as the maximum allowable flow rate to avoid picking up significant amounts of regolith. However, this experiment was conducted in a 1 G environment. The primary factors resisting the pick-up of regolith involve weight and friction of particles; both these factors are proportional to gravity. Hence, to estimate an appropriate maximum flow rate for a furnace operating on the moon, we divide by a factor of six to yield a flow rate of 32 cm/s.

Assuming a mass flow rate through the furnace 0.002 kg/s and a linear flow velocity of 32 cm/s, we require a furnace with a cross-sectional area of approximately 0.069 square meters.

Given this cross-sectional area, we now want to calculate the height of the furnace. There are three primary factors that must be considered in calculating the height of the furnace: the volume occupied by the regolith, the distribution of regolith, and pick up of regolith during hydrogen flow.

Using a low estimate for the density of lunar regolith of 1.5 grams per cubic centimeter, a ten kilogram batch of regolith would occupy approximately 0.007 cubic meters. Assuming a friction angle of 60 degrees [Heiken, 1991] this results in a conical pile of regolith approximately 0.305 m in height. We add 0.060 m to this height since the gas flow rate experiment suggests that regolith is not likely to blow up above approximately 0.05 m. We also add approximately 10% to the radius and height of the cylinder to account for the volume of resistive heating elements. This results in a furnace with the following geometry.

Table 2.5: Furnace Geometry

<table>
<thead>
<tr>
<th>Shape</th>
<th>Inner Furnace Wall</th>
<th>Outer Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cylindrical</td>
<td></td>
</tr>
<tr>
<td>Radius (m)</td>
<td>0.148</td>
<td>0.172</td>
</tr>
<tr>
<td>Height (m)</td>
<td>0.385</td>
<td>0.443</td>
</tr>
</tbody>
</table>
2.2.5 Furnace Interfaces

Furnace interface elements are summarized in the table below.

<table>
<thead>
<tr>
<th>Interface</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace-radiator</td>
<td>Quartz filter</td>
</tr>
<tr>
<td></td>
<td>Valve</td>
</tr>
<tr>
<td>Furnace-Hydrogen Gas Input</td>
<td>Quartz filter</td>
</tr>
<tr>
<td></td>
<td>Valve</td>
</tr>
<tr>
<td></td>
<td>Pump</td>
</tr>
<tr>
<td>Furnace- Lunar Environment</td>
<td>Actuated Open/Close for Top/Bottom Caps</td>
</tr>
<tr>
<td></td>
<td>Actuated engage/disengage pressure seal</td>
</tr>
<tr>
<td></td>
<td>Vent</td>
</tr>
</tbody>
</table>

The furnace-radiator interface and furnace-hydrogen input interface both require a quartz filter to ensure regolith particles do not contaminate the other ISOPS subsystems. Quartz filters withstand temperatures up to 1273 K [SKC, 2005] making them a feasible alternative for application. These interfaces require a valve to isolate the furnace from the rest of the ISOP system during the furnace depressurization associated with loading and unloading lunar regolith. The furnace-hydrogen input interface also requires a pump to flow hydrogen through the furnace.

The furnace interfaces with the lunar environment during loading and unloading require that the top and bottom furnace caps be actuated to open and close and actuated to engage and disengage a pressure seal. The furnace also requires an actuated vent to evacuate the furnace of all water vapor at 400 K. These two interfaces are among the few moving parts in the system design which are exposed to the harmful effects of the regolith. The hinges of these mechanisms should be lubricated. Wet lubrication is not effective at 40ºK, so dry lubrication must be used. Dry lubricants have a short service life, but it is expected that each set of doors will go through about ten cycles, which is within the bounds of dry lubricant service life. There are several dry lubricants which will suffice for our system; sputter-deposited molybdenum disulfide is one such lubricant, as are epoxy and polyamide-bonded films [Oswald, 2005].

2.2.6 Furnace Subsystem Mass

The mass of the furnace system includes mass of the: furnace wall, insulation, heating elements, quartz filters, valves, pump, actuated top/bottom furnace caps, and vent.

The mass of the furnace wall is based on the geometry calculated in Section 2.2.4. Assuming the furnace wall is made out of 2 mm thick Ti-6Al-4V (with a density of 4.42 g/cm²), the furnace wall mass is 6.6 kg.
We calculate the mass of the high temperature multi-layer insulation using a thickness of 0.35 m. This particular high temperature MLI has a density of 48 kg/m³ [Daryabeigi, 1999] which results in a mass of 11.0 kg.

A breakdown of furnace subsystem mass is presented in the table below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Estimated Mass (kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace Wall</td>
<td>4.4</td>
<td>Based on calculation</td>
</tr>
<tr>
<td>MLI</td>
<td>9.2</td>
<td>Based on calculation</td>
</tr>
<tr>
<td>Quartz filters</td>
<td>&lt;0.1</td>
<td>Based on laboratory apparatus</td>
</tr>
<tr>
<td>Valves, Pump, and Vent</td>
<td>&lt;0.5</td>
<td>Estimate</td>
</tr>
<tr>
<td>Actuated Top/Bottom Caps</td>
<td>&lt; 2</td>
<td>Estimate</td>
</tr>
<tr>
<td>Furnace/Regolith Scale</td>
<td>&lt; 2.5</td>
<td>Based on commercially available product</td>
</tr>
<tr>
<td>Resistive Heating Elements</td>
<td>&lt; 1</td>
<td>Based on laboratory apparatus</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>&lt; 19.7</strong></td>
<td></td>
</tr>
</tbody>
</table>

### 2.3 Design of the Radiator

#### 2.3.1 Thermal Calculations

The radiator design consists of an aluminum tube covered with multi-layer insulation radiating to a surrounding temperature of 40ºK. The purpose of the radiator is to condense and cool water vapor exiting the furnace at about 900ºC to between 5 ºC and 95ºC. The preliminary design of the furnace includes four parameters: the mass flow of water vapor and hydrogen gas through the radiator, the diameter, thickness, and length of the aluminum tube.

We would like the mass flow rate of water vapor and hydrogen gas through the radiator to be as low as possible, because this results in lower hydrogen flow rates through the furnace and thus a smaller furnace cross-sectional area. However, we would also like a radiator that is capable of performing its function even if lunar dust is deposited on it. We assume that the radiator has an efficiency ($\eta$) of 0.9 and that this efficiency will decrease by no more than 10% if dust is deposited on the radiator.

The first step in the preliminary design is to calculate the thickness of the radiator. Since we know that the heat radiating from the furnace must be equal to the heat conducted through the furnace, we can calculate thickness with Equation 1.2:

$$Thickness = \frac{k(T_{mass\_flow} - T_{surroundings})}{\varepsilon\sigma(T_{mass\_flow}^4 - T_{surroundings}^4)} ,$$

(Eq. 2.11)
In this equation, we use the thermal conductivity (k) of high temperature multi-layer insulation: 0.0083 W/mK [Daryabeigi, 1999]. $T_{\text{surroundings}}$ is 40K, the temperature in the permanently shadowed crater. We assume that the small amounts of water vapor (0.0001 kg/s) leaving the furnace at 1173 K comes to equilibrium with hydrogen gas flow (0.002 kg/s) leaving the furnace at 298 K. Therefore, the resulting mass flow $T_{\text{max flow}}$ through the radiator is at 342 K. The emissivity of MLI is given by $\varepsilon = 1$ (corresponding to a very thin polished metal), and $\sigma$ is the Boltzmann constant. The resulting quantity tells us we must cover the aluminum tube with a layer of high temperature multi-layer insulation which is 0.003 meters thick.

We assume the diameter of the radiator is 0.05 meters. We then calculate the length ($L_1$) of tube necessary to cool the mass flow one degree (from 342 K to 341 K) using Equations 1.3 and 1.4.

\[
L_1 = \frac{Power}{\eta \varepsilon \sigma (T_{\text{max flow}}^4 - T_{\text{surroundings}}^4)2\pi r_{\text{outer}}}, \quad \text{Eq. 2.12}
\]

\[
Power = m_{\text{in}}C_p\Delta T, \quad \text{Eq. 2.13}
\]

where $T_{\text{max flow}}$ is 342 K K, $\Delta T$ is 1 K, and $C_p$ is the coefficient of pressure at 342 K.

Next, the mass of that length ($L_1$) of the radiator can be calculated by using the inner radius of the aluminum and the density of that material as seen in the following equation.

\[
Mass = \rho \pi (r_{\text{outer}}^2 - r_{\text{inner}}^2)L_1, \quad \text{Eq. 2.14}
\]

where $r_{\text{outer}}$ and $r_{\text{inner}}$ are the outer and inner radius of the radiator.

We then calculate the length ($L_2$) of the tube necessary to cool the mass flow another degree (from 341 K to 340 K) and the mass of $L_2$. We continue these calculations until the water has reached the desired temperature, and then add the segments to find the total length and mass of the radiator.

Assuming lunar dust is not reducing efficiency and we condense and cool the water vapor to 5°C, the length of the radiator must be 0.04 meters. However, we expect that the excavation process will deposit lunar dust onto the multi-layer insulation. Therefore, we assume that the efficiency of the radiator may be reduced by 10% over a one month period. In this case, it is important that the water is below 100°C as it exits the radiator. Further analysis shows that if the efficiency of the radiator is reduced to 0.8, the temperature of the water as it exits the radiator will not exceed 95°C. Therefore, the preliminary radiator design is capable of withstanding a coating of lunar dust that reduces efficiency by less than 10%.
2.3.2 Radiator Mass and Power Requirements

Based on the furnace geometry, the mass of the radiator aluminum tubing is calculated to be 0.05 kg, and the mass of the high-temperature MLI is calculated to be less than 0.01 kg. It is also necessary to include heating elements to the radiator system to ensure that the radiator does not cool below 0°C during periods when no water vapor is flowing, which might cause the formation of ice that would block the tube. These heating elements are expected to weigh less than 0.1 kg, and require much less than 1.0 W for operations during furnace heating. A summary of these results is shown in the table below.

<table>
<thead>
<tr>
<th>Table 2.8: Radiator Mass and Power Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator Mass (kg)</td>
</tr>
<tr>
<td>Power Required (W)</td>
</tr>
</tbody>
</table>

2.4 Design of the Electrolysis System

In this section, we present a concept of operations for the Electrolysis Subsystem. We then present the electrolyzer chosen for our detailed design. We provide a power budget, which includes a schedule for electrolysis and heat losses to the environment. Finally, we present a mass budget for the Electrolysis Subsystem.

2.4.1 Electrolysis Subsystem Concept of Operations

The purpose of the Electrolysis Subsystem is to measure the amount of water (and thereby the amount of oxygen) produced during processing, and electrolyze the water into hydrogen gas and oxygen gas.

To minimize the amount of power required for electrolysis we must maximize the amount of time available to electrolyze the water collected. We do this by electrolyzing concurrently with furnace heating and processing.

To make concurrent electrolysis possible while still taking mass measurements of each batch of water, a dual-chamber mass measuring instrument will be used between the radiator and the electrolyzer. The dual-chamber decouples water collection from water electrolysis, and introduces a natural mechanism for obtaining accurate mass measurements. The operation of a dual chamber mass-measuring instrument is diagrammed in Figure 2.9 below.
Figure 2.2: Dual-Chamber Mass-measuring Instrument.

The water produced by the furnace is collected in the upper chamber. Once the batch of regolith in the furnace has been completely reduced, the chamber is weighed. The upper chamber opens and allows water into the lower chamber. The upper chamber then closes before the furnace begins to heat the next batch of regolith. The water from the next batch of regolith collects in the upper chamber, while the water in the lower chamber is electrolyzed. When the water in the lower chamber has been completely electrolyzed and the batch of regolith in the furnace has been completely reduced, the chamber is weighed again. This operation of the Dual-Chamber Mass Measuring Instrument provides the electrolyzer the maximum time possible to electrolyze each batch of water, thus minimizing the electrolysis power requirement.

2.4.2 Design of Electrolyzer

Based on the CDR trade study of electrolyzers, we incorporate a Proton Exchange Membrane (PEM) electrolyzer into the ISOPS system. The PEM electrolyzer is made up of small, compact stacks. Also the PEM does not pose any safety hazards; it has no hazardous waste and the set up of each stack makes it impossible for hydrogen to enter the oxygen stream. The PEM electrolyzer is also capable of high density current and also higher-differential pressure (up to 3,000 psi), but can operate at room pressure and temperature. It also allows for quick start up (Chewonki, 2004). This is a convenient advantage and will be discussed further in the next section.

The figure below shows the components of a two-stack PEM Electrolyzer.
Figure 2.3: Diagram of a Two-cell PEM Stack (image from SGL, 2005)

The stacks are held together by two end plates made of stainless steel. Inside of that are ½ bipolar plates on each side to hold the anode and cathode (SGL, 2005). The bipolar plates are made of Delrin, which is a good insulator, resists moisture and is non-reactive to both hydrogen and oxygen. The Delrin plates have grooves to allow particle flow across the entire cathode surface for greater surface area contact with the membrane.

Next is the nickel screen that serves as a gas diffuser. It is in contact with the platinum covered membrane and has high electrical conductivity to help transport the gasses. In the middle of each stack is the proton exchange membrane that is coated with Platinum, which acts as a catalyst necessary to liberate electrons from the hydrogen and support a reaction of protons with oxygen. The amount of Platinum needed is usually in a tenth of a milligram per square meter. The membrane itself is made of Nafion, manufactured by DuPont. It is essentially a perfluorinated polymer similar to Teflon and treated with sulfur and carbon to establish an ion path that can conduct protons (Elliott, 2005).

The electrolysis process is initiated when water particles enter the anode side on the left hand size of Figure 1.8. The electromotive force (EMF) and catalytic reaction then break the H$_2$O bonds. The membrane separates hydrogen from oxygen and carries the protons to the cathode side where a current of electrons feeds negative charges. The proton goes to the cathode side, receives an electron, and forms H$_2$. The oxygen back on the anode side is stripped of its extra electrons and forms a diatomic O$_2$. Though its outer valence is not full, the single occupation of two $p$-orbitals with parallel spins is predicted to be most stable according to Hund’s principle.
Figure 2.4: Diagram of PEM Electrolyzer Processing

The O\textsubscript{2} and H\textsubscript{2} then travel through tubes to the oxygen collection system and the hydrogen recycling system, respectively.

2.4.3 Electrolysis Subsystem Power Requirements

2.4.3.1 Power for Electrolysis

The power required to carry out electrolysis for a certain mass flow rate of water is calculated at standard temperature and pressure with the following steps: first, calculate the Gibbs Free Energy (the ideal amount of energy that must be supplied from the power source) based on calculations of the change in enthalpy required and the amount of energy provided from the environment; second, scale the energy required for an electrolyzer with a 90% energy efficiency; third, use the mass of water and desired electrolysis rate to calculate power required. Small deviations from standard temperature and pressure do not impact power requirements.

The rate at which we electrolyze the water must vary throughout the mission due to power constraints. The maximum time budgeted for the ISOPS mission objectives is three weeks (504 hours). Assuming 49 hours of heating time for each batch and 1 hour processing time, the electrolyzer has a maximum of 454 hours for operation. This is because the first batch must be heated and processed (50 hours) before the electrolyzer has water to begin electrolyzing. Assuming a maximum oxygen yield of 2% by weight of regolith, calculations show that the electrolyzer requires on average 17.8 W for operation.

Based on iteration through the ISOPS design process, we have identified an electrolysis power schedule that results in an average of 17.8 W during the three week ISOPS mission timeframe, and achieves the overall system objective of operations within 100 W. While the furnace is heating from 40 K to 723 K, the electrolyzer will operate at 22.7 W. The electrolyzer will then be shut off for 91 seconds while the furnace vents water vapor to the lunar environment. This is because an additional 7.1 W are required for furnace heating during the 91 seconds it take to vent the water vapor to the lunar environment. Once the venting operation has terminated, the electrolyzer is turned on again. The electrolyzer will operate at 15.8 W while the furnace is heating from 723 K to 1173 K. During hydrogen reduction processing, the electrolyzer will operate at 43.8 W.
2.4.3.2 Heat Losses to the Environment

Since the PEM electrolyzer requires an operating temperature of at least 21 C (room temperature) for effective functioning [Cobden, 2005] and the Dual-Chamber Mass-measuring Instrument requires water in liquid form, we must heat the Electrolysis Subsystem. To calculate the losses to the environment associated with this heating, we encapsulate the volume of the Electrolysis Subsystem with multilayer insulation.

The volume of the Electrolysis Subsystem consists of the volume of the PEM electrolyzer and the volume of the Dual-Chamber Mass-measuring Instrument. We estimate the volume of the PEM electrolyzer based on commercially available models to be approximately 0.2 m x 0.2 m x 0.2 m, or 0.008 cubic meters, [Quintech, 2005]. We estimate the volume of the Dual-Chamber Mass-measuring Instrument based on commercially available products to be approximately 0.2 m x 0.2 m x 0.2 m [Inscale, 2005] or 0.008 cubic meters. Therefore we can provide a conservative estimate that the Electrolysis Subsystem and heating elements are contained within 0.4 m cube. We assume this cube is maintained at a temperature of 21 C, and covered by MLI with a thermal conductivity of 0.0002 W/mK [Eckhart, 1999] and thickness 0.05 m. This results in 0.3 W of heat losses to the environment.

2.4.3.3 Summary of Electrolysis Subsystem Power Requirements

<table>
<thead>
<tr>
<th>Furnace Operation Mode</th>
<th>Electrolysis Power (W)</th>
<th>Heat Loss to Environment (W)</th>
<th>Power for Regulatory/Control Functions (W)</th>
<th>Total (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating from 40 K to 723 K</td>
<td>22.7 ( -7.1 W for 91 seconds)</td>
<td>&lt; 0.3</td>
<td>&lt; 1.0</td>
<td>&lt;24.0</td>
</tr>
<tr>
<td>Heating from 723K to 1173 K</td>
<td>15.8</td>
<td>0.3</td>
<td>&lt; 1.0</td>
<td>&lt;17.1</td>
</tr>
<tr>
<td>Processing</td>
<td>43.8</td>
<td>0.3</td>
<td>&lt; 1.0</td>
<td>&lt;45.1</td>
</tr>
</tbody>
</table>

2.4.4 Electrolysis Subsystem Mass

The mass of the Electrolysis Subsystem includes the mass of: the PEM electrolyzer, Dual-Chamber Mass-measuring Instrument, elements, multilayer insulation, resistive heating.

We estimate the mass of the PEM electrolyzer to be 1.5 kg based on a commercially available 7-stack product capable of operating at up to 50 W [Quintech, 2005]. We estimate the mass of the Dual-Chamber Mass-measuring Instrument to be less than 3 kg, also based on commercially available products [Inscale, 2005]. The mass of the multilayer insulation is calculated to be 2.3 kg, assuming a density of 48 kg/m³ [Daryabeigi, 1999]. Finally, we estimate the mass of the resistive heating elements to be less than 1 kg based on our laboratory apparatus.

The table below shows the mass budget for the Electrolysis Subsystem.
Table 2.10: Electrolysis Subsystem Mass Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Estimated Mass (kg)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM Electrolyzer</td>
<td>1.5</td>
<td>Based on commercially available product</td>
</tr>
<tr>
<td>Dual Chamber Mass-measuring Instrument</td>
<td>2.5</td>
<td>Based on commercially available product</td>
</tr>
<tr>
<td>MLI</td>
<td>2.3</td>
<td>Based on calculation</td>
</tr>
<tr>
<td>Resistive Heating Elements</td>
<td>&lt; 0.5</td>
<td>Based on laboratory apparatus</td>
</tr>
<tr>
<td>Total</td>
<td>&lt; 6.8</td>
<td></td>
</tr>
</tbody>
</table>

2.5 Design of the Hydrogen Recycling System

2.5.1 Overview of Hydrogen Flow through ISOPS

The flow path the hydrogen takes through the oxygen production system starts at the hydrogen storage tank. A pump at the interface of the hydrogen gas tank and furnace controls the hydrogen flow out of the hydrogen tank and into the furnace, where the hydrogen combines with the oxygen released from the regolith to form water vapor. The water vapor and extra hydrogen then flows through the furnace, and into the electrolyzer, where the oxygen is separated out of the water vapor and pumped into an oxygen storage tank. This leaves the extra hydrogen and the hydrogen that was bonded to the oxygen in the water vapor. This total hydrogen mass flow returns and is pumped back into the hydrogen tank through the hydrogen recycling system. The following figure shows the mass flows through this system, assuming a 10 kg batch size of regolith.

Figure 2.5: Hydrogen Flow Through the Oxygen Production System

The total mass flow of 0.002 kg/s was chosen to optimize the performance of the radiator, as well as to create a reasonable cross-sectional flow area of the system. Previous research done with regolith processing indicates that the flow velocity through the furnace should be 0.01 m/s or greater to optimize the oxygen extraction process [McKay 1996].
2.5.2 Verifying Adequate Hydrogen Flow through Furnace

The first step in the hydrogen recycling system design is to verify that hydrogen flow through the furnace is greater than 0.01 m/s given the radiator design parameters. Mass flow is determined by the product of density, flow velocity, and area. For the flow velocity in the furnace to be greater than 0.01 m/s, the furnace must have a cross-sectional area smaller than 2.18 m² and a radius less than 0.834 m. As discussed in Section 2.2, our design incorporates a flow rate of 0.32 m/s, resulting in a furnace cross-sectional area of 0.069 square meters. Therefore, we are assured to have adequate hydrogen flow through the furnace to fully reduce the batch of regolith.

2.5.3 Hydrogen Recycling Trade Study

Without a hydrogen recycling system, all hydrogen that cycles through the system would need to be brought in a hydrogen tank. This would be prohibitively heavy since the hydrogen needs to flow continuously for 1 hour for each batch. Only a small fraction of the hydrogen that flows through the regolith actually reacts with the oxygen, so without recycling, a lot of hydrogen will be lost. The following table shows the total amount of hydrogen that would be necessary for each batch size of regolith without hydrogen recycling and with hydrogen recycling.

<table>
<thead>
<tr>
<th>Total Hydrogen (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Recycling</td>
</tr>
<tr>
<td>With Recycling</td>
</tr>
</tbody>
</table>

The total amount of hydrogen without hydrogen recycling is the product of the hydrogen flow rate, processing time (1 hour per batch), and the number of batches.

The mass of hydrogen circulating in the hydrogen recycling system is calculated by multiplying the hydrogen mass flow rate and the time it takes to circulate through the return piping. The time for circulation depends on the flow velocity through each section of the system. The distance of circulation at a velocity of 0.32 m/s is estimated by Equation 2.15 to be 1.05 m.

\[ D_{\text{circulation}} = 2 \times (\text{furnace}_\text{inner}_\text{height}) + 2 \times (\text{radiator}_\text{length}) + 0.051, \quad (\text{Eq. 2.15}) \]

where 0.901 meters is the estimated length of the connection ends. For constant flow velocity of \( v = 0.32 \) m/s through the system, the approximate time for circulation is 3 seconds.

The data shows that hydrogen recycling is vital for designing a system of reasonable mass.

2.5.4 Hydrogen Recycling Subsystem Mass and Power

The hydrogen storage tank can easily hold twice the amount of hydrogen gas required for recycling and be less than 0.5 kg in mass, assuming aluminum density of 2800 kg/m³, maximum yield stress of 410 MPa, and 25°C = 298 K operating temperature.
We assume that the majority of the hydrogen recycling tubing is composed of aluminum (density $= 2800 \text{ kg/m}^3$). Based on a wall thickness of 0.01 m, this results in a hydrogen recycling tubing mass of 0.4 kg.

The operating temperatures (approximately 25 deg C) and pressures (standard pressure) of the electrolysis subsystem introduce water vapor into the recycled hydrogen flow as well as the produced oxygen gas. This contributes to a loss of some fraction of the water produced. Calculations of the relative humidity in the hydrogen and oxygen gas flow indicate that water vapor results in a loss of approximately 1.7 percent of the collected oxygen. This calculation assumed a hydrogen flow that is dried and then recycled; and a hydrogen mass flow an order of magnitude greater than that specified for our system design. This results in an overestimate of the impact moist hydrogen gas has on process efficiency measurements and suggests that mechanisms do not need to be designed into to capture, collect, and electrolyze moisture from hydrogen flow. However, to avoid the potential problem of the water vapor freezing and creating a blockage, we maintain the Hydrogen Recycling Subsystem at a temperature of 298K. Assuming the Hydrogen Recycling System is covered with 0.05m of MLI, we require less than 1 W to maintain temperature. The weight of the MLI and resistance heating elements are assumed to be included in the conservative estimate for hydrogen storage tank mass.

A summary of the Hydrogen Recycling Subsystem mass and power requirements is presented in the table below.

| Table 2.12: Summary of Hydrogen Recycling Subsystem Mass and Power Requirements |
|---------------------------------|---------------------------------|
| Hydrogen Recycling System Mass   | 0.9 kg                          |
| Power Required (W)              | < 1 W                           |

2.6 Design of the Oxygen Storage Tank

The goals for the oxygen tank analysis are to design the most lightweight oxygen tank capable of holding the oxygen collected by the system. The following analysis uses the potential oxygen tank material’s maximum allowable yield stress to design the thickness and radius which optimizes this goal.

2.6.1 Oxygen Tank Design

We make three assumptions to carry through a design of the oxygen storage tank. In the lunar crater destination, the operating temperature is assumed to be 40 degrees Kelvin, which is below the solidification point of oxygen at 1 atm. Approximately 2 kg of oxygen is extracted from the regolith batch during hydrogen reduction and must be stored in the Oxygen Storage Tank. Also, the geometrical shape for the oxygen tank is cylindrical with the height equal to the diameter.

The operating temperature of the Oxygen Storage Tank is investigated to determine the optimal design temperature. A lower operating temperature decreases the volume and weight
required for the tank. However, at too low a temperature the oxygen will solidify, which would cause complications such as blocking of the tank inlet valve. To overcome the potential problem of oxygen solidification, the oxygen tank will also carry helium separated by a membrane which is free to move. A pressure-monitoring relief valve on the helium side of the tank will release helium as oxygen enters the tank, thus maintaining constant pressure within the oxygen tank. The oxygen tank will operate at 60K, rather than the lunar environmental temperature of 40K. The 60K is above the solidification temperature of oxygen, 55K, as well as for helium, 4.5K.

The operating temperatures (approximately 25 deg C) and pressures (standard pressure) of the electrolysis subsystem introduce water vapor into the oxygen gas as well as recycling hydrogen flow. As described in Section 2.5, calculations of the relative humidity indicate that water vapor results in a loss of approximately 1.7 percent of the collected oxygen. This is an overestimate of the impact water vapor has on process efficiency measurements and suggests that mechanisms do not need to be designed into to capture, collect, and electrolyze this moisture. However, this introduces the possibility that water vapor will freeze and block the inlet to the Oxygen Storage Tank. To mitigate this problem, we place a desiccant filter in the tubing between the Electrolysis Subsystem and Oxygen Storage Tank. We assume the mass of the desiccant filter is negligible.

![Diagram of Oxygen Storage Tank](image)

**Figure 2.6: Diagram of Oxygen Storage Tank**

### 2.6.2 Oxygen Storage Tank Mass and Power

Several lightweight materials were considered in designing the oxygen tank. We use the following equations to calculate the weight of the Oxygen Tank for each material.

\[
P = \frac{mRT}{V},
\]

(Eq. 2.16)

where \( m \) is 2 kg, \( R \) is the gas constant for oxygen (260 J/kgK), \( T \) is the temperature of 60K, and \( V \) is the volume of the Tank.

The Tank wall width (\( W \)) necessary to contain the oxygen at a safe pressure for each material is calculating using,
\[ W = \text{radius}_{\tan k} \frac{P}{\text{Yield Stress}_{\text{Max}}}, \quad \text{(Eq. 2.17)} \]

where \( \text{Yield Stress}_{\text{Max}} \) is the maximum yield stress for each material and \( \text{radius}_{\tan k} \) is given by,

\[ \text{radius}_{\tan k} = \left( \frac{3V}{4\pi} \right)^{\frac{1}{3}}. \quad \text{(Eq. 2.18)} \]

The optimized mass of the oxygen tank is then simply the density times the shell volume of the oxygen tank. Results of the material trade study are shown in Table 2.13.

**Table 2.13: Oxygen Tank Material Trade Study**

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength (MPa)</th>
<th>Density (kg/m$^3$)</th>
<th>Tank Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum (2014-T6)</td>
<td>410</td>
<td>2800</td>
<td>0.6</td>
</tr>
<tr>
<td>Super alloyxm-19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Strength Annealed</td>
<td>127</td>
<td>7750</td>
<td>5.7</td>
</tr>
<tr>
<td>Aluminum5052 H38</td>
<td>44</td>
<td>2685</td>
<td>5.7</td>
</tr>
<tr>
<td>Haynes188</td>
<td>103</td>
<td>8968</td>
<td>8.2</td>
</tr>
<tr>
<td>Aluminum Tread-Brite</td>
<td>27</td>
<td>2740</td>
<td>9.5</td>
</tr>
<tr>
<td>Monel K-500</td>
<td>65</td>
<td>8442</td>
<td>12.2</td>
</tr>
</tbody>
</table>

The study shows that the smallest tank mass of 0.6 kg is obtained using the material Aluminum (2014-T6). This result is independent of Tank volume. However, we are required to add a safety factor (SF) of 1.5 to the wall thickness to account for variability in the expected amount of oxygen to be collected. This results in Tank masses which are not independent of Tank volume. Since we are not constrained by volume, we present a range of results in Table 2.14.

**Table 2.14: Radius and Width of Oxygen Tank Wall**

<table>
<thead>
<tr>
<th>Volume (m$^3$)</th>
<th>Radius (m)</th>
<th>New Mass with 1.5 SF (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.32</td>
<td>0.63</td>
</tr>
<tr>
<td>0.3</td>
<td>0.36</td>
<td>0.83</td>
</tr>
<tr>
<td>0.4</td>
<td>0.40</td>
<td>1.00</td>
</tr>
<tr>
<td>0.5</td>
<td>0.43</td>
<td>1.16</td>
</tr>
<tr>
<td>0.6</td>
<td>0.46</td>
<td>1.31</td>
</tr>
<tr>
<td>0.7</td>
<td>0.48</td>
<td>1.45</td>
</tr>
<tr>
<td>0.8</td>
<td>0.50</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Based on these results, we estimate that the Oxygen Storage Tank with heating elements and MLI will weight less than 2 kg. Also, calculations show that maintaining the Oxygen Storage Tank at a temperature of 60K requires much less than 1W. These results are summarized in the table below.
### Table 2.15: Summary of Oxygen Storage Tank Mass and Power Requirements

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen Storage Tank</td>
<td>&lt; 2</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

### 2.7 Summary of ISOPS Mass and Power Requirements

#### Table 2.16: Summary of ISOPS Mass

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Estimated Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace</td>
<td>19.7</td>
</tr>
<tr>
<td>Radiator</td>
<td>&lt; 0.2</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>&lt; 6.8</td>
</tr>
<tr>
<td>Hydrogen Recycling</td>
<td>&lt; 0.9</td>
</tr>
<tr>
<td>Oxygen Storage Tank</td>
<td>&lt; 2.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>&lt; 29.6</td>
</tr>
</tbody>
</table>

#### Table 2.17: Summary of ISOPS Power Requirements

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Heating from 40 K to 723 K</th>
<th>Heating from 723 K to 1173 K</th>
<th>Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace Power (W)</td>
<td>73.1 (+7.1 W for 91 seconds)</td>
<td>78.2</td>
<td>49.2</td>
</tr>
<tr>
<td>Radiator Power (W)</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Electrolysis Power (W)</td>
<td>&lt; 24.0 (-7.1 W for 91 seconds)</td>
<td>&lt; 17.1</td>
<td>&lt; 25.1</td>
</tr>
<tr>
<td>Hydrogen Recycling Power (W)</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Oxygen Storage Tank Power (W)</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>&lt; 100</td>
<td>&lt; 98.3</td>
<td>&lt; 77.3</td>
</tr>
</tbody>
</table>

### 2.8 Controls and Process Efficiency Measurements

#### 2.8.1 Controls and Regulation

**Furnace**

The furnace requires one control mechanism to initiate furnace heating. It also requires regulation sensors to maintain processing temperature and verify operating pressure. The actuated furnace caps require a control mechanism to open/close and engage/disengage pressure seal. Finally, the furnace vent and interface valves require a control mechanism to open/close.

**Electrolysis Subsystem**

The Electrolysis Subsystem requires a temperature sensor and control mechanism to maintain ambient temperature. Also, two actuators are required for the control of the chamber door and quick-disconnect door to the dual-chamber mass measurement. When water stops running into the chamber from the radiator, the chamber doors open for a predetermined time window...
(two seconds) for the water to drop to the lower chamber. At a time later (two seconds) the doors close again and the balances takes a mass measurement of the water in the lower chamber. The quick-disconnect to the electrolyzer then opens and the water is able to flow into the electrolyzer. From that point on, the quick-disconnect must be closed before the chamber doors open for the next incoming batch.

**Hydrogen Recycling System**

The hydrogen recycling system will require a flowmeter and pump control mechanism to regulate the flow of the recycled hydrogen through the ISOPS.

**Oxygen Collection System**

There is a pump between the electrolyzer and oxygen collection system to pressurize oxygen in the storage tank. Also, the oxygen tank will have a relief valve to guard against unsafe conditions.

2.8.2 *Process Efficiency Measurements*

Three sensors are necessary to measure process efficiency. A scale will weigh the regolith in the furnace continuously throughout processing. First, regolith is heated to drive off any existing water, and the water-ice content of a sample is measured as the change in mass of the regolith. Second, regolith is reduced using hydrogen, and oxygen yield as measured as the additional change in mass of the regolith. These two measurements are critical to determining what percentage of total oxygen yield is due to water-ice and bound oxygen. Next, the water collected in the Dual Chamber Mass-measuring Instrument is weighed. The amount of oxygen bound in the collected water is compared to the mass of the regolith before processing to yield another measure of process efficiency. Finally, a pressure sensor in the oxygen tank can be used along with tank volume and temperature to calculate the total amount of oxygen collected.

2.9 *Process Demonstration and Experiments*

The goals of preliminary laboratory work include familiarization with the system, process, and equipment needed to extract oxygen from lunar simulant soil. A furnace is setup and experiments are designed and carried out to reproduce the results published by Allen, Morris and McKay (1996) and simulate our ISOPS process design.

2.9.1 *Brief Literature Review*

Allen, Morris and McKay (1996) examined oxygen extraction from sixteen lunar soils and three lunar pyroclastic glasses. The samples were reduced by flowing hydrogen at a temperature of 1050°C for 3 hours. And, the oxygen extraction was measured by the weight loss of the sample. They found that the oxygen yield was strongly correlated with initial Fe$^{2+}$ abundance; in fact, though there was evidence that oxygen was extracted from TiO$_2$ and SiO$_2$, the oxygen yield from lunar regolith can be predicted solely from the amount of iron in the regolith.

In addition to examining the oxygen extraction potential of various soils, Allen, Morris and McKay (1996) performed experiments to determine the effect of gas flow rate on oxygen
extraction. Using lunar soil stimulant JSC-1, they tested linear hydrogen flow rates of 0.18, 1.0 and 2.0 cm/s which resulted in oxygen yields of 2.41, 3.06 and 3.05 %wt, respectively. These results agreed with previous results that indicated above a linear flow rate of 1.0 cm/s the oxygen yield is independent of the gas flow rate.

Other experiments conducted by Ogiwara (2000) studied the hydrothermal reduction process on lunar simulant, and showed results similar to those found by Allen, Morris and McKay. Ogiwara also noted that grain size is a key factor is controlling the rate of reaction. Also, Zhao and Shadman have conducted laboratory experiments on ilmenite reduction with both hydrogen and carbon monoxide. They concluded that the reduction rate using hydrogen was faster than using carbon monoxide for pure ilmenite feedstocks (Zhao 1993).

2.9.2 Description of Laboratory Apparatus

A labeled photograph of the laboratory setup is shown in the figure below. Experiments are conducted using JSC-1 lunar simulant, a glass rich basaltic ash which approximates the chemical composition, mineralogy, particle size distribution, and engineering properties of lunar mare regolith. A sample of JSC-1 is held in place in a quartz tube with a porous plug; the quartz tube is then inserted into the furnace such that the sample is contained in the zone of constant temperature within the furnace. One tank of argon and one tank of hydrogen gas are connected to one end of the quartz tube by a series of copper and rubber tubing such that the gas passes through a flow meter before entering the quartz tube. Attached to the other side of the quartz tube is a moisture trap to extract the water vapor from the flow.
During an experiment, argon is passed through the system until the furnace has reached the desired temperature. Once the sample has reached the desired temperature, the argon flow is stopped and the hydrogen flow is turned on. The moisture trap is not connected to the quartz tube until hydrogen is flowing through the system because the moisture trap drying material absorbs moisture from the air. Since the change in weight of the moisture trap drying material indicates the amount of water vapor produced during the experiment, contamination from the air must be minimized.

2.9.3 Description of Demonstration Experiments and Results

To date three experimental runs have been conducted with the purpose of reproducing Allen, Morris and McKay’s (1996) experimental results using JSC-1 lunar simulant. Two additional experimental runs have been conducted which better simulate our ISOPS processing design.

During the first three experiments, samples are reduced at a temperature of 1050 degrees Celsius for a duration of three hours, as carried out by Allen, Morris and McKay. For these trials, we use a 6 mm diameter quartz tube, process approximately 5 grams of regolith, and flow hydrogen gas through the heated sample at a rate of one standard cubic centimeters per
second. In an attempt to reduce errors due to small sample size and better simulate our ISOPS process design, we expanded our apparatus. During the fourth and fifth experiments, samples are reduced at a temperature of 900 degrees Celsius for a duration of three hours and a flow rate of approximately 50 cm/s. In these experiments we use a 3.81 cm diameter quartz tube, and process approximately 60 grams of regolith.

For the experiments conducted in this project, the amount of oxygen released from the sample is measured in two ways. First, the sample is massed before and after reduction as done by Allen, et al. Second, the drying material in the moisture trap is massed before and after reduction to quantify the amount of water, from which the oxygen yield is calculated. These two measurements should provide results indicating the same oxygen yield; differences between the two results help to identify and quantify sources of experimental error, and provide a basis for improving system design and experimental procedures.

LunarDREEM experimental results are compared to Allen, Morris and McKay’s results in the figure below. Trials 1, 2, and 3 correspond to experiments performed at 1050 deg Celsius with approximately 5 gram samples. Trials 4 and 5 correspond to experiments performed at 900 deg Celsius with approximately 60 gram samples. The red circle represents the percent oxygen yield by weight of sample calculated by massing the moisture trap drying material before and after each experiment. The black asterisk represents the percent oxygen yield by weight of sample calculated by massing the JSC-1 lunar simulant sample before and after each experiment. The blue lines indicate the lower and upper bounds of results for similar experiments carried out by Allen, et al.

![Figure 2.8: Process Demonstration Experiment Results](image)

The figure above shows that oxygen yield measurements are within the range of published results. These results indicate that the experimental apparatus successfully reduces the lunar
simulant sample. Ideally the results from moisture trap drying material measurements and sample weight measurements would be identical; however the first three experiment results show a consistent error of approximately 20% between the two numbers. Expanding our apparatus to process larger amounts of regolith reduced this error to approximately 4%.

2.9.4 Flow Rate Experiment

The purpose of this experiment is to investigate the maximum velocity that hydrogen can flow through the furnace without significantly disturbing the regolith. The maximum allowable flow velocity directly impacts the furnace geometry, which affects system mass and power requirements.

2.9.4.1 Summary of Results

We found that for a vertical tube, the maximum velocity that hydrogen can flow through the tube is approximately 192 cm/s. For a horizontal tube, the maximum velocity is at least 345 cm/s, the highest which our flow meter can measure. When the tube is held vertical, the regolith is resting on the quartz stopper and covering the entire cross-sectional area, so the hydrogen must flow through the regolith sample. The maximum horizontal flow rate is higher than the vertical flow rate because in the horizontal case the hydrogen diffuses rather than flows through the regolith sample. Therefore, we have decided it is necessary to use a vertical set up for the furnace so the hydrogen can properly react with the regolith. Thus, the hydrogen can be flowed through the furnace at a maximum of approximately 192 cm/s without significantly disturbing the regolith sample.

2.9.4.2 Experiment Procedure

A hydrogen tank is connected hooked up to the flow meter through a series of copper tubing. Additional copper tubing connects the flow meter with the quarter inch diameter quartz tube, attaching it with a tightened rubber tube around the base to prevent hydrogen from escaping (see Figure 2.9 for set up). The flow meter is adjusted until it is level with the ground.

![Figure 2.9: Set-up for the Vertical Flow Rate Experiment](image-url)
Before regolith is loaded into the quartz tube, we check for any leaks in the system by stopping the end of the quartz tube and verifying no gas flow through the flow meter. The hydrogen flow is then stopped, and the quartz stopper and lunar simulant are loaded into the vertical quartz tube. The hydrogen flow is slowly raised at increments and observations are recorded.

2.9.4.3 Observations

Observations from the vertical flow rate experiment to determine the maximum hydrogen velocity through the furnace. In the table below we present the tube reading (the scale reading on the flow meter), the approximate flow velocity of hydrogen gas, and accompanying qualitative observations.

<table>
<thead>
<tr>
<th>Tube reading</th>
<th>Approx. Flow Velocity (cm/s)</th>
<th>Qualitative Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>39</td>
<td>90</td>
<td>very small pieces beginning to pick up</td>
</tr>
<tr>
<td>54</td>
<td>130</td>
<td>small pieces picked up to a maximum of 1/2&quot;</td>
</tr>
<tr>
<td>62</td>
<td>148</td>
<td>small pieces are blown around 1-1.5&quot;</td>
</tr>
<tr>
<td>82</td>
<td>192</td>
<td>small pieces are blown around 1.5-2&quot;, medium pieces are blown around 1-1.5&quot;</td>
</tr>
<tr>
<td>93</td>
<td>216</td>
<td>medium pieces are more turbulent, 1.5-2&quot;, small pieces are blown up to 7&quot;</td>
</tr>
</tbody>
</table>

Based on these results, we choose 192 cm/s as the maximum allowable flow rate to avoid picking up significant amounts of regolith. However, this experiment was conducted in a 1 G environment. The primary factors resisting the pick-up of regolith involve friction and mass of particles; both these factors are proportional to gravity. Hence, to estimate an appropriate maximum flow rate for a furnace operating on the moon, we divide by a factor of six to yield a flow rate of 32 cm/s
3. REGOLITH EXCAVATION, COLLECTION, AND DELIVERY SYSTEM

Excavation, Collection and Delivery System – an integrated system for the excavation and transfer of lunar regolith from the lunar surface to experiment test chambers.

The Excavation System is composed of two subsystems: an Excavator Subsystem to collect regolith, a Regolith Delivery System to transfer the regolith to other subsystems, and a Bulk Physical Characteristics Test Chamber to measure bulk physical properties of the lunar regolith. In this section we present designs for each of these subsystems, including operational profiles, mass and power budgets, and laboratory work.

3.1 Design of the Excavation System

The Excavator Subsystem is the module that will have first contact with the regolith. The Excavator Subsystem must collect regolith up to one meter below the surface, and must collect at least 100 kg of regolith within one month. The Excavation Subsystem must then deliver the regolith to experiment chambers. The design must mitigate exposure to the abrasive, dusty lunar environment and preserve the volatiles contained in the lunar regolith. These goals are to be met while minimizing mass and power usage to meet mission constraints.

Based on preliminary analysis, we have chosen an Auger concept to continue forward with a detailed design and laboratory work. The Auger has been utilized on past lunar missions, and possesses fewer moving parts and exposes fewer moving parts to abrasive lunar regolith than other concept analyzed. The Auger shaft is the only component that will be exposed to the lunar environment; it is possible to hermetically seal all other mechanisms, including motors. This decreases the risk of abrasive particles interfering with operation.

3.1.1 Excavation Concept of Operations

The Auger System consists of an auger bit, auger housing, collection bin, and motors to actuate operations. Once the rover reaches the location to be excavated, the Auger is lowered through the collection bin. Power will be distributed to two motors: one that will apply a vertical force to the Auger and another that will apply a torque to the Auger. The Auger will have a cutting edge that will allow it to cut into and through the lunar regolith. A diagram of the Auger is shown in the figure below.
As the Auger moves downward, the regolith that is broken up by the cutting edge will travel up between the auger flights and housing to be deposited into the collection bin. We will implement peck-drilling to insure that the flights do not fill up entirely and lodge the Auger into the surrounding regolith. Peck-drilling is used for deep drilling operations when it is difficult to clear material out of the drilled hole. The Auger periodically withdraws from the hole after it has advanced a certain distance allowing regolith to loosen from the flights. Such a method facilitates the collection of regolith, prevents the Auger from being lodged, and protects the motor from stalling.

3.1.2 Mass of the Excavation System

In calculating the mass of the subsystem, we consider four separate parts: the auger bit, the auger housing, the collection bin, and the motors used to power the auger. We look at the way mass varies with auger diameter and the number of holes drilled to obtain the required 100 kg of regolith. First, we discuss some of the assumptions made to calculate the mass of these parts. Then we detail the mass calculations.

Assumptions

First, we assume that the density of the regolith is constant and approximately equal to 3100 kg/m$^3$. This number is taken from The Lunar Sourcebook, which lists measured densities based on depth. We have used the density corresponding to a depth of one meter, which is the maximum depth to which we are required to drill. In doing this, we assume that the density of regolith at the poles is not significantly different than at the equator. Second, we assume a pitch on the auger bit of 10 degrees (0.175 radians). This is obtained by looking at augers used in the construction industry.

Next, we must select materials for the Excavation Subsystem. The three major issues that arise in selecting materials are the extreme cold on the surface of the moon, the extremely low pressure, and the abrasiveness of the lunar regolith. We assume that the temperature in a permanently shadowed crater is about 40ºK; this low temperature will affect the physical properties of the materials we choose. In addition, our system will presumably be built at room temperature; the system will thus go through a temperature change of over 200ºK as it
is transported from Earth to the moon. The vacuum environment will lead to large amounts of friction between any moving parts. The regolith itself will create problems if it works its way into any of the moving parts of the system, because of its small particle size and abrasiveness. All three of these factors must be taken into account when selecting materials. Also, the large temperature change undergone by the system will cause changes in the volume of the materials used. To alleviate problems created by these contractions, the auger bit, auger housing, and collection bin will be all be composed of aluminum alloy, so that each part contracts at the same rate. Also, aluminum alloys’ properties (such as shear, compression and bearing strengths, and moduli of elasticity) improve at very low temperatures [Cobden, 2005]. For the following calculations we assume that aluminum has a density of 2700 kg/m³.

The only parts of the system that may not be made of an aluminum alloy are the motors. The motors will most likely be made of several different materials. This system will be too complicated to handle the large temperature change, so the motors should be heated to a temperature above 273ºK. The motors will be housed in hermetically sealed containers to allow this heating to take place. The hermetically sealed containers will provide the added bonus of preventing any regolith from entering the motors and destroying them.

The calculations for mass are computed as a function of the number of holes drilled. Using the assumption that 100 kg of soil is extracted, and that all the regolith from the hole is collected in the collection bin, we calculate the required radius of the hole to be drilled. This radius is then used to calculate the size of the auger bit and its housing.

The Auger Bit

For the bit, we assume that a helical auger shape would be appropriate for extracting soil. Coming up with a general formula for the mass of this shape is somewhat difficult. The volume of the inner shaft of the bit is simple to calculate, but the helical fins are complex to generalize. Their mass depends on several variables: the radius of the hole we are drilling, the pitch of the helix, and the thickness of the fins. The first approach is to do a volume integral about the axis of the shaft, but the result proved hard to generalize. To simplify calculations we assume a auger cross-section described by Figure 3.2.

![Figure 3.2: Auger Cross-section](image)

The radius of the circle corresponds to the radius of the shaft, and the length of the rectangular section corresponds to the difference between the radius of the hole and the radius of the shaft. However, it is the width, w, which is more complex to compute with respect to the variables discussed above. The value of the variable (w) depended on the thickness of the helical flute (measured normal to the regolith-carrying surface of the flute) divided by the sine of the pitch of the helix as given by Equation 3.1.
\[ w = \frac{t}{\sin(\theta)} , \]  
(Eq. 3.1)

where \( \theta \) is equal to the helical pitch.

The size of the shaft is varied according to the radius of our hole. Using the torque calculations discussed in the next section, we calculate the torque required as a function of the radius of the holes we drilled. The torque felt by the inner shaft of the bit is assumed to have this same value. We used a value of 186 MPa as the shear strength of aluminum to determine what the radius of the shaft needed to prevent failure due to shear. The final equation for the mass of the auger bit is described in Equation 3.2.

\[
Mass_{\text{auger \_bit}} = (2700 \text{ kg} / \text{m}^3) \times (1 \text{ m}) \times \left[ (\text{radius}_{\text{inner}})^2 \times \pi + w \times (\text{radius}_{\text{outer}} - \text{radius}_{\text{inner}}) \right] ,
\]
(Eq. 3.2)

The Auger Housing
The Auger Housing is modeled as a hollow cylinder just big enough to contain the auger bit. In calculating mass, we assumed a thickness of 0.25 cm, since the housing would simply be used to contain the particles of regolith the system extracts, and not bear any load. Also, we assumed that the material used would be aluminum. That led to the following formula:

\[
Mass_{\text{auger \_housing}} = (2700 \text{ kg} / \text{m}^3) \times (2\pi) \times (1 \text{ m}) \times (.0025 \text{ m}) ,
\]
(Eq. 3.3)

The Collection Bin
Calculating the mass of the collection bin is similar to calculating the mass of the Auger Housing. We assume a bin in the shape of a triangular prism, with a square, open top, the size of which is determined by the volume of regolith collected for each hole. The depth of the bin is determined by the volume collected, and the angle of the sides is determined by the angle of friction of the lunar regolith. We assume that regolith friction angle is less than 60 degrees [Heiken, 1991]. Then the mass of the bin was computed using a thickness of 0.25 cm and the density of aluminum (2700 kg/m^3), just as for the Auger Housing. This is the equation for the mass of the conical bin:

\[
Mass = (\text{Density}_{\text{aluminum}}) \times (.0025 \text{ m}) \times \pi \times \frac{\text{depth}}{\tan(\text{frictionangle})} \times \sqrt{\text{depth}^2 + \left(\frac{\text{depth}}{\tan(\text{frictionangle})}\right)^2} \times 1.5 ,
\]
(Eq. 3.4)

where,

\[
\text{depth} = \frac{\sqrt{3} \times \text{Volume}_{\text{collected}} \times \tan(\text{frictionangle})}{\pi} .
\]
(Eq. 3.5)

The formula comes from the volume and surface area formulas for a cone, and the factor of 1.5 in the first equation accounts for the extended section used as a “catch-all” for the regolith.

A simple diagram of the bin is pictured below.
The Motors

We assume the motors to be of constant mass. To obtain approximate values for their mass, we have researched commercially available motors. Since the power of our system is limited to 100 watts, we assume that the most powerful motor we could ever need would require 100 watts for operation. We propose that the Auger would best be powered by two separate motors: one to provide a torque to drive the bit, and the other to provide a force which could drive the shaft down into the ground. For good measure then, we assume two 100 watt motors will be used. A typical 100 Watt motor weighs approximately 2 kg each (Bosch, 2005). Because these motors must be heated to 273 K, we assume that this conservative estimate of mass includes resistive heating elements and MLI covering.

Note that we are not assuming that both motors will be used simultaneously at their maximum power levels or that even one motor would be operated at 100W, since this would not leave any power for other operations. However, in case of a problem in penetrating the regolith or in extracting the Auger, the motors should have the capacity to operate at maximum power if this is deemed operationally necessary. Other operations would be suspended until the problem is resolved.

The total mass of the system is found by summing the masses of the four components. In the figures below we present the mass of the Auger System as a function of auger radius and number of holes drilled.
Iteration through the ISOPS and Excavation System designs indicates that we require an Excavation System that weighs less than 15 kg in order to meet the overall mass constraint of 50 kg. This indicates that our auger diameter must be less than 0.07 m, and we are required to drill at least 15 holes.

3.1.3 **Excavation System Power Requirements**

The length of the Auger is constrained to be at least 1 meter long in order to meet the excavation depth requirement stated in the competition guidelines. Mass considerations constrain the radius of the auger bit to be less than 0.05 m. In this section, we analyze power requirements for the Auger System. In industry, drill and auger manufacturers are not limited by power and are therefore able to produce more torque than is needed to power their auger. The diameter of our Auger must be accurately determined to insure that we can efficiently excavate lunar regolith within the power constraint. In this section we investigate power required to drill as a function of auger radius. We also calculate the power required to maintain the temperatures of the Excavation System motors within normal operating limits.

**Power Required to Rotate Auger**

The free-body diagram below illustrates how the cutting edge of the auger applies a force along its radius. This force creates a torque about the center of the auger and counteracts a
disturbance torque, $\tau_f$, created by the mechanical properties of the lunar regolith. For the Auger to move with constant angular velocity through the regolith, the torque created by the Auger must equal $\tau_f$.

$$\sum \tau = (F \times r) - \tau_f = J\ddot{\theta}$$

$$Fr - \tau_f = 0$$

$$Fr = \tau_f$$

**Figure 3.6: Auger Free-body Diagram and Governing Equations**

In order to calculate $\tau_f$, we assume that the force applied by the cutting edge to the regolith is proportional to the area on which it acts. As the area of the Auger increases, the force required to turn the auger increases. It can then be said that there is a pressure constant, $\kappa$, between the force and the area on which it acts, as shown in Equation 3.6.

$$F = \kappa A,$$  \hspace{1cm} (Eq. 3.6)

By analyzing the forces along the radius of the cutting edge, the sum of the torques along the radius can be found by,

$$dF = \kappa 2\pi r dr$$

$$dF \times r = 2\pi \kappa r^2 dr \times r$$

$$\int rdF = \int 2\pi \kappa r^2 dr$$

$$\int_0^R d\tau = 2\pi \kappa \int_0^R r^2 dr$$

resulting in an expression for torque required to drill through regolith given in Equation 3.7.

$$\tau_f = \frac{2}{3} \pi \kappa r^3.$$  \hspace{1cm} (Eq. 3.7)

There is a direct relationship between the cubed radius of the auger and the torque required to operate it. The pressure constant, $\kappa$ depends on the mechanical properties of the material that is being drilled into. In our calculations we decided to use the shear strength, $\tau_{SHS}$ of the lunar regolith as the constant of proportionality between the cubed radius of the auger and the
required torque. The force required to break up a sample section of lunar regolith will depend on the shear strength of the area.

The shear strength was calculated using the class Mohr-Coulomb Equation 3.8 listed in The Lunar Sourcebook.

\[ \tau_{SHS} = c + \sigma \tan \varphi, \]  

(Eq. 3.8)

where \( c \) is the cohesion, \( \sigma \) is the normal stress, and \( \varphi \) is the angle of friction.

A maximum normal stress (given in Equation 3.9) is calculated by estimating the pressure that our entire system would have on the area of our cutting edge against surface of the Moon. We estimated our cutting edge to have a radius range of less than 0.05 m and a thickness of 10mm. We also assume that the maximum force the auger exerts on the regolith, \( F_{\text{max}} \), is given by the mass of the Excavation System (dependent on auger diameter) times the lunar gravitational constant. Therefore normal stress is given by,

\[ \sigma_{\text{max}} = \frac{F_{\text{max}}}{A} = 817.5 \text{kPa}. \]  

(Eq. 3.9)

The shear strength (given in Equation 3.10) of our regolith sample section is determined for the worst possible scenario. We have used the highest cohesion (3.8kPa) and highest angle of friction (50°) values listed in The Lunar Sourcebook.

\[ \tau_{SHS} = 3.8 \text{kPa} + (817.5 \text{kPa}) \tan(50^\circ) \approx 978 \text{kPa}. \]  

(Eq. 3.10)

By substituting the pressure constant, \( \kappa \) for the shear strength, \( \tau_{SHS} \) of a sample of lunar regolith, we calculate the torque (Eq.3.7) required to drill various hole radii. Assuming the Auger is able to devote up to 80 W to rotation, we also calculate the rotational speed for each various hole diameter. We summarize the results in the table below.

**Table 3.1: Torque and RPM as a function of Auger Diameter**

<table>
<thead>
<tr>
<th>Auger Diameter (m)</th>
<th>Torque (N-m)</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.2</td>
<td>405</td>
</tr>
<tr>
<td>0.04</td>
<td>1.0</td>
<td>77</td>
</tr>
<tr>
<td>0.06</td>
<td>2.9</td>
<td>28</td>
</tr>
<tr>
<td>0.08</td>
<td>6.2</td>
<td>13</td>
</tr>
<tr>
<td>0.10</td>
<td>11.2</td>
<td>7</td>
</tr>
</tbody>
</table>

*Power Required to Vertically Translate Auger*

In the following figure we present the power required to vertically translate the Auger as a function of Auger radius. These calculations assuming the Auger is full of regolith, we lift the auger no more than 1 m/s, and lunar gravity is 0.167 m/s².
Power to Vertically Translate Auger

![Graph showing Power Required to Vertically Translate Auger](image)

**Figure 3.7: Power Required to Vertically Translate Auger**

*Power Required to Heat Motors*

Both the motor for auger rotation and vertical actuation must be heated to 273K. Based on commercially available motor dimensions [Bosch, 2005] we estimate that must heat a cute with a volume of 0.03 cubic meters for each motor. Assuming a MLI thickness of 0.05 m, this contributes an additional 2 W to the Excavation System power budget.

3.1.4 *Laboratory Experimentation*

3.1.4.1 *Objectives*

The primary objective of laboratory experimentation is to quantify the regolith mass excavation rate associated with different auger radii; we are not able to accurately quantify this metric with theoretical calculations. This information is vital to validating that our Excavation System design meets mission time constraints. Secondary objectives are to verify theoretical torque and power calculations and demonstrate an excavation method that meets power consumptions requirements, to the extent possible in a laboratory environment.

3.1.4.2 *Description of Laboratory Setup*

A labeled picture of our experimental auger setup is shown below. The three augers of different radii (1” diameter wood auger, 2” and 4” Earth auger) attach to an aluminum coupling shaft. This coupling shaft is then connected to a steel rod which also interfaces with the 24V DC gear motor. The steel rod is supported between two planes of plywood held 6” apart and stabilizes the auger as it turns. The motor is housed within a 4” diameter PVC pipe and can be vertically raised and lowered manually. Regolith stimulant for excavation tests (composed of commercially available sand product) is compacted into a 5-gallon bucket and serves as our “lunar surface” for excavation rate experiments. The bucket is fitted with a regolith collection bin made for each auger and used to collect the excavated regolith. A small container of JSC-1 simulant is used with the 1” wood auger to validate (to the extent possible) theoretical torque and power calculations presented in Section 3.1.3. Our laboratory apparatus also includes a tachometer to measure the angular velocity of each auger during testing, and a power supply capable of providing the motor 80 W.
3.1.4.3 Experimental Procedure

Before experimentation, initial weight measurements are made for the regolith collection bin and the auger assembly (motor, motor housing, couplings, and auger). The collection bin must be weighed in order to calculate the mass of regolith collected at the end of each auger test. A piece of reflective tape is placed on each auger shaft for detection by the tachometer. We then slowly increase the voltage applied to the motor to approximately 24 W. Initial values of voltage, current, and auger rotation speed are then recorded.

The auger is lowered slowly into the lunar soil simulant and is allowed to excavate the material. Each auger excavates to a fixed depth and measurements of the voltage, current, and auger speed are recorded during excavation. We set a limit of 3.6 amps on the amount of current being conducted into the motor to ensure that the motor is not damaged. Whenever the current reaches this limit the auger is lifted out of the soil and the simulant collected in the flights of the auger is removed. The auger is then lowered again into the regolith to excavate more soil. This process of “peck-drilling” prevents damaging of the motor and facilitates regolith collection.

Each auger is tested three times for two minutes at a time. The number of peck drills is also recorded for the duration of the experiment. After each test, the collection bin is removed and weighed. The data for three experiment trials for each auger is presented in the next section.

3.1.4.4 Results

In the following table, we present the excavation data collected during laboratory experimentation of different diameter augers. We use these experimental results to estimate the time for excavation for different auger diameters. We also investigate the validity of our theoretical torque calculations to the extent possible.
Table 3.2: Excavation Experiment Data Table

<table>
<thead>
<tr>
<th></th>
<th>1&quot; (0.025 m) Diameter Auger</th>
<th>2&quot; (0.051 m) Diameter Auger</th>
<th>3&quot; (0.102 m) Diameter Auger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight of Collection Bin</td>
<td>Trial 1</td>
<td>Trial 2</td>
<td>Trial 3</td>
</tr>
<tr>
<td>[kg]</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Weight of Auger Assembly (Initial) [kg]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal Force [N]</td>
<td>4.90</td>
<td>4.90</td>
<td>4.90</td>
</tr>
<tr>
<td>Required Load [kg]</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
<tr>
<td>Initial Voltage [V]</td>
<td>21.5</td>
<td>21.5</td>
<td>21.5</td>
</tr>
<tr>
<td>Initial. Current [A]</td>
<td>0.20</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Initial Auger Speed [RPM]</td>
<td>165</td>
<td>165</td>
<td>166</td>
</tr>
<tr>
<td>Initial Auger Speed [rad/s]</td>
<td>17.3</td>
<td>17.3</td>
<td>17.4</td>
</tr>
<tr>
<td>Excavation Auger Speed [RPM]</td>
<td>155</td>
<td>156</td>
<td>165</td>
</tr>
<tr>
<td>Excavation Auger Speed [rad/s]</td>
<td>16.2</td>
<td>16.3</td>
<td>17.3</td>
</tr>
<tr>
<td>Peck Out Auger Speed [RPM]</td>
<td>155</td>
<td>156</td>
<td>165</td>
</tr>
<tr>
<td>Peck Out Auger Speed [rad/s]</td>
<td>16.2</td>
<td>16.3</td>
<td>17.3</td>
</tr>
<tr>
<td>Max Voltage [V]</td>
<td>21.5</td>
<td>21.5</td>
<td>21.5</td>
</tr>
<tr>
<td>Max Current [A]</td>
<td>0.40</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Max Auger Speed [rpm]</td>
<td>165</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>Max Auger Speed [rad/s]</td>
<td>17.3</td>
<td>17.3</td>
<td>17.3</td>
</tr>
<tr>
<td>Max Electrical Power [W]</td>
<td>8.6</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Efficency, GearBox</td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
</tr>
<tr>
<td>Max Mechanical Power [W]</td>
<td>4.9</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>Max Torque[N-m]</td>
<td>0.28</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>Duration of test [s]</td>
<td>120</td>
<td>120</td>
<td>121</td>
</tr>
<tr>
<td># of peck-drills</td>
<td>13</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>Weight of Collection Bin with Regolith [kg]</td>
<td>0.68</td>
<td>0.68</td>
<td>0.68</td>
</tr>
<tr>
<td>Amount of Regolith Collected [kg]</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Excavation Time
To estimate the excavation time for an auger on the moon, we must relate the amount of regolith collected per unit time in our experiment to the amount of regolith per unit time that an auger on the lunar surface would collect. First, we assume that the volume of regolith collected per unit time directly scales with the auger rotational velocity during excavation. Therefore, we can calculate the excavation rate on the moon by,

\[ R_{\text{excavation\_moon}} = \frac{d_{\text{regolith}}}{R_{\text{moon}}} \cdot \frac{RPM_{\text{moon}}}{RPM_{\text{experiment}}} \cdot \frac{R_{\text{experiment}}}{d_{\text{sand\_product}}} \cdot 1, \quad \text{(Eq. 3.11)} \]

where \( R_{\text{excavation\_moon}} \) is the mass of regolith collected per hour on the moon, \( R_{\text{experiment}} \) is the mass of sand product collected per hour during experimentation (extrapolated from two minute trials), \( d_{\text{sand\_product}} \) is the density of the sand product measured to be 1660 kg/m\(^3\), and \( d_{\text{regolith}} \) is the density of lunar regolith taken to be 1500 kg/m\(^3\). We choose the lower bound on regolith density stated in our assumptions to provide a conservative estimate of the mass excavation rate. \( RPM_{\text{experiment}} \) is the angular velocity measure during experimentation, and \( RPM_{\text{moon}} \) is the theoretical maximum angular velocity that can be achieved during lunar excavation assuming 80 W as described in Section 3.1.3.

The figure below relates the excavation rate in our experiment to the excavation rate for a same diameter auger on the moon. These calculations average the three trials for each auger.

![Excavation Time vs Auger Diameter](image)

**Figure 3.10:** Excavation Time as a function of Auger Diameter

Since the ISOP System requires three weeks out of the four week mission to process regolith, excavation must be constrained to one week (168 hours). As we can see in Figure 3.9, all three augers tested meet this constraint with much time to spare.

Investigation of Validity of Theoretical Torque Calculations
The secondary objective of laboratory experimentation was to investigate the validity of the theoretical torque calculations presented in Section 3.1.3. To do this, we apply Equations 3.6 through 3.10 to estimate the theoretical torque required for the 1” (0.0254 m), 2” (0.0508 m), and 4” (0.1016 m) augers to drill into the sand product. We estimate the friction angle of dry sand to
be approximately 30 degrees (Walashek, 2005), and cohesion of dry sand to be approximately 0.2 kPa (Tae-Hyung, 2005). A comparison of theoretical vs experimental torque is presented below.

Figure 3.11: Graphical Comparison between Experimental and Theoretical Torque

<table>
<thead>
<tr>
<th>Drill Diameter (m)</th>
<th>Exp. Max Torque (N-m)</th>
<th>Theo. Max Torque (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0254</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>0.0508</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>0.1016</td>
<td>4.2</td>
<td>9.9</td>
</tr>
</tbody>
</table>

These results are inconclusive in determining the validity of theoretical torque calculations. Experimentation with a larger range of augers with different diameters is required to achieve a more accurate experimental comparison. However, such an experiment was not possible for two reasons. Augers with diameters larger than 10 cm are too massive to drive with a 100 W power constraint. Also, we were unsuccessful in finding manufacturers that sold augers with smaller diameter graduations - i.e.: 1.25, 1.5, 1.75, 2 cm) Nevertheless, our theoretical torque calculations appear to accurately predicted values that are on the same order of magnitude as the experimental values for augers with diameters from 0.025 m to 0.055 m. Therefore we believe theoretical torque calculations can serve as a first-order predictive tool for augers with diameters less than 0.055m.

3.1.5 Summary of Excavator System Mass and Power Requirements

Based on experimental data, we find that a 1 inch (0.025 m) diameter minimizes system mass and excavation time. Therefore, we present a summary of mass and power requirements for an Excavation System with a 1 inch (0.025 m) diameter auger.

Table 3.4: Summary of Excavation System Mass and Power Requirements

<table>
<thead>
<tr>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.6</td>
<td>82.2</td>
</tr>
</tbody>
</table>
3.2 Regolith Delivery Mechanism

Once the Auger has collected 100 kg of regolith, the Excavation System requires a mechanism to transfer this regolith to experimental test chambers. We propose a sliding door mechanism to carry out this function. A diagram of the proposed Regolith Delivery Mechanism is shown in the figure below.

![Figure 3.12: Regolith Delivery System](image)

The Excavation Collection Bin discussed in Section 3.1.2 has a hole at the low point of the Bin. Our aim is to provide a mechanism to control the regolith mass flow out of this hole. To do this, we propose using a Bin Door with a hole the same size as the Collection Bin hole. When the two holes line up, regolith is gravity-fed from the Collection Bin into a test chamber (such as the ISOPS Furnace) at the maximum mass flow rate. When the two holes do not line up, regolith is contained in the Collection Bin. Partially overlapping holes allow continuous control of the regolith mass flow rate out of the Collection Bin.

The Bin Door is connected to a Partially Threaded Lead Screw; this Lead Screw is coupled to a motor shaft and is threaded through a stationary block. As the motor turns the Lead Screw, both the Lead Screw and Motor translate horizontally. This action actuates the motion of the Bin Door.

We contain the Motor, Linear Bearing, and Block inside the structure or enclosure of the rover to avoid exposing moving parts to the harmful effects of lunar regolith which may be disturbed during excavation. Both the Linear Bearing and the Block will need to be lubricated. Since wet
lubrication is not effective at 40ºK, dry lubrication should be used. Although dry lubricants have a short service life, these mechanisms are only expected to go through approximately ten cycles and this is within the bounds of dry lubricant service life. We estimate that these mechanisms will undergo about ten cycles because the ISOPS system requires 10 kg batches of regolith, resulting in the ten deliveries of regolith to the Furnace during the mission timeframe. There are several dry lubricants which will suffice for our system; sputter-deposited molybdenum disulfide is one such lubricant, as are exopy and polyamide-bonded films [Oswald, 2005].

We calculate the power required to operate the Regolith Delivery Mechanism by estimating the Motor output power required to actuate the Bin Door, and the power required to keep the Motor at 273K. To estimate the amount of power that the Motor must produce we must calculate the force to move the Regolith Delivery Mechanism and estimate the velocity as which we want it to translate. We calculate that 2W are required to translate the Bin Door assuming the following:

- the total mass of the Regolith Delivery Mechanism is approximately 1 kg,
- we want the Bin Door to accelerate at 1.0 m/s\(^2\) and translate at a maximum velocity of 0.1 m/s,
- our Motor has an efficiency of 0.5.

Based on dimensions of commercially available 2 W motors [Mcmaster, 2005], we estimate the volume of the heated motor housing to be an 0.13 m cube. Assuming the Motor is covered in 0.05 m thick MLI, we require less than 1 W to maintain 273 K.

3.3 Design of the Bulk Physical Characteristics Test Chamber

Based on previous analysis presented in the PDR, we have selected a Compression Chamber concept for the Bulk Physical Characteristics Test Chamber. In this section, we present the Compression Chamber design and describe laboratory testing we are currently in the process of conducting to identify subsystem requirements and optimize subsystem mass.

3.3.1 Compression Chamber Concept of Operation

The Compression Chamber, shown in the figure below, is based on an educational brief put out by NASA on the Mechanics of Granular Materials project. The module consists of a compressive piston, four feedback sensors (two displacement, two voltage), and a split rectangular chamber – one of which is connected to an actuator via a piston. The sample is loaded into the chamber and compressed. Compressibility data is gathered by recording the voltage applied to the actuator moving the compressive piston to achieve the desired displacement. From the voltage we have the required force for a given displacement- this defines the compressibility of a material.
After the compression cycle is completed, voltage applied to the shear actuator is slowly increased until there is a displacement in the along the shear line. When this displacement occurs the voltage is recorded and converted into a force value. The force required to cause a displacement along the shear line is the shear stress of the material.

By forming a data set consisting of varying compressions and their shear stresses, it would be possible to find the modulus, which predicts the shear stress for any displacement. For instance, if the plot turns out to be linear, we can predict the shear stress of any given compression by taking the slope of the line and using it as a transformation constant.

It is important to mention that there are several assumptions which impact the validity of the test chamber measurements. Measuring bulk physical characteristics in the manners proposed assumes that each individual particle of regolith acts in the same manner as an atom in a densely packed material. Under stress, yield occurs due to disruption of the theoretical particle assembly structure. Frictional reactions between individual particles can be correlated to atomistic bond interactions. Our system, however, will not act like a crystalline material until it has been compressed enough to assume a lattice structure. Another consideration is that our tests do not account for possible fracture of regolith particles under high stresses. In addition, the particles or regolith have to be spherical in structure to act like atoms and thus, incorporate the elements of the theoretical model. In theory, a complete analysis would require consideration of the specific structure of individual particles of regolith as well as other interparticle forces besides friction, such as electrostatics, which are not being included in our Bulk Physical Characteristics Test Chamber.

3.3.2 Laboratory Testing of the Compression Chamber

The objective of laboratory testing of the Compression Chamber is to quantify the following key design considerations:

1. What is the force of compression required to define the compressibility of regolith?
2. What is the force seen in the chamber walls during compression of the regolith? Although the chamber walls are not directly under compression, there is friction between the compressed regolith and chamber walls. Quantifying the force on the chamber walls is
necessary to optimize the chamber wall thickness, and therefore minimize subsystem mass.

3. What effect does the friction of the chamber along the shear line have on shear measurements? What effect does the friction between the test chamber and the surface the chamber rests on?

We are in the process of conducting several experiments on a laboratory prototype to quantitatively answer these questions. Experiments results and final Compression Chamber design will be discussed at the Final Presentation. Our compression chamber prototype is machined from brass, and is approximately 6 inches (0.15 m) by 3 inches (0.76 m) by 3 inches (0.76 m) with quarter inch (0.0064 m) thick walls. Our test material is JSC-1 lunar stimulant. The experiments we are conducting will enable us to make more informed decisions about material selection, size motors, understand lubrication requirements, and determine subsystem dimensions required to meet system mass and power constraints.

3.3.2.1 Experiment Procedure

The two identical halves of the chamber are placed on top of one another such that the brass block can be inserted cleanly into both pieces. The system is placed in an Instron Machine, an electromechanical test instrument, which is used to test a wide range of materials in tension or compression. This allows us to apply loads to our test piece and analyze the forces required for changes in the system. A load cell is affixed to the bottom portion of the chamber, driven by a motor connected to the cell with a screw shaft. Also, four strain gages are placed on the compression chamber, allowing us to record the deformation of the material and better understand the forces inside of the material.

We run our initial experiment without any regolith inside of the chamber. The two pieces are positioned on top of one another, and the load cell records the force required for an initial displacement of the bottom portion of the chamber. This measurement enables us to record the frictional forces that are present between the two pieces of the chamber, as well as the frictional forces that exist between the bottom chamber the surface of the Instron Machine.

After obtaining the values of the frictional force, the experiment is run again with the regolith simulant. The two chambers are placed on top of one another, and regolith is inserted inside of the chamber, filling up two-thirds of the system. The Instron machine applies a load to the block and records the force required to compress the regolith. After the regolith is compressed, we apply a lateral force to the system using a load cell, screw shaft, and motor. The load cell measures the force at which the regolith begins to shear.

3.3.2.2 Experiment Analysis

When external forces are applied to a stationary object, as in our experiment, stress and strain are induced. Stress is defined as the object's internal resistive force, which is a product of the material properties. For a uniform distribution of internal forces, stress can be calculated by dividing the force applied by the area of contact. Yield strength is the applied stress under which an object experiences plastic deformation. This should not occur in our experiment, as the yield strength for brass is very high and we are dealing with small displacements. The force required to cause displacement along the shear line is the shear stress of the material.
The strain gauges affixed to the test chamber allow us to convert the load in the test chamber walls into electrical signals. Four strain gages are used to obtain maximum sensitivity and allow for temperature compensation. Two of the gauges are in tension, and two are in compression. When weight is applied, the strain changes the electrical resistance of the gauges in proportion to the load. This will enable us to record the forces in the chamber walls throughout our experiment for a variety of displacements. This allows us to choose chamber wall material, calculate minimum allowable wall thickness and therefore minimize subsystem mass.

By forming a data set consisting of varying compression forces and their associated shear stresses with and without regolith we can determine if the shear stress if the material is greater than or less than the friction inherent in the system. If friction inherent in the system is greater than the shear stress of regolith, our system requires lubrication. Once we have established that the friction inherent in the system is less than the shear stress of the regolith, we can find the modulus of the material which predicts the shear stress for any displacement.

3.3.2.3 Estimated Mass and Power Requirements for Compression Chamber

Although we do not yet have experimental data to finalize the Compression Chamber mass and power requirements, we can place a bound on these parameters by estimating the system mass and power available after specifying ISOPS and Excavation Designs.

The Compression Chamber may weight up to 7.8 kg in order for the overall system design to meet a 50 kg constraint. Also the Compression Chamber may operate during Furnace Processing and draw up to 22.7 W.
4. MISSION CONCEPT OF OPERATIONS

Mission operations consist of robotic operations on the Moon and ground operations on the Earth. Lunar operations include excavating and processing regolith, and are divided into 3 phases: Initialization, Excavation, and Processing. In the following sections, we develop each of these phases. Ground operations runs throughout the duration of the mission and are addressed for each mission phase.

4.1 Initialization Phase

Once the rover is landed on the lunar surface and positioned in a permanently shadowed crater, the Initialization Phase of operations is initiated by ground control. The Initialization Phase includes system checkout and calibration of sensors. Once the robotic lander is situated in the permanently shadowed crater, it will spend up 60 hours testing the communications, power, and excavation and processing systems. First it will automatically verify and report to ground control that the controls and regulation sensors associated with the ISOP System are showing nominal pre-processing states. This includes verifying that the Radiator, Electrolysis, Hydrogen Recycling and Oxygen Storage Tank Subsystems are being maintained at the appropriate temperature and pressure. Then the lander will automatically verify and report to ground control that the excavation system is in the pre-deployed configuration through the Excavator System’s position sensors.

Next, ground control will initiate a test of the processing systems. The lander will then automatically run through one processing cycle without regolith loaded in the furnace (this takes 49 hours of the 60 hours allotted to the Initialization Phase). The furnace will heat up to processing temperature, and the electrolyzer subsystem will warm to operating temperature. Next, ground control will initiate a test of the hydrogen recycling system and verify nominal pressure readings through the ISOPS system. During this test of the processing system, the system will automatically calibrate its sensors. Finally, ground control will initiate a test of the Excavation System by actuating all motors and ensuring proper functioning. The test will end with the Excavation System in the pre-deployed position so that the lander is capable of maneuvering to characterize the landing site.

4.2 Excavation Phase

After initialization, preparations begin to spend the next 20 hours excavating 100 kilograms of regolith. First, the lunar lander must characterize the landing area. One ground operator will specialize in controlling the lander mobility and visualization functions to carry out this task. This may include taking 360-degree panoramic photographs. From these photographs, ground support will document ten to twenty-five potential excavation areas which are not likely to impede the functioning of the Auger. Ground support must then path plan to detail how the lander will traverse from one drilling site to the next.

Ground control provides commands to the lander to traverse to the first drilling site and initiate peck-drilling. Once at a drilling site, excavation proceeds automatically with ground support monitoring. In the event the lander detects any anomalies, the lander stops excavating and waits for instructions from ground control. During excavation, a sensor monitors the torque applied to the auger shaft and adjusts the forces exerted on the auger accordingly. The torque feedback is
crucial to avoid damaging the Auger on rocks. Regolith is broken up by the auger end, travels up the flute, and is deposited in the Collection Bin. Once the Auger has either excavated regolith to a depth of one meter or is impeded by rock, the Auger retreats to the pre-deployment configuration. Ground control then provides the lander commands to traverse to the next drill site, and the process repeats. The lander continues excavating sites until either 100 kg of regolith has been collected or 35 hours have elapsed. Unimpeded excavation would require less than 5 hours. However, by allotting a maximum of 40 hours to excavation, we provide a buffer for unforeseen circumstances during excavation as well as processing.

4.3 Processing Phase

Once the Excavation Phase has ended, ground control commands the lander begins to process the regolith it has collected. Processing then proceeds automatically with ground support monitoring. In the event the lander detects any anomalies during processing, the lander reverts to pre-processing states and waits for instructions from ground control. The Processing Phase is expected to last 504 hours but may take as long as 557 hours, the rest of the mission timeframe. First, a small amount of regolith from the Collection Bin is released into the Compression Chamber to measure bulk physical characteristics. Ten kilograms of regolith is then delivered to the Furnace and heating is initiated. The regolith is heated to drive off any existing water, and the water-ice content of a sample is measured as the change in mass of the regolith. Then, hydrogen flow and recycling is initiated. The regolith is reduced using hydrogen, and oxygen yield is measured as the additional change in mass of the regolith. The water vapor is then condensed. Once the entire first batch has been processed, Furnace heating shuts off and the electrolyzer begins operating. Oxygen is collected in the Oxygen Storage Tank.

As the water from the first batch is being electrolyzed, another small amount of regolith from the Collection Bin is released into the Compression Chamber to measure bulk physical characteristics. Then the second batch of regolith is loaded in the Furnace and heating is initiated. From this time forward, heating/processing and electrolysis happen concurrently. This processing cycle continues until all 100 kg of regolith in the Collection Bin have been processed.
5. OUTREACH REPORT

The student team participating in the ISRU University Design Competition is part of the LunarDREEM project, an ongoing student-initiated research endeavor at MIT devoted to advancing the cause of space exploration through the use of extraterrestrial resources. Even before the announcement of the 2004-05 NASA ISRU competition, LunarDREEM members were working on lunar ISRU research and sharing the excitement of this work. The team has continued to enthusiastically share project work with scientific, engineering, and public communities. In this report, we describe team outreach activities for the 2004-2005 academic year.

Conference Activities
Student team members participating in the ISRU Design Competition presented an outreach poster at the SpaceVision2004 Conference held at MIT from 11-14 November. This was the first poster session many students on the team had participated in, and this experience generated a lot of excitement among team members. The team presented the design competition challenge, design options for a lunar oxygen production system and excavator system. They also presented and gained useful feedback on the trade study methodology that was ultimately applied to the Competition Proposal. This was the team’s first opportunity to gain feedback on their work towards the ISRU proposal, and we greatly appreciated positive feedback from space-enthusiasts in government, industry, and academia; students attending the conference also showed a great deal of enthusiasm for the competition work.

Three team members also attended the 1st Space Exploration Conference, held in Orlando, Florida from 30 January – 1 February. The MIT team conference attendees were proud to present a paper describing their summer work related to lunar ISRU. They were also honored to be formally recognized as ISRU Design Competition finalists. This experience provided team members an opportunity to discuss their progress on the design competition with other competition teams and members of the space community, and raise interest and support for lunar ISRU activities.

1st Space Exploration Conference: Meeting members of the different ISRU competition teams
Classroom Activities
The MIT student team has been particularly excited about sharing our experiences with elementary and middle school students. Once the MIT team learned that their proposal had been accepted, they initiated discussions with Cambridge public schools to organize a classroom outreach program. During January and February the team worked very closely with the Haggerty Elementary School to develop an outreach presentation for 4th, 5th, and 6th graders. Team members met with school teachers three times to develop, review, and practice a one-hour presentation that complemented science curricula and helped to prepare students for their end of the year standardized exams. Team members then made two separate trips to the Haggerty School to present to the 4th, 5th, and 6th grade classes.

The team developed a powerpoint and activity-based presentation describing the scientific case for ice at the poles of the moon that complemented the Sun and Shadows curriculum for the 4th, 5th, and 6th grade classes. The presentation involved hands-on classroom activities, handouts, and an assessment of the material presented. The learning objectives for the presentation were:

- Impart an intuitive understanding for why permanently shadowed craters may exist (Sun and Shadows) at the poles of the Moon through powerpoint graphics and hands on demonstration and activities.
- Impart an understanding of the important role models play in investigating whether permanently shadowed craters exist.
- Provide an intuitive reference for understanding how cold the temperature in a permanently shadowed crater is (40K) through the use of temperature scales to show: a hot day, a cool day, a snowy day, the temperature of dry ice, the temperature in a permanently shadowed crater. A demonstration with dry ice emphasized this learning objective.
- Discuss evidence of lunar ice returned from the Clementine spacecraft and Lunar Prospector spacecraft. Impart an understanding that this evidence is not “proof”, only “supporting evidence.”
- Provide motivation for why ice on the moon is a big deal, and generate interest in sending humans to the Moon and Mars.

Three team members visited delivered the presentation. The powerpoint/activity-based segment lasted approximately 40 minutes. MIT students then spent 20 minutes with the students for a question/answer session and free time to do the activities again in smaller groups.
After the presentation, the MIT team created a homework assignment for the students to review and discuss what they had learned in the presentation. The team felt that the presentation was well received and thoroughly enjoyed the experience. A note from the Haggerty School is attached at the end of the Outreach Report. Recently, the MIT team has received an invitation from the Tobin Middle School to give this presentation to 7th and 8th grade classes and is in the process of coordinating with Tobin School teachers.

**Webpage**

The team has given a great deal of consideration to how to maximize the outreach impact of our webpage, and has one team member devoted to its implementation. The MIT LunarDREEM Team website was created to share the information, ideas, and passions of the team with the student community. The website also helps extend to the community through three links that direct students to material appropriate for different age groups: K-8, 9-12, and university-level students. In coming weeks before the final presentation, this website will be publicized on the MIT Aero/Astro homepage, and in the Aero/Astro Department Electronic Newsletter. Our website can be found at: [http://web.mit.edu/activity/m/mitseds/LunarDREEM/index.html](http://web.mit.edu/activity/m/mitseds/LunarDREEM/index.html),

In this section, we describe the design and implementation of this website.

The website was made through use of the program MacroMedia Dreamweaver MX 2004. This formidable program allowed the team the flexibility and complexity to build an appealing, easy to navigate site complete with professional-quality features. The majority of pictures found on the website are NASA in origin, and all pictures found on the site are free from copyright. A picture taken during an Apollo mission is utilized to provide the header picture. Photoshop 7.0 was also heavily utilized to provide the graphics found on the webpage, as well as help with any modifications made to existing pictures. A series of filters were used to give the abstract moon found in the background. All buttons were made from scratch, as were the backgrounds.

The navigation bar found on the left provides a natural method of transportation throughout the website. The buttons found are Competition, Team, Design, Community, Grades K-8, Grades 9-12, University, Files, Links, and Webmaster. The navigation bar is found on all pages.
The home page, which can be navigated to by clicking on the header graphic, will welcome visitors to the MIT LunarDREEM Team website. Brief explanations of some of the features and highlights found on the website will be provided for first time users. On the right side will be a bar providing “quick links” to other places of interest, and more relevant information that may interest visitors.

The Competition page explains in short the competition, the time-frame, and the sponsors. The importance of the work is also discussed and its relevancy to the new focus of returning to the Moon and extending outwards to Mars is presented as well.

The Team link describes the team and the history of the LunarDREEM group. The list of student team members, supporting faculty, and advisors are listed at the bottom, with contact information for the team leader Julie Arnold and supervising faculty member Jeffrey Hoffman.

The Design page provides a short description of the lunar rover and the specifications of its mission and goals. A brief description of our design is provided at a general level. More detailed descriptions of the design can be found in the community pages, and in the downloadable files throughout the website.

The Community page details the past activities and future plans of the student team in extending into the community.

The Grade K-8, 9-12, and University pages are designed to provide links to material appropriate for the respective age groups. The Grade K-8 page contains two main features. One is a general purpose PowerPoint presentation created specifically for visitors to the webpage, and the other is a link to a previous presentation given to the Haggerty Elementary School on March 26th. There are a number of reasons for using PowerPoint presentations as the method of delivery, instead of a linear progression of web pages. Mainly, a PowerPoint presentation will provide a clean, concise, and uncluttered form to learn from. Teachers can access the webpage and download the relevant presentations, save them to disk, and show them to their students through whatever method they see best. Teachers can also modify the presentation to target the specific level of the class, or to target specific lessons. In short, PowerPoint presentations provide a flexibility to help students learn material that a progression of web pages is not able to provide.

Materials for elementary and middle school students consist of qualitative, high-level descriptions that help put ISRU in a bigger context. Descriptions of the lunar robot and mission will also be provided at a level that is easy to understand. The “Grade 9-12” and “University” pages are very similar to the “Grade K-8” page, but provide information that is more technical and exploring the details of the competition and the design not provided in the pages “Competition” and “Design.”
The “Files” page contains a listing of all the files that can be downloaded off of the webpage. Under each file is a short description, a listing of the file type, and its file size. Some of the files included are the team’s proposal, the Preliminary Design Report, and in time, the Detailed Design Report.

The “Links” page contains a listing of all relevant links that visitors may be find interesting. The links provide further information on the competition and the sponsors, sites for more information about space exploration and the moon, community sites, and links to learn more about the Massachusetts Institute of Technology and some of its departments.

The “Webmaster” page provides contact information to the maintainer of the site, as well as further bibliographic information.

The different divisions on each page are made through the use of “layers” (as opposed to tables). This allows the overlaying of different layers for atheistic effects. The trade-off is that older browsers may render layers with only varying success. The website has been tested on Safari v1.3, Internet Explorer v5.2, Netscape Explorer 7.0, and Opera 6.03, and FireFox v1.0, on both Macintosh, Windows OS, and Linux computers. Cascading Style Sheets (CSS) are used to define the styles and attributes of the various texts and divisions on the site. This allows the website to be consistent between pages, despite small changes that are made throughout development. However, CSS is a relatively new feature support, that may lead to varying results between browsers. According to Dreamweaver’s browser error checks, the only conflicts that arise are in the use of Netscape Navigator 4.0. However, it is believed that layers and CSS have been around long enough that it can be safely assumed that any viewers will have no difficulties in viewing the website, meaning the trade-offs in the use of layers and CSS is appropriate.
May 4, 2005

To Whom It May Concern:

The Lunar Dream team came to the Haggerty School in March and April, and gave their presentation to 4th, 5th, and 6th graders. Although this is a wide age span, all the classes loved the presentation, and talked about it for some time afterward. They were intrigued by the possibility of there being ice on the moon, and enthusiastic about the plans for the mission to find out.

Students wrote about their impressions, and appeared to have retained quite a lot of information from the presentation, which included a power point show, demonstrations, and an activity for the students in which they used flashlights and egg cartons, and saw how craters could be in perpetual shadow.

The presentation was well done, balanced between talking, pictures, and activities, and included interactive discussions with the students. It was organized beautifully.

We all wish the students luck with their project, and hope that it will eventually end up on the Moon!

Sincerely,

Deyne Meadow

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