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Ammonia/Water Thermodynamic Cycle For Lunar Power Applications

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AMMONIA/WATER THERMODYNAMIC CYCLE FOR LUNAR POWER APPLICATIONS

by

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DEDICATION

To Bridgett, my amazing wife, who has made it possible for me to finally complete this work and to Chloe, my incredible daughter, who has unlimited potential and is already making her mark upon the world.

ABSTRACT

For long-term presence on the lunar surface, a reliable and efficient power source is required. A novel thermodynamic bottoming cycle which utilizes ammonia and water—the Kalina Cycle—is evaluated for use on the lunar surface. Terrestrial utilization of the Kalina Cycle shows higher efficiencies at lower temperatures and more compact packaging when compared to some other solar-powered systems. The research question is, "Can an ammonia-water thermodynamic cycle have benefits over other proposed power generation schemes on the lunar surface?" To analyze this question, an analysis of alternatives is performed which evaluates the Kalina Cycle against previously analyzed lunar power systems. Eight steps based on the Simple Multi-attribute Rating Technique (SMART) are taken leveraging requirements development of standard space systems engineering processes. The results of this analysis have six top level functional requirements with associate performance requirements. In addition to the functional, performance, and human factor requirements, ten operational scenario variants give the bounding scenarios for which system architectures can be compared. Using the requirements, candidate ammonia-waterer thermodynamic architectures for the task of providing power for a growing lunar base are developed and analyzed. The candidate architectures thermodynamic size and efficiencies are modeled using Engineering Equation Solver (EES) and Microsoft Excel. The data developed from the thermodynamic analysis provide the economic analysis data to use for comparison. The candidate system's mass at launch, component expenses, life cycle costs, reliability, and monetary impacts of power production expansion are compared. The study determined that a

Kalina cycle can provide some economic benefit in select situations and scenarios. A Kalina cycle system has lower estimated launch costs than a photovoltaic system for medium size bases at the lunar equator, but not at the lunar pole. Compared to a Brayton cycle, a Kalina cycle requires a smaller thermal heat sink due to higher system thermodynamic efficiencies across a variety of operating temperatures. A smaller heat sink equals lower launch and equipment costs. A nuclear-powered thermodynamic system has lower costs for medium and large size power demands. The benefit that a Kalina-cycle system has over a nuclear-powered system is heat source life and safety. A nuclear-powered system only lasts 12-15 years before needing a new nuclear core. If a base has a lifespan which lasts decades, the estimated launch costs mount for nuclear systems. In summary, an ammonia-water thermodynamic power scores higher than competing systems in select scenarios at the lunar equator, not the lunar pole.

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CHAPTER 1
INTRODUCTION

1.1 Overview and Purpose

1.1.1 Overview

The creation of a permanent manned lunar base presents a unique and difficult challenge requiring a wide range of planetary and space technologies. For any type of long-term presence on the lunar surface, one will need to have a reliable and efficient power source. An efficient power source is a pacing technology required by a lunar outpost for life support systems, productivity, and science (Brinker & Flood, 1988). Due to the projected evolutionary nature of lunar missions, the power requirements developed for a lunar mission are mission dependent and vary over time. The varying requirements lead mission architects to build expandability and flexibility into the system designs. One should understand that properly designed and developed power system technologies will lead to the utilization of lunar resources—which allow for more ambitious projects, e.g., construction of lunar science facilities such as telescope facilities on the farside of the Moon, and many other operational activities on the lunar surface. The lunar surface is a very unique environment. Any power system supporting a continuously manned site has to be designed and tested with the ability to sustain operations through the lunar day and night—whose length is dependent on the lunar site location.

A novel bottoming cycle has been identified which utilizes ammonia and water. This process has not been analyzed previously as a potential lunar power source. There are several advantages on Earth for the use of this type of power generation cycle such as higher efficiencies at low and variable temperatures and compact packaging as compared to photovoltaic systems. Fully understanding whether there are any potential advantages to utilizing an ammonia-water thermodynamic power cycle on the lunar surface is one step toward furthering humanity's understanding of how best to harness the unique lunar environment.

1.1.2 Purpose and Statement of the Problem

For many years, there have been discussions of opening up new frontiers of space to colonization and industrial operations. Proposals have ranged from large orbiting habitats to lunar bases to large Martian bases to living on Saturn's moon, Titan (Wohlforth & Hendrix, 2016). Each of these locations will require some type of power to either run life support systems or conduct industrial operations. Due to the wide variety of inputs from different non-terrestrial environments, this research chooses one of the potential operating scenarios to analyze environmental issues related to power generation. Due to its close proximity to Earth and stable environment, the lunar surface was chosen as the operational scenario to analyze. The high-level research question is, "Can an ammonia-water thermodynamic cycle have benefits over other proposed power generation schemes on the lunar surface?" To answer the resulting research question thoroughly, several technical and policy areas need to be reviewed. The high-level steps are outlined in the upcoming section 1.3, Organization of the Text.

1.2 Background

A brief background on previously analyzed power generation schemes and associated public policy issues are outlined to frame the research question. The data provided here are leveraged in several of the following analysis chapters.

1.2.1 Available Lunar Power Schemes

First, what type of power generation schemes are available to utilize on the lunar surface? There are three major types of power generation schemes which can be considered for powering a lunar base or lunar industrial operations: photovoltaic, nuclear-powered thermodynamic, and sun-powered thermodynamic. Sun-powered thermodynamic includes the power system central to the research question.

The first power scheme is photovoltaic. This type of power is what the average individual will associate with space power. Generally, it consists of solar panel arrays, electrical support equipment, such as power inverters, and a power storage system, such as batteries or water/hydrogen/oxygen fuel cells. Researchers view the utilization of photovoltaic as initially viable, but eventually a nuclear-powered Brayton cycle is preferable for any sizeable lunar base (Hickman & Bloomfield, 1989). An artist conception of a lunar solar array is shown in Figure 1.

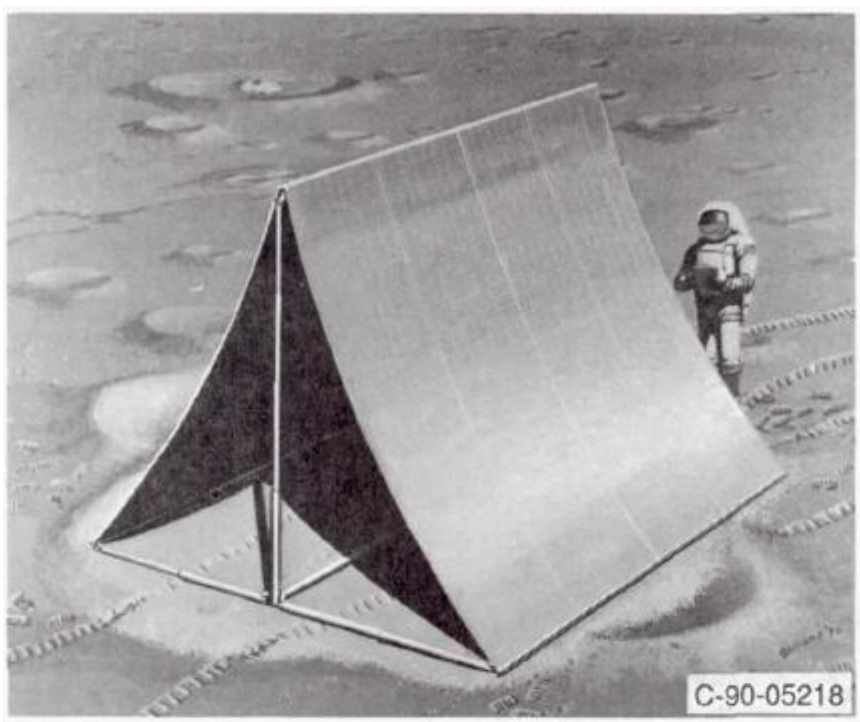

Figure 1: Photovoltaic Power System on Lunar surface (Hickman et al., 1990)

A photovoltaic system is simpler than the other types of power generation systems. The most visible part of the system is the solar panels. The location and emplacement of the panels is labor intensive and should be considered carefully. Lunar base architects have to consider how the panels may impact current and future scientifically significant features of the lunar surface. Will the panels require digging to anchor them or will they be placed in the surface? Emplacement on the surface would be least intrusive to the surface environment. Battery selection will prove important in determining what type of containment system is required. A determination of the leakage potential of the batteries needs to be resolved. If the batteries have the potential to leak, then a liquid containment system needs to be installed prior to operation. Fuel cells utilize hydrogen and oxygen instead of acids or other solid-state power storage systems. This does not mean fuel cells do not need consideration from an environmental standpoint. The biggest issue on the lunar surface with fuel cells center on the potential explosion issue. Hydrogen and oxygen are known to be explosive if stored improperly. An explosion could damage equipment, injure or kill humans, and cause other leaks or environmental degradation issues. Architects need to consider remediation with a solar panel system especially when it comes to end-of-life issues. How will used equipment be disposed of? Can the old used equipment be recycled and is there need for some type of landfill on the lunar surface? The conservation of resources is the easiest issue to mitigate with the photovoltaic system. Since the only process consumable is sunlight, a photovoltaic power system is very much a conserver of lunar resources (Gunerhan, Hepbasli, & Giresunlu, 2008).

The second type of power generation, as shown in Figures 2 and 3, is a nuclear-powered thermodynamic cycle. This type of power generation consists of a nuclear fission reactor which generates heat, a working fluid to be heated in a boiler, a turbine to convert heat energy to rotational energy, a generator which turns rotational energy into electricity, a radiator which rejects waste heat, and a variety of pumps, heat exchangers, and other supporting mechanical devices. Nuclear power systems can come in a variety of sizes and power outputs. Kilopower Reactor Using Stirling TechnologY (KRUSTY)—shown in Figure 2—can be scaled from 1-10 kWe (Gibson et al., 2018). The SP-100 model shown in Figure 3 was sized for 100 kWe and 550 kWe (Mason, Rodriguez, McKissock, Hanlon, & Mansfield, 1992).

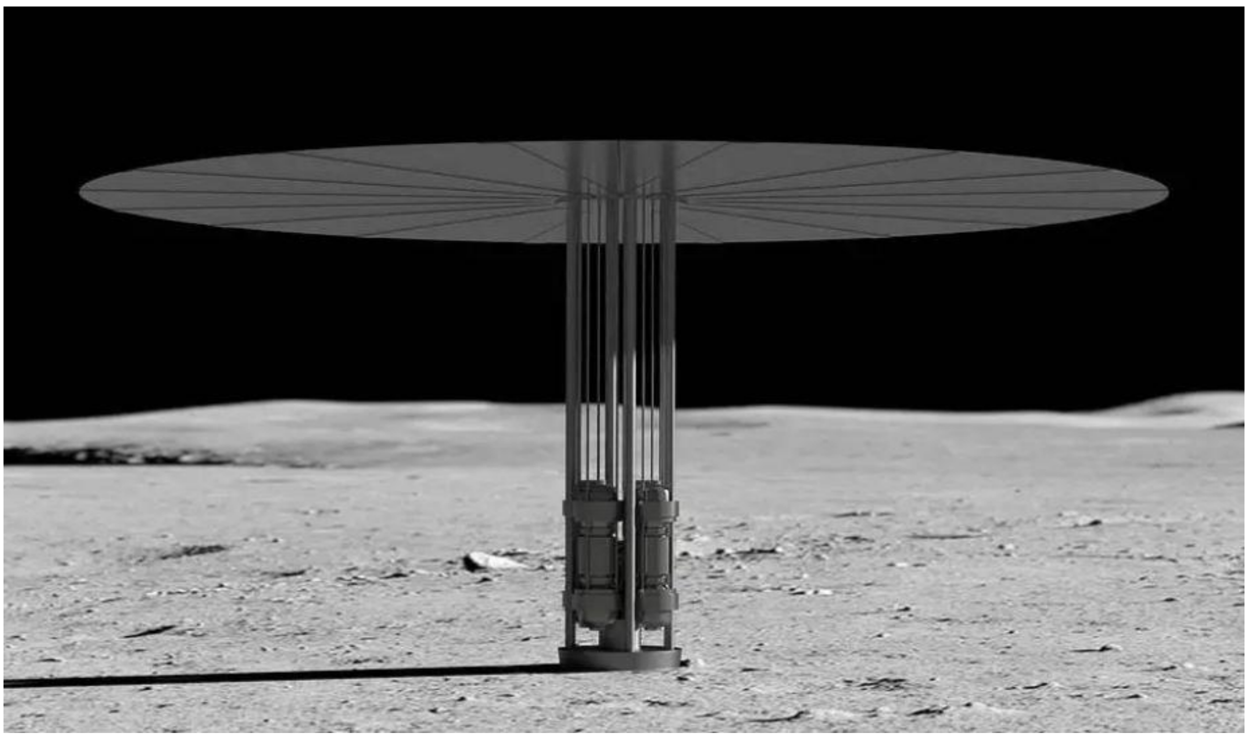

Figure 2: Artist Conception of KRUSTY on the Lunar Surface (Gibson, 2018)

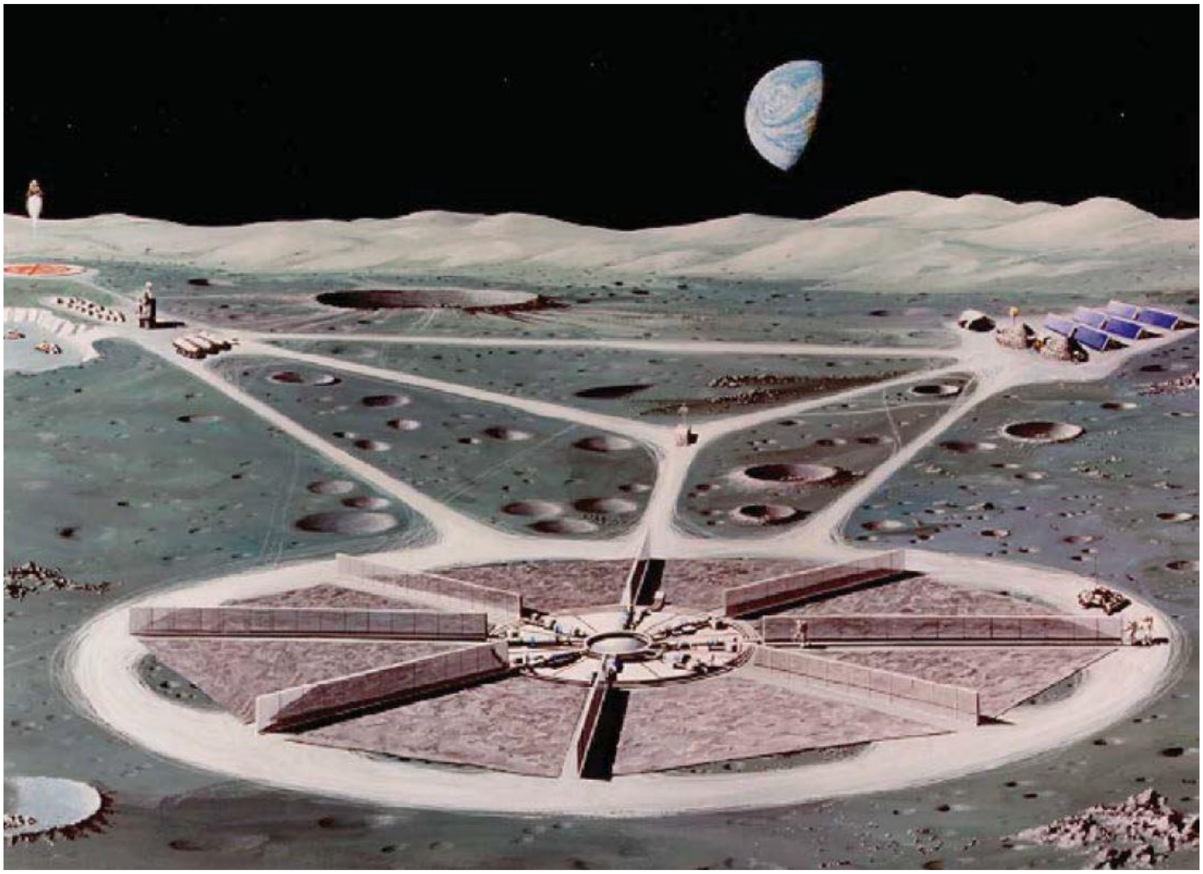

Figure 3: Artist Conception of SP-100 Nuclear Reactor on the Lunar Surface (Mason, 2013)

Nuclear systems are compact and efficient but are not without faults. The emplacement of a nuclear-powered thermodynamic system is much more invasive to the local geology than photovoltaic systems. The footprint is much smaller but the system requires burying to insulate human habitats and any industrial operations from nuclear radiation and to protect the system from potentially fatal micrometeorite impact damage. The result will include irradiated soil around the nuclear reactor site and disturbed/excavated soil from the reactor site. Much analysis was conducted on NASA's SP-100 system related to nuclear generated power on the lunar surface. As shown in Figure 4, a 2.5 MWt SP-100 type reactor requires a 1.5 m diameter by 3.5 m deep hole (Harty & Durand, 1993).

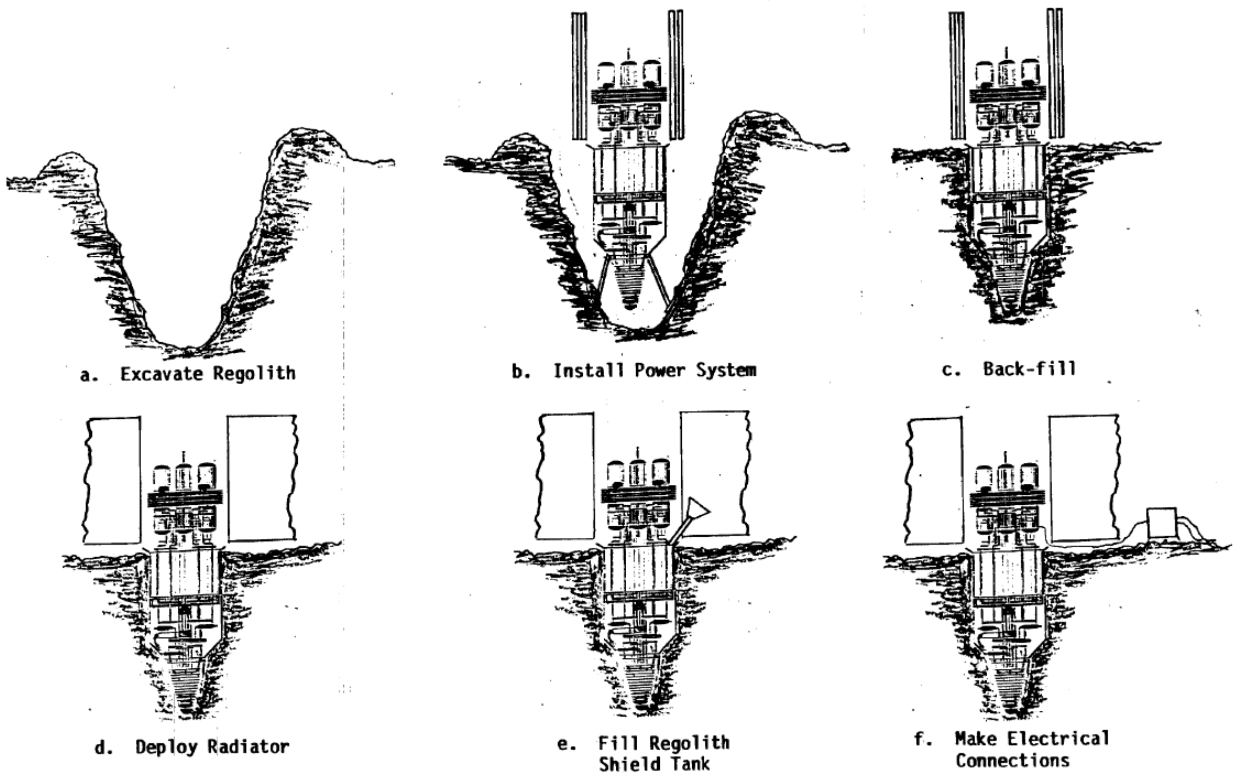

Figure 4: Typical Reactor Emplacement (Harty & Durand, 1993)

To create this hole, Harty and Durand (1993) recommend excavating the hole by explosives. The buried SP-100 will result in 5 rem of radiation at 7 m from reactor centerline during a 6 month period (Mason et al., 1992). As a reference, the US Nuclear Regulatory Commission (2017) says the average American receives 0.62 rem per year or 0.31 rem every 6 months. Astronauts are allowed 100-400 rem in their career depending on age and sex (Russo et al., 2007). Mason et al. (1992) recommend that the nuclear power system be located up to 1 km away from any other systems. This will necessitate buried power lines which will impact the environment with the required trenching. The burying will reduce electromagnetic impact from solar and galactic cosmic radiation. Leakage of working fluid may contaminate the local environment. If leakage occurs in buried pipes or pipes above ground which carry the working fluid, the local environment may or may not be permanently altered from its natural state. In the vacuum environment, much of the fluid may instantly freeze, sublimate, or evaporate. In other words, the material will dissipate to space. The gravity of the Moon is not strong enough to hold a substantial atmosphere due to low escape velocity (2.38 km/s). In addition to low escape velocity, solar wind ionization will carry away gas molecules from the surface of the moon (Heiken, Vaniman & French, 1991).

Remediation from nuclear radiation on the lunar surface may be tricky. There has not been any analysis on the difference between soil irradiated from a man-made nuclear device as compared to the radiation that the lunar surface receives naturally from the Sun and galactic cosmic radiation. According to NASA, the Apollo 14 astronauts received an average of 1.14 rem over a 9-day mission on the lunar surface. This works out to be 22.80 rem over a 6-month period (Rask, Vercoutere, Navarro & Krause, 2008). The amount of radiation that the lunar regolith receives from the reactor does not appear to be more than what the top of the lunar surface receives naturally. Since nuclear power does not directly consume any local material such as ground water or coal, the issue of conservation of resources does not strongly apply with this system. The system may need additional working fluids and repair parts. Other than those two items, the system will be sustainable for the life of the nuclear fission material.

The third type of power generation, as shown in Figure 5, is sun-powered thermodynamic. This type of power generation is similar to a nuclear-powered thermodynamic system; however, the heat source is the Sun and there may be need for a heat storage system. A heat storage system allows power to be generated during the lunar night. This type of generation scheme consists of a solar concentrator such as a parabolic mirror or trough to capture the Sun's heat energy, a working fluid to be heated in a boiler, a turbine to convert heat energy to rotational energy, a generator to turn rotational energy into electricity, a radiator to reject waste heat, a variety of pumps, heat exchangers, and other supporting mechanical devices, and a thermal heat storage system. As with the nuclear-powered system, the issue of containment of potential working fluid remains. The big additional issue resulting from the utilization of the sun as the heat source for a lunar thermodynamic cycle is the utilization of thermal heat storage (Barna & Johnson 1968).

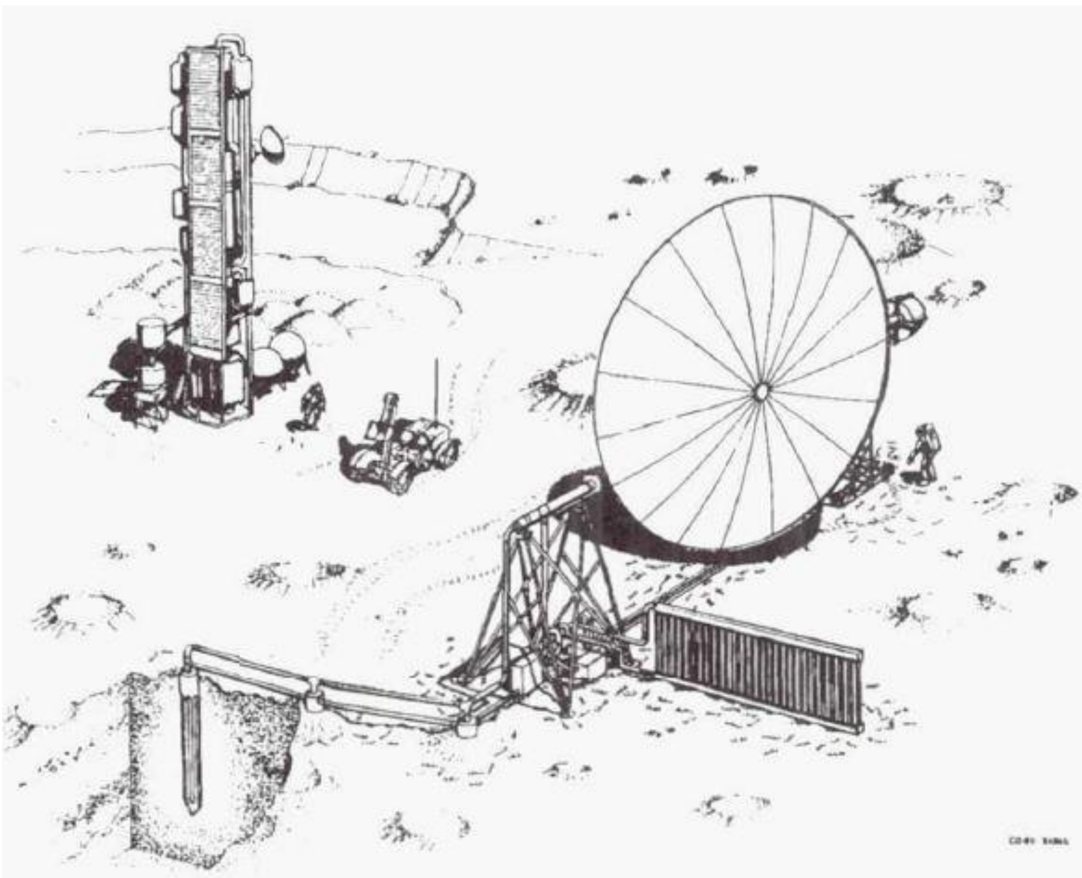

Figure 5: Artist Conception of a Sun powered Thermodynamic System on the Lunar Surface (Richter, 1993)

Unless batteries or fuel cells are utilized—as with a photovoltaic system—a thermal heat storage system is necessary for continual power production. Several types of thermal heat storage have been proposed over the years. Heat storage utilizing lunar surface material as a heat storage device has been looked at as far back as 1968 (Barna & Johnson, 1968). Initially, utilization of lunar surface regolith to store latent heat was not looked upon favorably. However, more recent researchers suggested storing heat as sensible heat in lunar regolith (Colozza, 1991). Although there are advantages to using lunar regolith to store heat, e.g., not needing to transport heat storage mass, there are other materials used on Earth which have better properties. Before 1980, the U.S. Department of Energy (DOE) had analyzed molten salts as thermal storage related to energy generation. Petri, Claar, and Ong (1983) analyzed high-temperature molten salt thermal storage systems for solar applications. The DOE study determined that molten salts were a prime candidate for thermal heat storage. Why does this matter? First, the utilization of lunar regolith as a heat storage device would mean that regolith would constantly be melted and solidified during the heat storage process—thermal storage and regolith properties are covered in chapter 7, specifically . 7.4.1.1.2 Thermal Storage (TS). This could impact the local geology and alter the local environment. With a molten salt heat storage system, the problem would be similar with other liquid systems on the lunar surface. If there is a leak, then how will it be contained?

The previous two types of power schemes—nuclear and solar—are thermodynamic in nature. Thermodynamic or dynamic systems are systems which convert heat input into a mechanical work. There are many ways—known as “cycles”—thermal energy is converted to mechanical motion. Common power cycles evaluated for use in space are Stirling, Rankine, and Brayton (Mason, 1999). The Kalina cycle is a variation of the Rankine Cycle. Toro and Lior (2017) analyzed and compared solar heat driven Stirling, Brayton, and Rankine cycles for space power applications. There are tradeoffs for each of the systems. The Brayton cycle has been developed by NASA due to its compact size and high efficiency (Mason, 1999). Toro and Lior

(2017) found the thermal efficiency of a regenerative-reheated-intercooled Brayton cycle to be the best between the Brayton, Stirling, and Rankine cycles. However, efficiency does not tell the entire story. As with all space systems, mass is a very important system aspect. Highly efficient systems often have large heat rejection systems. Toro and Lior (2017) found the power to radiator area ratio to increase with the introduction of reheating for both the Rankine and Brayton cycles. They also found Stirling cycles to have lower efficiencies than Brayton and Rankine; however, Stirling cycles' power to radiator area ratio is about half of those obtained by Brayton cycles and higher than those obtained by Rankine cycles.

1.2.2 Policy

It is important to understand how space policy and law impact lunar power system design. Analyzing policy allows one to understand whether there are any advantages—policy-wise—for utilizing a sun-powered ammonia-water power cycle instead of photovoltaic, nuclear-powered Brayton or Rankin cycle, or sun-powered Brayton or Rankin cycles.

A power production system which powers any terrestrial industrial operation has an impact on its local environment. Impact on its local environment means changing the physical properties of the local environment to something different than what it was prior to an industrial operation. Terrestrial power does impact local environments. One example is coal power which outputs carbon dioxide emissions, requires local ground water input, and discharges heated water and other chemicals into local aquifers. Another example is sun-powered "towers of power" which are known to kill birds by catching them on fire (Ho, 2016). The physical lunar environment is much different than its terrestrial counterpart. The lunar environment has extreme temperature fluctuations, gravity which is 1/6 of the Earth's, virtually zero atmosphere, ionizing radiation, micrometeoroid bombardment, electrostatically charged lunar dust, and unusual lighting conditions (Heiken et al., 1991). The lunar operating environment introduces factors which influence how a power system will be designed, built, and operated. Several subcategories exist under each type of power generation scheme, but the three overarching categories will provide a basis for policy analysis as it relates to the lunar environment.

Historically, proposed terrestrial environmental policies can be divided into several different areas. The first area is called anthropocentric environmentalism. This type of environmentalism views non-human creatures and objects with value only to the extent that human's value them. The second area is called ecocentric environmentalism. This type of environmentalism views the environment itself as having intrinsic value and humans have value only to the extent that we play a role and support the environment as a whole (Flournoy, 2003).

These two views have influenced the current calls and analysis associated with cosmocentric environmentalism or astroenvironmentalism (Bohlmann, 2003; Miller, 2001). As with historical terrestrial environmental policy discussions, there are two different approaches to space environmental policy creation. There are anthropocentric space environmentalists and ecocentric space environmentalist. An ecocentric view of space environmentalism views celestial bodies as pristine wildernesses that need to be protected instead of conquered (Miller, 2001). Some anthropocentric space environmentalists view the environment of space as being so bad in its natural state that it cannot get much worse in view of human value and, therefore, anything goes (Huebert & Block, 2007). Extreme ecocentric space environmentalist would say that any touching or altering of the pristine space environment is unacceptable. On the other hand, laissez faire anthropocentric space environmentalist say that the space environment cannot get any worse than it already is from a human point of view. If the environment cannot get any more toxic, then there is no point in controlling what happens to the local environment of any space operation (Huebert & Block, 2007). Understanding the differing approaches to policy ties into why space laws are enacted which feed requirements for a lunar power system. Space law and policy broken down further and analyzed in reference to lunar surface power in the Chapter 5 and Appendix 1 of this dissertation.

1.3 Text Organization

To analyze the research question, several areas need to be developed in depth. An eight-step analysis of alternatives is conducted. Eight steps based on the Simple Multi-attribute Rating Technique (SMART) are taken leveraging requirements development of standard space systems engineering processes (Edwards, 1971). First, a baseline of requirements which drive lunar power system design is needed. The requirement development process builds on customer needs. Lunar physical environment, lunar location, space law and policy, and lunar environmental impacts are considered during the requirements development process. Building on the requirements, an ammonia-water thermodynamic cycle design is selected. Previously analyzed thermodynamic, nuclear, and photovoltaic architectures are also identified for comparison. Third, a thermodynamic study of the ammonia-water thermodynamic cycle is conducted which allows the mass and volume of the system to be developed. The system efficiency can be studied by looking at the thermodynamic entropy and exergy efficiency from which the required solar concentrator area, radiator area, and thermal storage sizing are determined. These equations of efficiency and mass sizing are modeled using the Engineering Equation Solver (EES), as well as Microsoft Excel Spreadsheets. Pre-developed, as well as custom, programing for determination of efficiencies is required within these programs. Results show numerical efficiencies of the ammonia-water cycle in comparison with more tradition cycles as they would be on the lunar surface. Fourth, an economic analysis uses the developed mass and volume to estimate system costs and evaluated reliability and maintainability. Knowing the economics of a power cycle allows one to view the power cycle relative to how expensive it will be to launch and operate. Economic comparisons are drawn between the ammonia-water power generation scheme and other types of power sources such as photovoltaic and organic Rankin cycles. Each candidate power system is given a score based on attributes produced in the requirement portion of the analysis. Each attribute is weighted based on customer definition. Based on the resulting scores, conclusions are drawn and future research recommendations suggested.

CHAPTER 2
Statement of the Problem

2.1 Introduction

In this chapter, the research questions, hypothesis, scope, and assumptions are presented. These topics will set up the follow-on literature review and research chapters.

2.2 Research Questions and Hypotheses

The overarching purpose of this work is to determine the value of using a solar-powered ammonia-water thermodynamic power cycle to provide power for a base or industrial process on the lunar surface. The lunar surface can vary widely in conditions. To bracket the problem, one primary research question with two sub-questions is posed.

Primary Research Question

Can an ammonia-water thermodynamic cycle have benefits over other proposed power generation schemes on the lunar surface?

Sub-Research Questions

1) Can an ammonia-water thermodynamic power cycle located at a lunar equatorial location operate at lower policy or lifecycle cost when compared to nuclear-thermodynamic, solar-thermodynamic, and photovoltaic power production schemes?

2) Can an ammonia-water thermodynamic power cycle located at a lunar pole location operate at lower policy or lifecycle cost when compared to nuclear-thermodynamic, solar-thermodynamic, and photovoltaic power production schemes?

Hypotheses

The two research questions lead to six hypotheses to test.

1) An ammonia-water thermodynamic power cycle located at a lunar pole location can operate at lower policy or monetary cost when compared to a nuclear-thermodynamic power production scheme.

2) An ammonia-water thermodynamic power cycle located at a lunar pole location can operate at lower policy or monetary cost when compared to a solar-thermodynamic power production scheme.

3) An ammonia-water thermodynamic power cycle located at a lunar pole location can operate at lower policy or monetary cost when compared to a photovoltaic power production scheme.

4) An ammonia-water thermodynamic power cycle located at a lunar equatorial location can operate at lower policy or monetary cost when compared to a nuclear-thermodynamic power production scheme.

5) An ammonia-water thermodynamic power cycle located at a lunar equatorial location can operate at lower policy or monetary cost when compared to a solar-thermodynamic power production scheme.

6) An ammonia-water thermodynamic power cycle located at a lunar equatorial location can operate at lower policy or monetary cost when compared to a photovoltaic power production scheme.

2.3 Limitations and Assumptions

1) Principal Player Assumption

a. Description: NASA is assumed to be the principal player for the lunar power systems.

b. Why: In reality, any government entity or private party with the means to access the lunar surface could be a potential customer. A full space system customer/customer/principal player analysis would require extensive analysis by teams of subject matter experts. This type of analysis is not realistic or necessary to answer the research question. To simplify analysis, NASA is recognized as an important potential customer and utilized as such. It is recommended that future analysis could explore impacts of various government entities and/or commercial companies on system design.

2) Life Expectancy Assumption and Limitation

a. Description: System and Component life expectancy is assumed to be no different between the lunar pole and equator.

b. Why: Other than the amount of sunlight received, the lunar environment at the pole and equator are very similar (Heiken et al., 1991). Evaluating each location's detailed temperature differences and its impact on component life is out of scope of this work. A full site environmental analysis would require extensive analysis by teams of subject matter experts.

3) Location Limitation

a. Description: Only two locations analyzed (equator on near side and pole location)

b. Why: Only two locations are chosen to limit the amount of analysis needed and create sufficient bounds for a system analysis.

Along with lunar base power demand, the location of the base on the lunar surface will influence power system design. The location of a lunar base can change the size and mass of individual components of a power system. Specific location impacts include power storage needs, radiator size, solar collector and photovoltaic array size, and thermal storage requirements. Proceedings from two Johnson Space Center workshops in April and August of 1990 are among the most comprehensive reports available regarding lunar siting and base needs (Morrison, 1990a; Morrison, 1990b). The reports state that the problem of lunar site selection is complex because location impacts systems engineering, process planning, simulator construction, preparation of materials, and training. Mission sets at potential sites include astronomy at a variety of wavelengths, space physics, geology, geophysics, and in-situ resource utilization. The 1990 workshop identified six lunar locations which could accommodate the five mission sets. For this analysis, the power systems are sized to accommodate the five mission sets at the two different bounding power demand locations. Location is important when sizing a system which relies on sun-power and/or has a large radiator to reject heat as part of a thermodynamic cycle. Some locations with permanent shade, such as the lunar poles, allow for optimal heat rejection through radiators. Locations around the equator can expect intermittent sunlight/shade. Most lunar equatorial and mid-latitude locations, which are geologically unobstructed, can expect approximately 15 days of illumination followed by 15 days of darkness. For the purpose of this analysis, the system sizing will have two bounding location variants: an equatorial (i.e., Riccioli) and a polar location (i.e., Amundsen). The lunar poles have complex illumination. Some sites provide continuous darkness and other sites have potential for very long illumination (Fincannon, 2008). If one sites a lunar base correctly, both long illumination and darkness can be utilized for sun powered electrical and heat generation.

Guzik, Gilligan, Smith and Jakupca (2018) conducted an analysis evaluating energy storage needs at various locations on the lunar surface. The analysis shows how specific power (W/kg) is impacted by whether one is located on the lunar equator or lunar pole. Figure 6 indicates the larger the power system the more power you get from each mass unit of the system. This is especially evident up to 1 kW for regenerative fuel cell energy storage (Guzik et al., 2018).

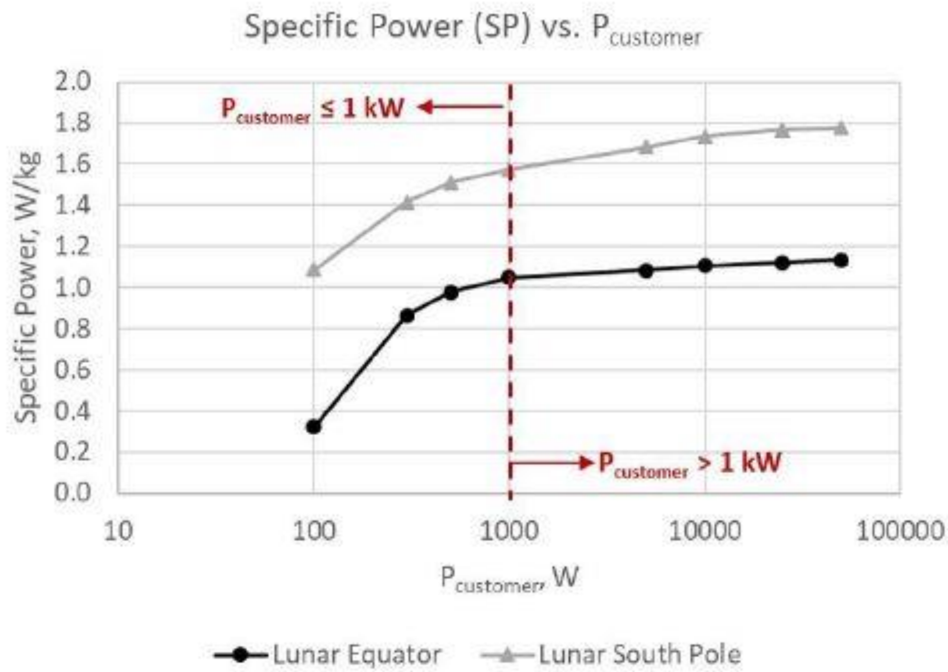

Figure 6: Specific Power (W/kg) at Lunar Equator and South Pole (Guzik, Gilligan, Smith & Jakupca, 2018)

4) Mobility Limitation

a. Description: The systems analyzed are stationary and non-mobile. Stationary power systems may be used to charge mobile systems for larger bases.

b. Why: Thermodynamic systems are not used in terrestrial or extraterrestrial applications for mobile power. Compact power supplies such as batteries are typically used for power mobile platforms.

5) Permanence Limitation

a. Description: Only permanent (not intermittently) occupied lunar outposts are considered in the design reference missions.

b. Why: A dynamic power system is complex and massive. Frequently turning such a system on and off is not realistic in an austere environment such as the lunar surface.

6) Radiator Limitation

a. Description: The systems designs evaluated only use radiators for heat rejection and not other forms of heat rejection systems.

b. Why: Heat transfer can be completed in three ways: convection, conduction, and radiation. On Earth, heat is typically dumped to the atmosphere or local environment through convection and conduction. Due to no atmosphere, low soil conductivity, and no natural liquid water, convection and conduction are not heat rejection options on the lunar surface. The only viable heat rejection method is radiation.

7) Power Cycle System Limitation

a. Description: Due to research uncovered in the literature review which points to efficiency increase for Kalina cycle over other thermodynamic cycles, the research will only look at a sun-heated ammonia-water thermodynamic systems coupled with heat storage.

b. Why: The available and realistic sources of heat for lunar thermodynamic processes are from nuclear decay and the Sun. Previous studies by Modi and Haglind (2014) show zero advantages of the Kalina Cycle over a Simple Rankine Cycle when constant heat sources are present without heat storage. Advantages are demonstrated when the heat sources are variable—such as with thermal energy storage.

8) High-level System Analysis Limitation

a. Description: Analysis will stay at a high-level architecture analysis and will not dive deep into individual component hardware such as radiators, concentrators, and thermal storage.

b. Why: Individual component analysis typically requires extensive analysis by teams of subject matter experts. This type of analysis is not realistic or necessary to answer the research question. General engineering equations are available for a high-level system analysis which is sufficient to produce an engineering mass estimate.

9) Software System Limitation

a. Description: Analysis will not evaluate power system software.

b. Why: To answer the research question, an understanding of system thermodynamics, cost, reliability, efficiency, and safety is needed. Diving into software control of systems would require much time not required to answer the research question. It is recommended that future analysis could explore impacts of software design.

10) Systems Requirements Review (SRR) Limitation

a. Description: Not conducting an SRR.

b. Why: A systems analysis typically has an SRR with the customer. This analysis is literature based. Bringing in potential customers and/or users is not funded or budgeted in time allotted for this analysis.

11) Lunar Environment Limitation

a. Description: This analysis is limited to the lunar environment

b. Why: The research question concerns use of a novel power system on the lunar surface. Other locations than the lunar surface are irrelevant when answering the research question.

12) Safety Analysis Limitation

a. Description: A full system safety analysis will not be conducted.

b. Why: A limited safety analysis focusing on identified hazards which are known to impact power system architectures is within scope. A full system safety analysis typically requires extensive analysis by teams of subject matter experts. This type of analysis is not realistic or necessary to answer the research question. It is recommended that future analysis could explore impacts of safety on design.

13) Reliability Analysis Limitation

a. Description: A full reliability, availability, and maintainability (RAM) analysis is beyond the scope of this research and will not be conducted.

b. Why: This research will utilize historic RAM analysis to develop requirements. A full RAM analysis typically requires extensive analysis by teams of subject matter experts. This type of analysis is not realistic or necessary to answer the research question. It is recommended that future analysis could explore impacts of RAM on design.

14) Risk Assessment Limitation

a. Description: A full risk assessment is beyond the scope of this research. However, requirements based on historical analysis will be developed.

b. Why: This research will utilize historic risk analysis to develop requirements. A full space system analysis typically requires extensive analysis by teams of subject matter experts.

This type of analysis is not realistic or necessary to answer the research question. It is recommended that future analysis could explore impacts of risk and risk mitigation on design.

15) Primary Power Limitation

a. Description: The analysis will be limited to the primary power for a lunar base or industrial process.

b. Why: Conducting trade studies analyzing secondary power, as well as power distribution, would require extensive analysis. To keep the research within reason, the researcher is limiting the study's focus to the primary power source for a lunar base or industrial process. Focusing on the primary power source alone will allow the research question to be answered.

16) Life-Cycle Stage Definition

a. Description: Since this analysis is not well developed, the first step of analysis (life-cycle-wise) is Pre-Phase A (NASA, 2016).

b. Why: Placing this study in the concept phase allows input from stakeholders which directly impacts how the requirements are developed.

17) Energy Storage Limitation

a. Description: Energy storage for the ammonia-power systems will be heat storage only.

b. Why: Studies have shown there is no benefit to utilizing an ammonia-water system without the use of a thermal heat storage system (Modi & Haglind, 2014).

18) Power System Sizing and Performance Limitation

a. Description: Power system(s) sizing and performance for the ammonia water are based on engineering calculations, not hardware performance test values.

b. Why: The ammonia-water power cycle is a well-developed terrestrial technology. Engineering calculation techniques have been verified with terrestrial hardware tests (Lu, Watson, & Deans, 2009). Development and testing of hardware are out of scope of this dissertation.

19) Thermodynamic Calculation Assumptions

a. Description: Assuming the following values for thermodynamic calculations

i. Turbine Isentropic Efficiency: 85%

ii. Pump Efficiencies: 70%

iii. Heat Exchanger Effectiveness Estimation: 80%

b. Why: The analysis is a Pre-phase A analysis. Hardware is not being developed or selected. These efficiencies are based on typical industry values. Additional detail and citations on where the numbers come from and why are shown in section 7.4.1.

CHAPTER 3
LITERATURE REVIEW

3.1 Introduction

This is a multi-disciplinary study covering a wide spectrum of topics including systems engineering, mechanical engineering, space policy and law, and lunar geology and environment. To cover this range, the literature review touches on previously analyzed power generation schemes, the ammonia-water thermodynamic power cycle (Kalina cycle), historic requirements studies to include mission types and progression, lunar mission locations, design reference mission framework, analysis of alternatives and requirements methodologies, and launch system costs.

3.2 Previously Analyzed Power Generation Schemes

The basic types of power generation schemes on the lunar surface are photovoltaic and thermodynamic which can be powered by the Sun or nuclear power. Each will be covered in detail.

3.2.1 Solar Dynamic Power System

Dynamic power systems were one of the earliest space power systems NASA evaluated. NASA researcher Lester Nichols (1969) produced several power system studies in the 1960s related to what he called magnetogasdynamics space power generation systems. Nichol’s initial studies were high level and idealized; however, they initiated the groundwork for future investigations. At first, Nichols looked at nuclear fission as the heat source in conjunction with a variety of working fluids such as lithium and neon. These working fluids were analyzed in an assortment of thermodynamic cycles, such as Brayton and Rankin (Nichols, 1969). From these initial studies, NASA started developing Closed Brayton Cycle (CBC) power conversion technology which can be coupled with a reactor, isotope, or solar heat source. The mid-1960s also produced research into the hardware behind the CBC (Kofskey & Glassman, 1964). NASA continued its research into solar dynamic (SD) power in the 1980s. The research centered on the SP-100 program and developments for the proposed Space Station Freedom. The SP-100 program utilized a nuclear reactor and included a design for a proposed lunar base. A 25 kW CBC solar dynamic power system was proposed for Space Station Freedom (Labus, Secunde, & Lovely, 1989). The technology that anchored the SP-100 and Space Station Freedom solar dynamic system was demonstrated in the 2kW Solar Dynamic Ground Test Demonstration Project (SDGTDP) (Shaltens & Boyle, 1994). Since the early 2000's, the research effort related to space dynamic power cycles has focused on CBC or Stirling engines linked to a space nuclear reactor. Several different initiatives have been pursued. The Jupiter Icy Moons Orbiter (JIMO) considered a 100 KW CBC reactor. This program was canceled but provided research which future programs built upon (Mason, 2003). Recent activities include a 2 kW Direct Drive Gas Brayton Test Loop, a 50 kW Alternator Test Unit, a 20 kW Dual Brayton Test Loop, and a 12 kW Fusion Power System (FPS) Power Conversion Unit design (Mason, 2009).

Much recent discussion related to solar dynamic power revolves around what type of dynamic power cycle is the best. The literature for solar dynamic power centers around Rankine, Brayton, and Stirling thermodynamic power cycles. The Rankine cycle has not been considered seriously since the 1960s. Rankine dynamic power systems have a level of complexity which is difficult to control in micro-gravity due to two-phase fluid management. Mason (2001) conducted a study which compared the Stirling and Brayton cycles. He concluded that smaller surface power systems, i.e., systems below 50 kW, are best served by the Stirling cycle. For greater than 50kW, a high-power reactor system is better served by a Brayton cycle. Both of these assessments are from a mass perspective.

Solar Dynamic power systems were studied extensively until the late 1990s. Solar dynamic systems culminated with NASA's 2KWe Solar Dynamic Ground Test Demonstration Project (SDGTDP). SDGTDP results are published in a three-volume project report (Alexander, 1997a, b, c). Not much research has been conducted to advance solar dynamic systems since SDGTDP concluded. SDGTDP did successfully demonstrate a solar powered closed thermodynamic power cycle in a relevant space thermal environment. The overall system efficiency was greater than 15% with all losses fully accounted for. However, the hardware used was not optimized. Pre-existing hardware was used to minimize cost and schedule. The next step in the development of solar dynamic space power is a flight test. No flight tests are currently scheduled for the SDGTDP. Due to the availability and flexibility of nuclear-powered dynamic systems compared to the location limitations and system complexity of the solar powered dynamic systems, nuclear-dynamic power is currently being pursued over solar-dynamic systems (NASA, 2005b).

Solar Dynamic System Advantages

Solar dynamic power has several advantages: higher efficiency as compared to photovoltaic power as systems get larger, availability of excess heat to be used for industrial operations, not suffering from policy issues related to the utilization of weapons grade nuclear material, and the utilization of a renewable energy source.

As power systems requirements get larger, solar dynamic systems have a higher power output per unit mass (W/kg) than photovoltaic. Wallin and Friefeld (1988) show for a 35 kW system that a photovoltaic system can be as much as 50% more massive than an equivalent solar dynamic system. Brandhorst, Juhasz, and Jones (1986) show that a 100 kW photovoltaic system is over 50% larger than a solar-dynamic system.

Heat generated in a dynamic power cycle can also be used in industrial processes. Crane and Dustin (1991) utilize a solar Brayton power generation unit to reduce ilmenite ore. Colozza and Wong (2006) evaluated a Stirling solar-dynamic system for lunar oxygen production. Utilizing such a system allows substantial weight savings as compared to photovoltaic systems.

Solar-dynamic systems do not use any nuclear material. A solar-dynamic system does not have any policy issues related to nuclear energy in space. Nuclear policy issues are covered in the Nuclear Power Systems section.

Solar-dynamic systems utilize the Sun as its energy source. This means the system will not run out of energy to operate in the next few billion years. Nuclear systems have a fuel life of 10-15 years.

Solar Dynamic System Disadvantages

Solar dynamic power has several disadvantages compared to nuclear and photovoltaic power systems. Solar dynamic systems are larger in volume and mass compared to nuclear dynamic systems. Both Wallin and Friefeld (1988) and Brandhorst et al. (1986) agree that solar dynamic systems are much more massive than nuclear dynamic systems. This means—compared to a nuclear system—more launches are required to emplace an equivalent power system resulting in a higher deployment cost. A state-of-the-art nuclear fission surface power system is 200-400 W/kg (McClure, 2017). A state-of-the-art photovoltaic array is approximately 80-100 W/kg with the newest laboratory arrays up to 1200 W/kg (Beauchamp, 2017). These photovoltaic array values do not include any energy storage systems which will greatly reduce the system W/kg values. The near-term state of the art for a solar dynamic system is 116 W/kg with potential up to 709 W/kg in the far term. (Mason, 1999). However, solar dynamic systems are not currently being heavily developed.

Both photovoltaic and solar dynamic systems require backup energy for lunar nights. Nuclear power systems do not. Backup systems require additional launch mass and add to system complexity. Solar dynamic systems can utilize batteries, thermal energy storage, or fuel cell technologies for backup power. Photovoltaic systems cannot utilize thermal energy storage. Thermal storage has been evaluated by NASA researchers. Colozza (1991) presented his findings on using lunar regolith as a heat sink for a solar dynamic system to utilize during the lunar night. It was determined the regolith will absorb heat from heat pipes during the lunar day and allow extraction during the lunar night. This could minimize mass required for energy storage during the lunar night on the lunar surface.

3.2.2 Nuclear Power Systems

There are two main types of nuclear power generation systems: radioisotope power systems (RPS) and fission power systems (FPS). RPS uses the natural decay from Pu238 to produce power up to 1 kW. FPS uses U235 to produce power from the kilowatt range up to the megawatt range (Mason, 2018). Nuclear systems are considered a favorable option for relatively long-duration power in space environments where sunlight is limited or non-existent.

The current version of RPS that NASA uses is called a General Purpose Heat Source (GPHS) module which supplies 250 W (thermal) at the beginning of the module’s life, i.e., Beginning of Mission (BOM). A mission which uses RPS typically puts several GPHS units together till it has sufficient power. For example, the largest RPS mission ever flown was Cassini in 1997. Cassini produced 826W (BOM) of electricity using 3 GPHS modules (Lockheed Martin, 1998).

Although several development efforts have been funded over the years, the United States has only flown one FPS system. SNAP 10A was a 500W unit which flew in 1965 for 43 days. Other US efforts include the SP-100 in the 1980s and Prometheus in the early 2000s. Mason (2018) states most efforts fall short due to technical complexity, high development costs, and aggressive performance claims. In addition to the shortfalls, the efforts typically try to develop new reactor fuel, structural materials, and power plant components in conjunction with a mission which demands a lot of power with low mass and a long operational life. Historically, this combination has resulted in program failure.

NASA is currently developing a new FPS system called Kilopower. Kilopower is slated to produce between 1 and 10 kW of electricity. A ground test of the Kilopower FPS system was recently completed. The Kilopower nuclear ground test is nicknamed KRUSTY—Kilopower Reactor Using Stirling TechnologY. NASA and contractor researchers published the results and lessons learned (Gibson et al., 2018). The nuclear ground test was the first of its kind in over 50 years and achieved a technology readiness level (TRL) 5. NASA defines TRL 5 as the components and/or breadboard has been evaluated in a relevant environment (NASA, 2016). All three of the technical objectives were met during the ground test. According to the published results, the nuclear reactor operated at steady state, precisely controlled the core temperature through several simulated nominal and off-nominal mission scenarios, and obtained data directly applicable to the next design iteration. The system is under consideration for a technology demonstration flight test in the mid-2020s with primary future mission applications being lunar and Mars surface power systems (Mason, 2018).

Mason (2018) compares the RPS and FPS nuclear power systems. His study provides a quantitative assessment of near-term nuclear heat sources and candidate energy conversion technologies. Small FPS systems up to 1 kWe do not provide any mass advantages to the typical RPS systems. However, as power demands start moving toward and above 10 kWe, FPS systems provide over 20% mass advantage over RPS systems.

Nuclear power has been evaluated and used in space since the 1960s. The primary reasons to use nuclear power in space are power density, operational capability in most environments, and simplicity. In 2010, following a request from the Decadal Survey Giant Planets Panel (GPP) and the NASA Science Mission Directorate, the small Fission Power System (FPS) study was initiated. The study evaluated the feasibility of a 1-kWe-class FPS for future NASA science missions (Mason et al., 2011). Nuclear dynamic power systems are currently being developed by NASA. In 2018, NASA completed the first space nuclear reactor test in over 50 years. Kilopower Reactor Using Sterling TechnologY (KRUSTY) is a complete reactor system design which incorporated flight prototypic materials and full-scale components (Gibson et al., 2018).

Concerning nuclear fuel availability, RPS systems use Pu238, which is in limited supply. Mason (2018) points out that NASA is the only recognized user of Pu238 and the costs and complexity of making it is quite high. NASA relies on the Department of Energy (DOE) to produce Pu238. DOE has only recent started producing the material after not manufacturing it for quite some time. Enriched U235 which is used in FPS is available in large quantities from the DOE. U235 is available from dismantled nuclear weapons and NASA is a minor user. Fuel availability trends for FPS are good; however, RPS fuel may have limited quantities available.

Nuclear Power System Advantages

Nuclear power systems can operate in more environments than solar-dynamic or photovoltaic. These environments include areas which are shadowed from the Sun and places where the Sun's luminescent intensity is reduced. The Jet Propulsion Laboratory (JPL) recently performed an assessment of solar power technology for future planetary science missions. The further one is from the Sun or when one is operating in Sun-shadowed regions, the more limited solar power is. The study shows that the latest solar power technology enables one to use solar power up to Saturn's orbit, but solar power is not feasible past Saturn's orbit (Beauchamp, 2017). Nuclear power does not suffer from this location limitation. It can operate in virtually all locations space power is needed.

As covered earlier, as power systems get larger, nuclear systems are much more compact and have a higher power to specific power ratio (W/kg) than solar powered systems.

Nuclear Power System Disadvantages

For systems which have a small power demand, a nuclear-powered system, RPS or FPS, is more massive than a photovoltaic system.

Radioactive material or contamination may cause policy issues related to nuclear energy in space. FPS uses weapons grade Uranium (U235). There is a potential acceptability issue with the use of a high specific mass nuclear reactor which uses weapons grade Uranium, such as KRUSTY, and the American voter. Lanius (2014) highlights the resistance that NASA has received over the years when utilizing non-weapons grade nuclear devices. The public fears nuclear contamination from space technology. The public has traditionally organized resistance against the use of nuclear technology in space. The fact that two significant anti-nuclear groups, the Union of Concerned Scientists and the Nuclear Proliferation Prevention Project, have expressed concerns with NASA's nuclear research speaks for what is to come. Diaz et al. (2019) make a good case for the need to pursue an intermediate nuclear space technology—which do not use weapons grade Uranium—instead of high specific mass space reactors. This policy issue may force space power architects to alter their typical choice of power production from nuclear to solar powered for high power demand lunar bases.

Pu238 is only available in limited amounts. As previously discussed, NASA is the only user of Pu238. DOE has just recently started back manufacturing Pu238 for NASA. The cost and complexity of Pu238 is significant (Mason, 2018).

Nuclear waste processing is an issue in space. At the end of life of the system, what happens to the nuclear waste? Not a lot of analysis and research is available concerning end of life plans for a high specific mass nuclear reactor on the lunar surface. Most high specific mass nuclear reactors have a published life of 10-15 years. The lunar architecture of the ESAS report show a fusion powered nuclear reactor needs a keep out zone of 2 km (NASA, 2005a). A 2011 NASA fission surface power architecture study placed the optimum service life of a reactor at 8 years (Mason & Poston, 2010). A paper published prior to ground test of Kilopower's KRUSTY reactor states a service life of 12 years. (Gibson, Oleson, Poston, & McClure, 2017). What happens at the end of life? More than likely the equipment will be abandoned in place (NASA, 2005b). A gap in research exists on the best technical, policy, and environmental paths for the end-of-life plans of nuclear reactors in space and on planetary surfaces.

3.2.3 Photovoltaic Power Systems

The current state-of-the-art space based solar power technology has culminated in the solar array on the International Space Station (ISS). The ISS's solar array is the largest ever deployed into space at a total of 240 kW (Baez, 2012). The ISS power system has been a test bed for large photovoltaic power systems and includes concentrating arrays, deep cycle batteries, rotating flywheels, and other lightweight technologies (Gietl, Gholdston, Manners, & Delventhal, 2000).

Hickman, Curtis, and Landis (1990) explored adapting photovoltaic power for use in lunar base and subsequent manufacturing. Their study has three important findings. First, a photovoltaic panel array is only a small percentage of the overall photovoltaic power system mass. Second, energy storage for the lunar night is a large mass driver. Third, the configuration of the photovoltaic array is important when generating power at dawn and dusk. As previously stated, the current state of the art photovoltaic arrays is approximately 80-100 W/kg with the newest laboratory arrays up to 1200 W/kg (Beauchamp, 2017). These values only include the arrays and not any energy storage systems.

The ESAS Lunar Architecture (NASA, 2005a) has baselined the power source options as either a photovoltaic system or a nuclear system. Photovoltaic arrays are modular, lightweight, reliable, but require an energy storage system during nighttime operation. Photovoltaic power has been used reliably in space and on the lunar surface, thus providing low technical risk. ESAS requirements call for an initial use of photovoltaic power during initial base set-up followed by a nuclear reactor as power requirements increase.

Photovoltaic power is trending toward panels which have low mass, high flexibility, high efficiency, and coupled with solar concentrators. Due to weight savings, energy storage for photovoltaic is trending toward regenerative fuel cell (RGF). Brinker and Flood (1988) state that an advanced photovoltaic/RGF system has a weight advantage over a photovoltaic/battery system.

Exploration Systems Architecture Study (ESAS) shows lunar base architecture as potentially having photovoltaic power up to the 100 kW demand level. The viability of solar power is highly dependent on the location of the lunar base. The study shows a mass fluctuation of over 50% for photovoltaic/RGF systems depending on location of base (NASA, 2005a).

Further work is required for a base photovoltaic system. Future work includes detailed analysis of the power management and distribution system (PMAD), thermal cycling of photovoltaic and RFCs, long term impact of lunar dust, further development of low mass energy storage systems such as RFCs, and continuing the development of low mass, deployable photovoltaic arrays.

Photovoltaic System Advantages

Photovoltaic systems do not contain radioactive material or contamination, thus have no policy issues related to nuclear energy in space. The system is much simpler architecture than solar or nuclear dynamic systems, thus a perceived higher relative reliability. Finally, photovoltaic systems are the least massive power production system until a certain point—approximately 100 kW (NASA, 2005b)—of power generation output.

Photovoltaic System Disadvantages

Photovoltaic systems do have a higher volume, area, and mass than solar and nuclear dynamic as a system gets larger. The system requires backup energy for lunar night and has a higher power degradation over time than dynamic systems.

3.3 Ammonia-water Thermodynamic Power Cycle

Ammonia-water as a working fluid in a thermodynamic power cycle was introduced in 1983 by Dr. Alexander Kalina (Kalina, 1983). His novel cycle, now called the Kalina Cycle, can utilize a variety of compositions of the ammonia-water working fluid in different parts of the power cycle. Initially, the Kalina cycle was planned as a bottoming cycle or a cycle which uses the hot exhaust from a gas turbine engine or diesel engine as a heat source (Kalina, 1983; Kalina 1984). Soon after the initial design, a variety of other cycle configurations were developed which utilize direct fired as well as geothermal as heat sources (Kalina & Leibowitz, 1989; Kalina, 1989). Researchers and industrial developers in Japan and Iceland have built geothermal power plants utilizing the power cycle (Sato et al., 2015; Mlcak, 2001). Dr. Kalina started a company called Exergy Inc. to develop the ammonia-water power cycle. Exergy worked with the United States Department of Energy's (DOE) Energy Technology Engineering Center (ETEC) near Canoga Park in California to develop a demonstration plant. The demonstration was able to run around 5 years before the DOE shut down the demonstration operation due to completion of demonstration objectives. The demonstration plant performed tests which established the base principles of the Kalina cycle technology (Leibowitz, 1993). Most studies focused on low grade heat for the cycle. There are a few analyses focused solely on the Kalina cycle powered by solar energy. Wang, Yan, Zhou, and Dai (2013) parametrically analyzed and optimized a Kalina cycle powered by the solar energy. They found the cycle's efficiency and power output less sensitive to turbine inlet temperature than a typical Rankine cycle. Sun, Zhou, Ikegami, Nakagami, and Su, (2014) optimized a solar-powered Kalina cycle which included an auxiliary superheater. Larsen, Pierobon, Wronski, and Haglind (2014) optimized a Kalina split-cycle with a genetic algorithm in MATLAB which focused on the turbine, mixing components, and boiler. The team also compared the performance of a split cycle to a normal Kalina cycle. The results showed the performance of a split Kalina cycle is thermodynamically better than a normal Kalina cycle but is also more complex and expensive to build. An exergy analysis of a Kalina cycle with a solar central receiver with direct steam generation was performed by Modi and Haglind (2014). They concluded both that the cycle layout and number of recuperators impact the cycle efficiency and that the Kalina cycle has benefits thermodynamically if thermal storage is utilized as compared to a standard Rankin cycle. In a following paper, Modi and Haglind developed an algorithm to optimize a high temperature and pressure solar-powered Kalina cycle (Modi & Haglind, 2014). Four different layouts for a Kalina cycle are optimized and performance calculated.

3.4 Historic Lunar Requirements Studies

The mission the power system supports will have a large impact on what type of power system is best. To determine mass and volume requirements, one needs to know how much power is required for various size bases or industrial processes and what power systems are available.

The 2005 Exploration Systems Architecture Study (ESAS) summarized many of the previous studies. Previous studies overviewed are shown in the following table.

Table 1: Summary of Previous NASA Architecture Studies (NASA, 2005a)

Office of Exploration (OExP) - 1988 Case Studies Human Expedition to Phobos Human Expedition to Mars Lunar Observatory Lunar Outpost to Early Mars Evolution	**First Lunar Outpost - 1993** **Early Lunar Resource Utilization - 1993** **Human Lunar Return - 1996**
Office of Exploration (OExP) - 1989 Case Studies Lunar Evolution Mars Evolution Mars Expedition	**Mars Exploration Missions** Design Reference Mission Version 1.0 - 1994 Design Reference Mission Version 3.0 - 1997 Design Reference Mission Version 4.0 - 1998 Mars Combo Lander (Johnson Space Center (JSC)) - 1999 Dual Landers – 1999
NASA 90-Day Study - 1989 Approach A - Moon as testbed for Mars missions Approach B - Moon as testbed for early Mars missions Approach C - Moon as testbed for Mars Outposts Approach D - Relaxed mission dates Approach E - Lunar outpost followed by Mars missions	**Decadal Planning Team (DPT)/NASA Exploration Team (NExT) - 2000–2002** Earth's Neighborhood Architecture Asteroid Missions Mars Short and Long Stay **Exploration Blueprint - 2002** **Space Architect - 2003**
America at the Threshold - "The Synthesis Group" - 1991 Mars Exploration Science Emphasis for the Moon and Mars The Moon to Stay and Mars Exploration Space Resource Utilization	**Exploration Systems Mission Directorate (ESMD) 2004–2005**

The studies shown in Table 1 show several commonalities and disagreements. Potential mission sets of astronomy, space physics, geology, geophysics, and in-situ resource utilization can condense into a single continuously expanding mission (Petri, Cataldo, & Bozek, 1990). Petri, Cataldo, and Bozek (2006) published a power requirements study for Lunar and Mars outposts. Note: the Petri, Cataldo, and Bozek (2006) study is an update of their 1990 Lunar and Mars outpost power requirement study (Petri et al., 1990). The requirements analysis identified power requirements across a variety of lunar development phases and surface elements. The power requirements were developed to support habitation, transportation, construction, workshop facilities, and industrial operations. Power requirements evolve as power demand grows. Cataldo and Bozek (1993) further refined lunar requirements for a first lunar outpost. Reliability and system lifetimes are stressed as critical to long term mission success. The requirements establish a minimum power demand for science equipment and outpost maintenance. A NASA study published in 2006 evaluated lunar outpost power system concept requirements needed for a mission such as what Artemis is proposing. The 2006 study showed five phases: Phase 0—Robotic Site Preparation (minimum or no human presence); Phase 1—Deployment and initial operations (3 to 4 personnel for 4 to 6 months); Phase 2—Growth Phase (approximately 10 personnel for a year); Phase 3—Self Sufficiency (ten to 100 personnel for extended periods); Phase 4—Science and Commercial (greater than 100 personnel for unlimited durations). The requirements evaluated a lunar base siting at the Lunar South Pole near the Shackleton Crater (Zavoico, Freid,Vranis, Khan, & Manners, 2006). Other important similar requirements studies include “America at the Threshold” (Stafford, 1991) and the Lunar Architecture Focused Trade Study Final Report (NASA, 2004).

The disagreements among the various studies revolve primarily around mission sets. Power systems which support each mission will vary due to need. A system which only needs a temporary or a small power system will utilize fuel cells, batteries, and solar panels. Longer term missions or missions which require high power inputs demand a solar or nuclear dynamic system which provides higher power per unit mass at high power outputs than photovoltaic panels, batteries, or fuel cells.

Petri, Cataldo, and Bozek (2006) summarize an evolutionary development path for a lunar outpost. Three phases are shown: emplacement, consolidation, and operations. The emplacement phase is to gain experience operating and constructing on the lunar surface. This phase will require the least amount of power and is best powered by photovoltaic panels coupled with batteries or regenerative fuel cells. A small human crew can be supported during the emplacement phase. The consolidation phase looks to develop an understanding of how to construct prefabricated habitats, how to utilize local resources, and testing new techniques applicable for a Mars mission. The consolidation phase is where a lunar base should transition from photovoltaic power to a dynamic thermodynamic system powered by nuclear or concentrated solar energy. The operations phase looks to transition the lunar base to self-reliance. Due to high power demands, a large dynamic power system is required to support industrial operations and base sustainment. The study outlines several constraints and requirements driving the design of the power system including part commonality, telerobotic or self-deployment, maintainability, safety, reliability, and power output per unit mass. Each of these constraints is driven to allow the mission maximum power at minimal cost. Part commonality allows for fewer spare parts; thus, less mass will be required to be placed on the lunar surface. Self-deployment means few construction trips for astronauts to the lunar surface.

Maintainability, safety, and reliability are important for the safety of the crew, reduction in surface costs, and the ultimate accomplishment of mission objectives (Petri et al., 2006).

Determining the power demand from potential industrial processes is dependent on material processed and how the process is done. How large a lunar base can be constructed and how much material one can process is limited by the amount of power available (Benaroya, Bernold & Chua, 2002). Eagle Engineering's study of oxygen extraction from ilmenite helps to determine power, heat, and other generic inputs needed for a planetary production or manufacturing process (Eagle Engineering, 1988). Buelke and Casler updated the Eagle Engineering study in 2016 (Buelke & Casler, 2016). Duke, Diaz, Blair, Oderman, and Vaucher (2003) evaluated commercial production of propellants at the lunar poles and the type of power systems and heat sources needed for the production.

3.5 Lunar Mission Locations

Lunar base location directly impacts lunar base requirements. These include power storage needs, radiator size, solar collector and photovoltaic array size, and thermal storage requirements. Proceedings from two Johnson Space Center workshops in April and August of 1990 are among the most comprehensive reports available regarding lunar siting and base needs (Morrison, 1990a; Morrison, 1990b). The reports state that the problem of lunar site selection is complex because location impacts systems engineering, process planning, simulator construction, preparation of materials, and training. A good site selection strategy utilizes four attributes. The site should be flexible, safe with good utility, multidisciplinary, and allow maximum human lunar exploration and exploitation. Mission sets at potential sites include astronomy at a variety of wavelengths, space physics, geology, geophysics, and in-situ resource utilization. Location is important when sizing a system which relies on Sun power and/or has a large radiator to reject heat as part of a thermodynamic cycle. Most lunar equatorial and mid-latitude locations, which are geologically unobstructed, can expect approximately 14 days of illumination followed by 14 days of darkness. At the lunar poles, one will experience complex illumination patterns. Some sites provide continuous darkness and other sites have potential for very long illumination (Fincannon, 2008). Both long illumination and darkness can be utilized for sun-powered electrical and heat generation. Guzik et al. (2018) conducted an analysis evaluating energy storage needs at various locations on the lunar surface. The analysis shows how specific power (W/kg) is impacted by whether one is located on the lunar equator or lunar pole. They show the larger a power system the more power you get from each mass unit of the system. This is especially evident until 1 kW.

3.6 Design Reference Missions

One of the important elements of this dissertation is the development of design reference missions. Duke, Hoffman, and Snook (2003) developed a guide to lunar surface reference missions. Another reference is actual proposed lunar missions. The ESAS summarizes many of the elements key important in a mission related to a power system (NASA, 2005a). ESAS Appendix 4G, Surface Power System, dives much deeper into detail concerning power system requirements relying heavily upon reference mission framework (NASA, 2005b). Petri, Cataldo, and Bozek (2006) show a three-phase permanent lunar occupancy framework. Progressive power capability is introduced throughout the various mission phases within the overall framework. Earlier mission power system specific framework is shown in Cataldo and Bozek (1993). Mission specific requirements for a lunar oxygen plant are developed by Kanamori, Watanabe, and Aoki (2013).

3.7 Launch System Costs

Size requirements and costs are tied directly to the mass and volume requirements. There are many various launch vehicles available. Very little data are available outlining launch costs. Jones (2018) presents the cost of launch vehicle to place mass in low earth orbit. Jones (2017) shows lunar surface emplacement costs in $/kg.

CHAPTER 4
METHODS

4.1 Introduction

This chapter develops the research process used in this study. To answer the research questions, an analysis of alternatives is conducted by performing a multi-attribute utility analysis with special emphasis placed on the space systems engineering process. By utilizing the analysis of alternatives, the system being investigated—an ammonia-water thermodynamic power cycle—is evaluated against previously analyzed lunar power systems.

When one utilizes multi-attribute utility theory, each alternative solution is defined and assigned a score whose value reflects its relevant attributes. Each attribute or value dimension is evaluated separately. Once the attribute is evaluated, relative weights are assigned to each attribute which further defines the trade-off between each attribute. The values and weights are then aggregated by means of a formal model from which an overall evaluation of the alternatives can be produced (Winterfeldt, Winterfeldt, & Edwards, 1986).

The method used to investigate the research question is based on the Simple Multi-attribute Rating Technique (SMART). Watson and Buede (1987) found this method to be very robust. Goodwin and Wright (2004) break down the SMART technique into its component stages and demonstrate its effectiveness for solving decision issues. Goodwin and Wright (2004) emphasize that the main objective of the SMART analysis is to enable the decision maker to obtain a better understanding of the decision problem. There are several variants of the SMART model. Edwards and Barron (1994) recommend the SMARTER model which simplifies the SMART model by assuming linearity between value functions. The SMARTER model has the decision maker rate the weighting in order of importance instead of asking for a number to represent the relative importance. Brownlow and Watson (1987) put forward a method to formulate a value tree for the SMART model which utilizes stage development. This allows the value tree to find compromises between the various criteria. Determining the tradeoffs of costs against benefits can be difficult with the SMART method. Edwards and Newman (1986) consider this to be one of the more difficult decisions with multiple objectives and recommend waiting to the very end of the analysis when the most information is accessible.

Utilizing SMART allows the ammonia-water thermodynamic power cycle to be evaluated against nuclear thermodynamic, solar thermodynamic, and photovoltaic power systems for use on the lunar surface. Each power system will be fully described and competing values weighed and scored as they relate to the issue of power requirements of a lunar base or industrial process. The identification and justification of the alternative power system schemes is developed in section 6.4, Alternate Mission Power Architecture. The main steps in the analysis are shown below as shown in Goodwin and Wright (2004):

1) Identification of the decision maker(s).

2) Identification of the courses of action.

3) Identification of the attributes which are relevant to the decision problem.

4) Assignment of values to measure the performance of the alternatives to the attributes identified in step 3.

5) Weight determination for each of the attributes determined in step 3.

6) Multiplication of the weight with the attribute value and determination of the score value for each of the power cycles.

7) Provisional determination of the best power cycle for a lunar base or industrial process.

8) Performance of a sensitivity analysis to see how robust the decision is and which requirements and attributes are most important.

Several charts are populated with this analysis. Table 2 shows the primary chart to be filled out.

Table 2: Lunar Power Cycle Scoring Chart

			Value Dimensions						
Lunar Location	Lunar Power	Power System Type	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Agg. Utility
Location	Value 1	KRUSTY	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SP-100	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SDGTDP	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		Photovoltaic	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		KC12	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
	Value 2	KRUSTY	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SP-100	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SDGTDP	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		Photovoltaic	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		KC12	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
	Value 3	KRUSTY	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SP-100	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SDGTDP	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		Photovoltaic	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		KC12	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
	Value 4	KRUSTY	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SP-100	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SDGTDP	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		Photovoltaic	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		KC12	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
	Value 5	KRUSTY	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SP-100	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		SDGTDP	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		Photovoltaic	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X
		KC12	x (X)	x (X)	x (X)	x (X)	x (X)	x (X)	X

Table 2 displays the attributes (value dimensions) to be scored and weighed, the weight of each attribute, the scores of each attribute for each power system, the multiplied value of the power system scoring and weight (the value in parentheses), and the final summed score (Agg.

Utility). The value scale will range from 0 to 100. For each attribute, a quantifiable variable will be assigned. A value function will be created for the attribute. The creation of the specific variables and value functions will be developed in Step 4. To develop the value function (AV), one identifies the minimum and maximum values for the quantifiable variable. With the minimum and maximum values, a value function formula can be created. Although AV development can vary, a general form is shown as equation 4.1.

$$AV_{variable} = (SpecificQuantifiableValue - min\ value)\ \frac{100}{max\ value - min\ value} \quad (4.1)$$

Following attribute development, further definition of system scoring is outlined in section 7.3.1.

The SMART tool is an additive model. With an additive model, the sums of weights and scores for each alternative help the researcher arrive at a single score for each alternative (Chesley, Larson, McQuade, & Menrad, 2008). One of the most important parts of this type of model is developing the rubric or standardized scale by which each of the alternatives is weighed. Once the standardized scale is developed and each attribute is well defined and given a weight, the power system schemes can be given a number, compared, and documented in a form such as shown in Table 2.

In this dissertation, steps 1-3 of the SMART method leverage requirements development of the standard space system engineering processes. The analysis techniques and steps are adapted from Space Mission Engineering’s Space Engineering Process (Wertz, Everett, & Puschell, 2011). Figure 7 shows the eleven steps as adapted and modified for this research from Wertz et al. (2011). The process adopted is for a need-based mission. A need-based mission is one which is to fulfill a specific set of mission objectives. The design reference missions are developed in step 3. A design reference mission provides reference for what the specific set of mission objectives are. The space engineering requirements process step 8 (shown in Figure 7) marries back up with the SMART method step 4.

Typical Flow	Step
	Define Objectives and Constraints
	1. Define the Qualitative Objectives and Constraints
	2. Define the Principal Players
	3. Identify Design Reference Mission (DRM)
	4. Define the Quantitative Requirements and Constraints
	Define Mission and Power System Concepts and Designs
	5. Summarize Likely Power System Drivers and Requirements
	6. Determine Ammonia-Water Power System Architecture
	7. Identify Alternate Mission Power Architectures
	Evaluate Power System Concepts
	8. Conduct Performance Assessments and System Trades
	9. Evaluate Mission Utility
	10. Define Baseline Concept and Architecture
	11. Summarize Results and Conclusions

Figure 7: Modified Space Mission Engineering Process

In addition to Wertz et al. (2011), NASA's Systems Engineering Handbook (2016) provides guidance for system design and analysis. Figure 8 displays the interplay between the various system design processes.

This study is a concept study which NASA defines Pre-phase A in a program or project life cycle. A concept study produces a broad spectrum of ideas and alternatives for missions from which new programs can be selected. Through the dissertation methodology, the feasibility of the analyzed system will be evaluated through development of mission concepts, performance assessment, cost and schedule feasibility, and technology needs and scope (NASA, 2016).

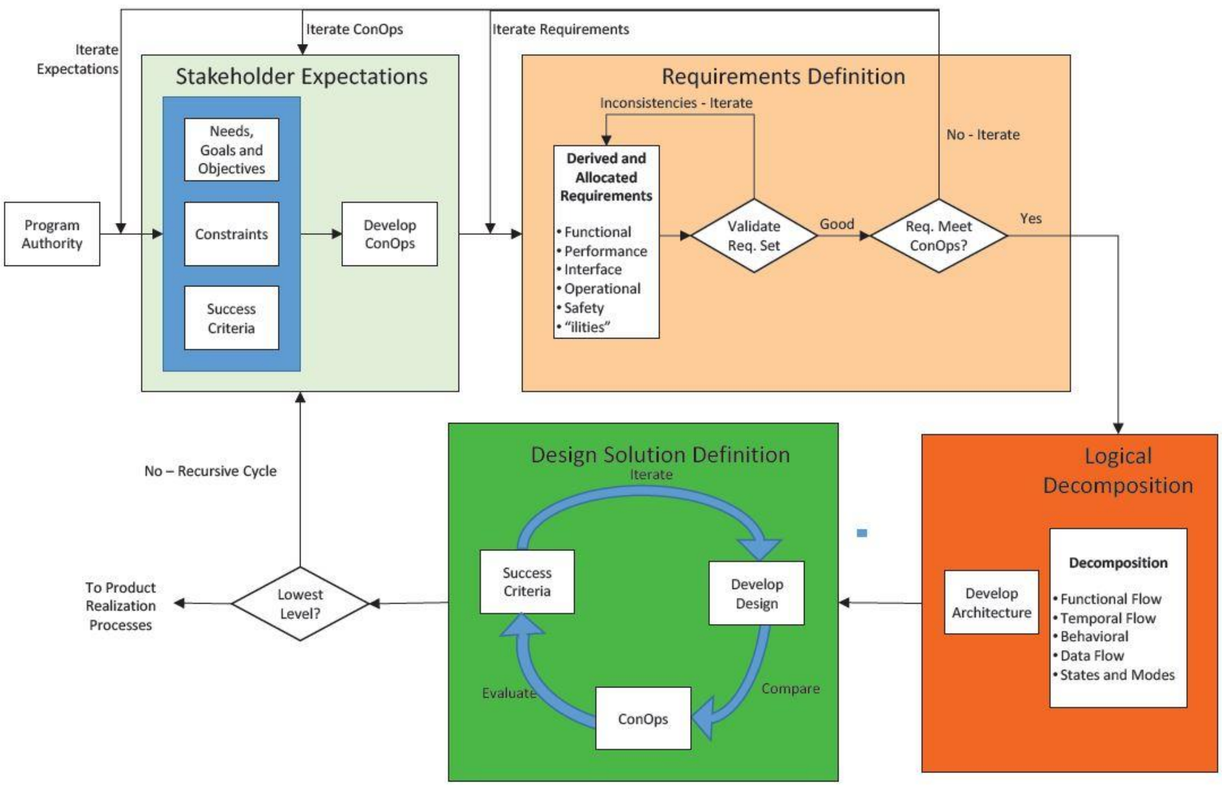

Figure 8: Interrelationships among the System Design Process (NASA, 2016)

For ease of reading, the dissertation analysis is broken into three chapters. The overall process is the SMART method. The first three steps of the SMART method utilized space systems engineering to identify decision makers, develop requirements and courses of action, and identify key attributes from those requirements which can be used to analyze the alternatives. The first analysis chapter, Chapter 5, defines objectives and constraints; the second analysis chapter, Chapter 6, defines the mission and power system concepts and designs; the third analysis chapter, Chapter 7, evaluates the lunar power system concepts. Each step in the SMART method will now be broken out and described.

4.2 Step 1: Identification of the decision maker(s)

This step lines up with the first two parts of the space systems engineering requirements development process. Step 1 defines qualitative objectives and constraints and then proceeds to define the principal players (Wertz et al., 2011).

4.2.1 Definition of the Qualitative Objectives and Constraints

The first step to any analysis is broadly defining what one is analyzing. Identification of high-level mission needs required to achieve system or mission success is essential. One asks, what are the qualitative goals and why? The goals are centered on answering the research question. Based on decision maker input, qualitative goals are drawn from available literature from stakeholder power system requirements analysis (Goodwin & Wright, 2004).

4.2.2 Definition of the Principal Players

This step identifies stakeholders and the section of the space community they identify with. The end user may not necessarily be the same as the group of individuals funding the activity. For example, the United States Congress may be funding a space technology, but NASA astronauts may be the end users of the product developed. By identifying the stakeholder, one may start to determine what their expectations are and what their requirements will be. Identifying customer expectations starts with defining who the “customer” or “stakeholder” is. The customer or stakeholder is any organization or person who has a vested interest in the development and performance of the lunar power system. The stakeholder’s expectations for the power systems are identified and resulting products and deliverables associated with the system are flowed down. Normally face-to-face meetings and workshops are held with stakeholders. However, for this dissertation, expectations will be developed from data available in literature. Explicit expectations will be represented as quantifiable requirements and performance parameters. Explicit expectations allow traceability to system requirements to be established and maintained. What defines explicit stakeholder expectations is defined by NASA in the Systems Engineering Handbook (NASA, 2016). Figure 9 shows the expectations to be developed.

Figure 9: NASA Stakeholder Expectations (NASA, 2016)

4.3 Step 2: Identification of the courses of action

The second step of the SMART method identifies the various courses of action available in the analysis. To do this, the design reference missions and quantitative requirements need to be developed. Once these are developed, the candidate ammonia-water thermodynamic cycle and alternate power architectures can be identified.

4.3.1 Identification of the Design Reference Mission (DRM)

After establishing customer expectations, operational scenarios are defined. Operational scenarios allow system baseline functionality to be developed. For this dissertation, two expanding Design Reference Missions (DRMs) are selected. The two DRMs, one at the lunar pole and one at the lunar equator, bracket the two extremes of the lunar environment. These two DRMs allow for the ammonia-water power system to be analyzed against previously analyzed power systems directly correlating with a stakeholder developed lunar mission set. Power system requirements are heavily dependent upon the operational scenario they support. Operational scenarios which allow for broad system understanding are important. Utilizing scenarios allow identification of system baseline functionality and operational requirements. Wertz et al. (2011) define operational requirements as defining how a system will be used. Baseline functionality lays the foundation for functional analysis and functional modeling. Functional analysis breaks down high level system functionality into required behavior necessary to support stakeholder operational mission expectations. Operations scenarios will be developed and based on data provided through moon base and industrial processes case studies present in literature. Duke et al. (2003) provide the guide which is used to develop the design reference mission scenarios. First, the objectives of the lunar mission are established including science, astronomy, and technology demonstrations for long term lunar presence, Mars exploration, and lunar economic activities. Second, functional descriptions are developed to include work activities and experiment requirements. Finally, missions and mission timelines are developed to support those activities.

4.3.2 Definition of the Quantitative Requirements and Constraints

This step takes the previously developed broad objectives and quantifies them based on operational needs, applicable technology, and cost. For this dissertation, three steps are taken to develop the quantitative requirements: a functional analysis is performed, system boundaries and interfaces are defined, and functional requirements are developed.

The functional analysis is completed to define the systems functional architecture. Wertz et al. (2011) define functional requirements as what a system is supposed to do and how well it must do it. The functional analysis adds definition to proper system architecture and refines system level requirements. A functional requirements baseline is derived and flowed down from the operational scenarios. By flowing from the operational scenarios, the operation requirements are kept at the tip of the functional hierarchy, allowing for traceability to the source requirements.

Following the functional analysis, defining the system boundaries and interfaces identifies any external influence which may impact the functionality of the system. Each potential influence is identified, captured, managed, and controlled to ensure the system integrity of all data—received from and transmitted to—external systems. The system of interest for this analysis is an ammonia-water thermodynamic cycle on the lunar surface. A limited interest of required interfaces, software, and hardware components is included. Other systems external to the power system must be considered. These external systems will provide direct and indirect inputs and outputs into functionality. External systems are minimally defined as mission supported equipment and external environment. As analysis progresses, additional external systems may be added as they are identified. External system interfaces and power demands are defined in quantitative terms. As the analysis iteratively progresses, the power systems physical architecture development will further identify and define other physical interfaces to which the functional interface requirements can be allocated.

System-level functions are based upon the DRMs developed in the previous section. DRMs allow system functionality to be derived from operational needs, thus allowing functionality to match stakeholder needs. Functional needs are developed directly from operational needs. Each function is further decomposed into leaf-level system functionality as needed. Each functional requirement will be represented as discrete events with quantifiable performance criteria. According to Rogers, Hale, Zook, Gowda, and Salas (2004), a complete functional requirement has two main aspects: basic required capability or function and a quantified performance criterion linked to the basic capability. More than one performance criterion may be linked to a single function or capability. Each performance criterion is directly linked to the function it supports. In the analysis, each performance criterion is defined for each supported function and a description of how well the functional requirements must perform. Performance criteria will be developed in the same way as functional requirements—as described in the previous section.

4.3.3 Determination of the Ammonia-Water Power System Architecture

Applicable ammonia-water system architectures will be identified and outlined based on the developed quantitative and qualitative requirements summarized in Table 11. Each major component identified will be outlined with respect to size and mass.

Terrestrial thermodynamic power cycles can have hundreds of system architectures. However, there are typical system setups which emerge in industry. Background analysis has been developed for a high temperature Kalina Cycle (ammonia-water) (Modi & Haglind, 2014).

Findings associated with terrestrial sun-powered ammonia water cycles will be outlined in detail. These terrestrial cycles will be used as a basis for a lunar case analysis.

Launch mass is a very important economic driver of any lunar system. One objective of this step is to look at component mass. For each component specific power (kg/kWe) will be established for use in future analysis. Kg/kW will be gleaned from available literature. The components to be evaluated are energy storage, radiators, solar energy collectors, separators, pumps, turbines, generators, heat exchangers, and supporting equipment such as pipes and fittings.

4.3.4 Identification of Alternate Mission Power Architectures

This step will be conducted in a similar manner as the previous step. To determine whether an ammonia-water thermodynamic power cycle has benefits over other proposed power generation schemes on the lunar surface, one must identify and outline what other power generation schemes have been proposed. The lunar operating environment introduces factors which influence and limit how a power system can be designed, built, and operated. To date there have been three major types of power generation schemes which have been analyzed for use on the lunar surface. The three schemes are photovoltaic, nuclear-powered thermodynamic, and sun-powered thermodynamic. Several subcategories exist within each type, but the three overarching categories provide a basis for system analysis as it relates to the lunar environment. From available literature, representatives from each of these categories will be identified and outlined. Major components and system architecture will be displayed and shown. One objective of this step is to look at each system’s specific power.

4.4 Step 3: Identification of the attributes which are relevant to the decision problem

Through the space system engineering processes shown in steps 1 and 2, we know who the decision makers are and what courses of actions are open to them. The next step identifies the attributes which the decision makers consider relevant to the question. According to Goodwin and Wright (2004), an attribute is used to measure the performance of courses of action in relation to the objectives of the decision maker. Each attribute needs to be assessed on a numerical scale. In this study, the attributes are gleaned from the Wertz et al. (2011) requirements development process utilized in steps 1-2 of the SMART method and outlined in Figure 7. Requirements which delineate the various power production schemes will be used. A value tree is constructed which addresses the various concerns of the decision maker in the form of requirements.

4.4.1 Summary of Likely Power System Drivers and Requirements

To construct a value tree of requirements, likely power system drivers and requirements need to be developed. One starts to apply broad requirements to system level applications. Physical characteristics, such as size and weight, and quality factors, such as reliability and maintainability, are developed from stakeholder requirements. The physical and quality factors developed will be high level due to the high level of this analysis. The applicable physical requirements will be associated with system availability, cost, and the user interface.

Policy, legal, and safety factors are rolled into this step. One objective of Step 3 is to ensure any policy, legal, and safety issues are addressed within the requirements development. Results of defining the policy, legal, and safety requirements may be rolled back into defining non-functional requirements, as well as functional and performance requirements.

4.4.2 Development of the Value Tree of Requirements

The value tree visually addresses the attributes which are of interest to the decision maker. The requirements developed are shown in tree form as they flow through the space systems engineering requirements development process. The customer expectations are broken down to a level where they can be assessed. When the tree is complete, the attributes which can be used to delineate each power system from one another will be identified and listed. Keeney and Raiffa (1976) have listed five criteria which one can use to judge the tree once the value tree is constructed.

1) Completeness: A complete tree will address all the decision makers' concern.

2) Operationality: Operationality is met when all the lowest-level attributes in the tree are detailed enough for the decision maker to take the attribute and compare the different options.

3) Decomposability: An attribute which can be judged independent of its performance on other attributes is considered to have decomposability.

4) Absence of redundancy: Attributes which basically repeat one another should be eliminated. If two attributes are duplicates, the attribute may end up being counted twice, thus skewing the results by adding undue weight to the final score.

5) Minimum size: The value tree needs to be as small as possible. For a large tree, meaningful analysis is extremely difficult. To minimize size, attributes should be decomposed to a level where it can be evaluated and no lower. The value tree may be reduced by eliminating attributes which do not distinguish between options.

The value tree process can be iterative. As more information is developed during the research, the value tree may grow or shrink depending on operability. As new insights are gained to the nature of the problem, the value tree should be reevaluated for impact (Goodwin & Wright, 2004).

4.5 Step 4: Assignment of values to measure the performance of the alternatives to the attributes identified in step 3

There are several parts to Step 4. To compare values, performance assessments and system trade studies are conducted. Among other criteria, the Step 3 analysis identified system costs related to mass and volume as an extremely important criterion for a lunar power cycle. The costs relate directly to launching the system from the Earth to the lunar surface. A second analysis takes system mass and volume information and places estimated costs to deliver the system to the lunar surface. Once these two analyses are complete, values are assigned which measure the performance of the Step 3 alternatives.

4.5.1 Conduction of Performance Assessments and System Trades

To evaluate the ammonia-water thermodynamic power system in reference to the other power production schemes, two types of analysis are required. The first analysis is a thermodynamic study of the lunar ammonia-water thermodynamic power architecture. The second analysis estimates system sizes and masses by applying the results of the thermodynamic study and data from historic space power systems.

The thermodynamic study is conducted in four steps shown in Table 3.

Table 3: Thermodynamic Study Steps

Step	Description
1	Identify appropriate thermodynamic equations to model ammonia-water system
2	Develop evaluation code and validate against previous studies
3	Perform analysis runs on ammonia-water architectures and previously proposed system architecturessunlight/decreased night at lunar pole
4	Consolidate and analyze results

Each of the thermodynamic study steps are sequential. The first step is developed from literature, which has well established thermodynamic analysis methodology for each of the components within the power system. The second step applies the equations identified in the first step to code which can be validated against calculated results found in peer-reviewed literature. The third step conducts the thermodynamic code calculations for the identified ammonia-water system. The third step specifically looks at the 14.75 terrestrial day lunar day/night cycle at lunar equator and increased sunlight/decreased night at lunar pole as specified by the design reference missions. The final step consolidates the results and provides interpretive results analysis.

The mass and volume analysis heavily relies upon the results from the thermodynamic study. The size of components identified in the prior step are directly related to the thermodynamic needs. For example, the area of the solar concentrator which collects solar heat for the thermodynamic cycle is directly related to the amount of heat the thermodynamic power cycle demands and the efficiencies a cycle can provide. The area of the collector will determine the mass required. Based on the amount of thermal heat required (kWt), the mass of the collector will utilize the kg/kWt value identified previously. Each of the components will follow a similar path to estimate the mass and volume values needed to launch the system from Earth's surface.

4.5.2 Performance of an Economic Analysis

To answer the research question, the mission's utility is evaluated with an economic analysis which develops a cost estimate based on launch mass and launch vehicle size requirements, lunar location impacts, ease of expansion, component expense, component life cycle costs, and component reliability. Each section of the economic analysis compares the Kalina cycle, photovoltaic, nuclear thermodynamic and sun-powered thermodynamic power generation schemes.

The first part of the economic analysis utilizes system mass developed in the prior step to calculated launch costs. Each power scheme has a different launch mass which result in a wide range of costs. The amount of mass required to be placed on the lunar surface will determine the number of launches and launch vehicles required. These launch costs are tabulated and compared.

The second section of the economic analysis compares system costs, component expenses, life cycle costs, reliability, and monetary impacts of power production expansion. A qualitative analysis is conducted to determine whether the Kalina cycle has any economic advantages over other power schemes when increasing the amount of power provided to the lunar base or industrial operation. Different power schemes increase the production of power in different ways. For example, photovoltaic systems need more power panels, inverters and batteries; whereas thermodynamic systems may need to add additional turbines, radiators, thermal capture capability and other components. Industry data are gathered qualitatively to comparable component expenses for the ammonia-water thermodynamic system as it compares with the other power schemes. The analysis should point to any advantages or disadvantages of each power schemes as it relates to operation costs, maintenance costs, and individual component expenses.

4.5.3 Performance Summary Development of How Well the Options Perform on Each Attribute

This step collects the findings from the thermodynamic analysis and economic analysis. The findings are compared against the attributes developed in Step 3 and assigned attribute values. According to Goodwin and Wright (2004), two methods are available to measure how well each power scheme performs in relation to the key attributes: direct rating and the use of value functions. Both methods are used in this dissertation. Direct rating is used for attributes which cannot be represented by easily quantifiable variables such as safety. Value functions will be used for attributes which can be represented by easily quantifiable variables such as system mass. Once each of the attributes are scored, the values will be placed in a table. The performance summary table will be used as the starting point for Step 5.

4.6 Step 5: Weight determination for each of the attributes determined in step 3

Step 4 determined how well each power scheme performed within a single attribute. Step 5 starts the process of aggregating the different attribute scores into one final score. Not all attributes carry the same importance. Goodwin and Wright (2004) attach weights to each attribute to delineate among the various attributes. The method used in this dissertation is the swing weight method developed in the SMARTER (SMART Exploiting Ranks) method (Edwards & Barron, 1994). The determination of weights can be broken into two parts: ranking the attributes from least to most important base on priority found in literature and assigning weights through the Rank Order Centroid (ROC) weights. A swing matrix defines what the researcher means in the decision context relating to the range and importance of value measurements. The swing matrix is a tool which outlines what measures should be weighted higher than others by differentiating the alternatives. Multiple design reference missions will be used for analysis. A different swing matrix and follow-on analysis is required for each mission.

4.6.1 Definition of Attribute Importance

To develop a swing matrix, one first must look at inherent customer expectations and rank them in importance of value to measure a decision. One must ask what the most valuable attribute of a lunar power system is. This answer will be derived from literature available from historic requirements studies. Immutable attributes should be higher than an attribute which the customer or requirement would like to have. Once the attributes are ranked, each attribute's value variation needs to be identified.

4.6.2 Placement of Value Measures into a Swing Matrix

The matrix now can be created, and the weights calculated. The swing matrix will be formatted like Table 4.

Table 4: Swing Matrix Design

	Value Dimensions						
Power Scheme	Attribute 1	Attribute 2	Attribute 3	Attribute 4	Attribute 5	Attribute 6	Agg. Utility
Kalina	X	X	X	X	X	X	X
Solar Brayton	X	X	X	X	X	X	X
Solar Stirling	X	X	X	X	X	X	X
Nuclear Brayton	X	X	X	X	X	X	X
Photovoltaic	X	X	X	X	X	X	X

The values for the attribute are determined in Step 4. Where this matrix adds value is the ranking of attributes across the top and the determination of the aggregate utility. The aggregate utility number is based on weight and is determined by utilizing the ROC weights. ROC weights are shown in Table 5.

Table 5: ROC Weights. Reprinted from "SMARTs and SMARTER: Improved Simple Methods for Multiattribute Utility Measurement," by Edwards, W., & Barron, F., 1994, *Organizational Behavior and Human Decision Processes*, *60*, p. 320. Copyright 1994 by Academic Press.

ROC WEIGHTS FOR INDICATED NUMBER OF ATTRIBUTES

	Number of Attributes							
Rank	9	8	7	6	5	4	3	2
1	0.3143	0.3397	0.3704	0.4083	0.4567	0.5208	0.6111	0.7500
2	0.2032	0.2147	0.2276	0.2417	0.2567	0.2708	0.2778	0.2500
3	0.1477	0.1522	0.1561	0.1583	0.1567	0.1458	0.1111	
4	0.1106	0.1106	0.1085	0.1028	0.0900	0.0625		
5	0.0828	0.0793	0.0728	0.0611	0.0400			
6	0.0606	0.0543	0.0442	0.0278				
7	0.0421	0.0335	0.0204					
8	0.0262	0.0156						
9	0.0123							

For example, the weight for a Kalina cycle with six attributes will be calculated by equation 4.2.

W_K = (0.4083 * Attribute 1 score) + (0.2417 * Attribute 2 score) + (0.1583 * Attribute 3 score) + (0.1028 * Attribute 4 score) + (0.0611 * Attribute 5 score) + (0.0278 * Attribute 6 score) (4.2)

Barron and Barrett (1996) tested this method for error-producing capabilities extensively with simulations and found ROC weights leading to the best option around 87% of the time.

4.7 Step 6: Multiplication of the weight with the attribute value and determination of the score value for each of the power cycles

The weight determined in step 5 is multiplied with each attribute value determined in step 4. The results are shown in table form.

4.8 Step 7: Provisional determination of the best power cycle for a lunar base or industrial process

Based on the values determined in step 6, one can make a provisional determination of which lunar base is best for the various situations. There will be multiple design reference missions where the various power systems will be analyzed. Literature review shows that power systems will vary in specific weight (kW/kg) as power system gets larger, which should lead to a different result depending on the design reference missions.

4.9 Step 8: Performance of a sensitivity analysis to see how robust the decision is and which requirements and attributes are most important

The final step to the dissertation is the sensitivity analysis. A sensitivity analysis is used to give the researcher an understanding of how robust the choice of an alternative is to changes in the figures used in the analysis (Goodwin & Wright, 2004). For this dissertation, starting with the heaviest weighted requirement, each weight will be evaluated at zero. The zeroing out of the weights will see how sensitive the values are to a certain requirement. A large change in the data is often required before one option becomes more attractive than another. Winterfeldt et al. (1986) refer to this phenomenon as a flat maximum.

4.10 Methods Summary

This dissertation utilized an analysis of alternatives to answer the research questions. The SMARTER method is the overall analysis method utilized with special emphasis placed on the requirements development process of Wertz et al. (2011). Because the analysis of alternatives is evaluating space hardware systems, Wertz et al. (2011) provide a requirements development process which is geared toward space hardware. At the end of the analysis, scoring is produced with which one can use to answer the research question. The chapter 5 will start with Step 1 of the analysis method presented in this chapter.

CHAPTER 5
OBJECTIVES DEFINITION

5.1 Introduction

This chapter frames the problem being addressed in detail. Qualitative requirements, quantitative requirements, customers, and constraints are defined. In addition to requirements and constraints, a design reference mission is identified and outlined. The information presented allows proper analysis of the ammonia-water power system and comparison of results to nuclear thermodynamic, solar thermodynamic, and photovoltaic power systems.

5.2 Qualitative Objectives and Constraints

The first step to answer the research questions is to define broadly what is to be analyzed. High level mission needs are outlined as qualitative objectives and constraints. Identifying applicable policy and law constructs the legal limits a system architect can work within. The second part of the initial qualitative process is identifying system and study constraints. To keep the analysis within reason, several bounds are established which provide analysis boundaries.

5.2.1 Applicable Lunar Policy and Law

International regulatory framework includes international space law, specifically The Outer Space Treaty, The Liability Convention, and the Use of Nuclear Power Sources (NPS) Principles; nuclear treaties, specifically The Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency. Domestic regulation and customs include the National Environmental Policy Act (NEPA) and U.S. Space Resource and Exploration Utilization Act of 2015. NEPA can become quite complex and not always easy to follow. However, NEPA attempts to take action consistent with public interest (Mirmina & Herder, 2005). Mirmina and Herder (2005) point out that with this process, citizens “have a standard by which to measure their government's actions. By following these practices, the US government is able to avoid unnecessary risks.” The United Nations (UN) has several recommended space power frameworks including the Safety Framework for Nuclear Power Source Application in Outer Space and Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space. Table 6 is a summary of the space policy and law which impact lunar space power systems. Space laws and policies are covered more in depth in Appendix 1.

Table 6: Summary of Applicable Lunar Policies and Laws

1	Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty)
2	Convention on International Liability for Damage Caused by Space Objects (Liability Convention)
3	The Principles Relevant to the Use of Nuclear Power Sources (NPS) in Outer Space
4	National Environmental Policy Act (NEPA)
5	Safety Framework for Nuclear Power Source Application in Outer Space
6	Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space
7	U.S. Space Resource Exploration and Utilization Act of 2015

5.2.2 Defining Policy, Legal, and Safety (PLS) Factors

The objective of this section is to ensure any policy, legal, and safety issues are addressed within the requirements development process. PLS factor requirements directly impact the power system architecture. The requirements dictate how a system can be safely and legally installed and operated. For more detail on Space Law and Policy, please see Appendix 1.

1) Avoid Harmful Contamination of the Lunar Surface (Article IX of the Outer Space Treaty)

PLS Requirement: Operate the power system in such a way as to avoid harmful contamination of the lunar surface.

Definition: A lunar power system can be viewed as somewhat invasive, especially a nuclear power system. A nuclear power system may require burying or heavy shielding to insulate the local area from radioactive contamination. These additional steps will result in secondary effects such as irradiated soil around the nuclear reactor site or radiated material surrounding a reactor. The soil around a buried reactor will also be disturbed or excavated resulting permanent alternation from its natural state. Virtually all power systems will utilize some type of working fluid. Leakage of working fluid may contaminate the local environment. If there is leakage in buried pipes or pipes above ground which are carrying the working fluid, the local environment may be permanently altered from its natural state. In the vacuum environment, much of the fluid may instantly freeze, sublimate, or evaporate. In other words, the material will litter the surrounding ground or dissipate to space.

2) Avoid Earth Contamination from Extraterrestrial Matter (Article IX of the Outer Space Treaty)

PLS Requirement: The power system should operate in such a way as to avoid adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter.

Definition: The power systems should not introduce extraterrestrial matter to the Earth's ecosystem. A system which requires minimal maintenance and interaction will reduce the possibility of Earth contamination.

3) Minimize Liability (Liability Convention)

PLS Requirement: The power system should be designed and deployed in such a way as to reduce the likelihood of damaging another party's vehicle or equipment. Damage could be caused by radiation, explosion, or numerous other means.

Definition: There are a few ways a power system could damage another party's vehicle or equipment. A nuclear power system can irradiate the vehicle or equipment. Proper burying or shielding is necessary. A solar powered thermodynamic system employs mirrors to concentrate sunlight. If equipment or vehicles are improperly located, damage could occur. Keep out zones can assist in prevention of property damage (Hearsey, 2016).

4) Minimize Use of Nuclear Power Sources (NEPA and NPS Principles)

PLS Requirement: The power system should restrict the use of nuclear power systems to missions which cannot be operated by non-nuclear energy sources in a reasonable way.

Definition: Due to radiating the local environment on the surface of the moon, a nuclear power system should be used sparingly and only if other power systems are not technically feasible. An operator of a lunar power system must consider potential health risks and accident scenarios.

5) Affordability

PLS Requirement: The power system needs to have affordable technology development cost, facility cost, operation cost, and cost of failure.

Definition: The economic analysis portion of this dissertation will be conducted in section 7.5. Since this is a new and immature technology—a lunar power system, the estimation should include research, development, test and evaluation, procurement, and operations and maintenance (Dhillon, 2009). The affordability requirement should use analogies to predict costs historical data.

6) Safe to Operate

PLS Requirement: Allows operation to fall within radiation and safety limits outlined in NASA Space Flight Human System Standards - NASA Standard 3001 and the NASA System Safety Handbook (NASA, 2015; NASA, 2019; NASA, 2011). All operation parameters need to be included such as keep out zones, system degradation, and any location sensitivities.

Definition: The NASA System Safety Handbook utilizes NPR 8715.3C and MIL-STD-882D for its definition of safety. The handbook defines safety as freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment. Safety can be put in quantitative terms. Safety can be quantified through probability calculation of how well undesirable consequences will be avoided or the how likely unwanted consequences will occur. The probability of unwanted consequences occurring is the most common way to quantify safety and is typically referred to as risk. The safe to operate requirement focuses on system safety. As the NASA Safety System Handbook states, “System safety is to safety as systems engineering is to engineering” (NASA, 2011). To look at power systems from a system safety analysis perspective, an evaluation is needed which looks at safety of the system holistically. To holistically look at system safety, one needs to identify what causes undesired consequences and the drivers that cause the scenarios to be critical. Figure 10 shows a flow down of the areas of safety which need to be addressed.

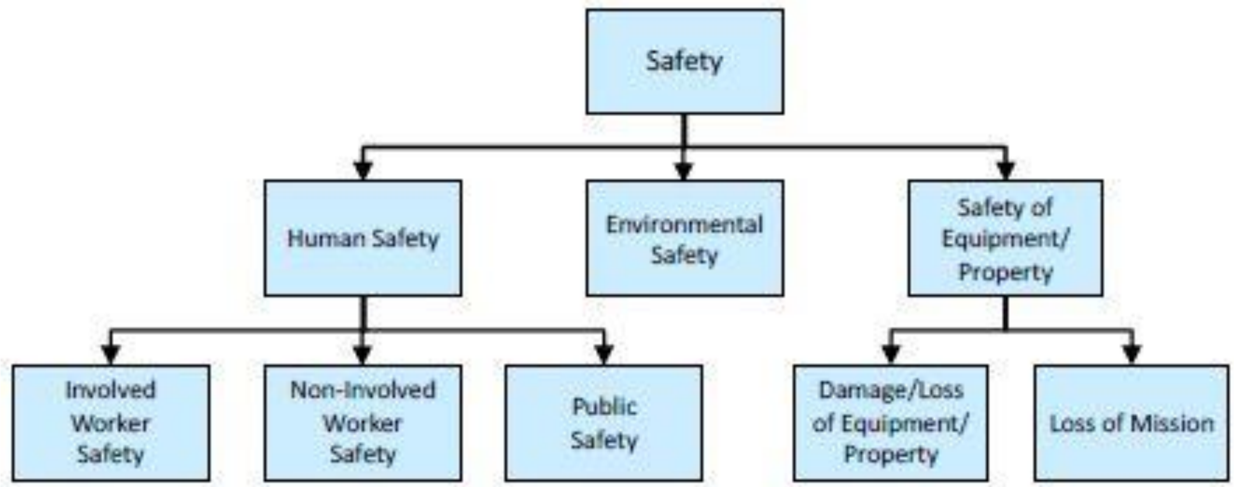

Figure 10: Impacted Populations within the Scope of Safety (NASA, 2011)

What areas of a power system need to be analyzed for safety to ensure it is an adequately safe system? NASA (2011) defines an adequately safe system as meeting or exceeding a minimum tolerable level of safety. Adequate safety for the impacted populations leads into the following sub-requirements.

a. Sub-requirement: A power system will radiate the habitat module no more than 5 rem/yr (NASA, 2005a).

Definition: The maximum radiation requirement is focused on nuclear power system architecture. Nuclear power system architectures need to be tailored with adequate shielding either brought with the system, movement of regolith, or location of the system far enough away from lunar habitats to minimize radiation.

b. Sub-requirement: Hardware and equipment shall not release stored potential energy in a manner that causes injury to the crew (NASA, 2019).

Definition: Improper energy storage can result in a safety hazard. Explosions, a damaged flywheel, and improperly handled thermal storage can cause injury. Site architecture may need to be designed to isolate storage to minimize safety hazards.

c. Sub-requirement: Hardware mounting and habitat enclosures shall be configured such that the crew is protected from projectiles and structural collapse in the event of sudden changes in acceleration or collisions (NASA, 2019).

Definition: Energy production and storage on Earth have been known to have meltdowns and explosions. Site architecture may need to be designed to isolate energy production and storage to minimize safety hazards.

d. Sub-requirement: Hardware and equipment shall not release stored fluids or gases in a manner that causes injury to the crew (NASA, 2019).

Definition: Energy production and storage on Earth have been known to have meltdowns and explosions. Site architecture may need to be designed to isolate energy production and storage to minimize safety hazards.

The purpose of this analysis is to establish a list of requirements by which a power system—used on the lunar surface for base power or in situ resource utilization—can be designed, measured, and compared. Table 11 shows a rollup of the resulting lunar power system requirements. Each of the performance requirements are directly linked to a function requirement. Although not shown in Table 11, each functional requirement is directly traceable to a customer expectation. In addition to Table 11, the physical characteristic requirements resulting from the operational scenario—shown in Figure 12—were developed to assist further analysis.

5.2.3 Qualitative Constraints

The dissertation analysis is limited to evaluating power systems located on the lunar surface. The lunar surface environment further limits what types of power systems can be utilized. Additional limitations will set scope to conduct dissertation research in a reasonable amount of time.

The lunar environment is a huge limiting factor. The physical lunar environment is much different than its terrestrial counterpart. The lunar environment has extreme temperature fluctuations, gravity which is 1/6 of the Earth's, virtually zero atmosphere, ionizing radiation, micrometeoroid bombardment, electrostatically charged lunar dust, and even odd lighting conditions (Heiken et al., 1991).

Realistically, the establishment of a manned lunar base, as well as any type of lunar industrial operation, will be very challenging. The technical issue of required power will necessitate an incremental approach. As our lunar presence grows, the power requirements for such a presence will grow. Initially, power requirements will be in the tens of kilowatts level. Eventually, megawatts of power may well be required. The consensus among technical experts in the space power community is consistent. Initially, photovoltaic power will be sufficient, but eventually some type of thermodynamic cycle such as a Brayton cycle heated by a nuclear or concentrated solar source will be necessary (Brinker & Flood, 1988).

5.3 Principal Players

Principal players drive any initial requirements. Defining the customers and their expectations will establish initial requirements.

5.3.1 Defining Principal Players

According to NASA's published system design process, the Stakeholder Expectations Definition Process is the first step in the systems engineering process. Expectation's definition lays the foundations from which a system is designed and the end product developed.

Since this study would be considered in life-cycle stage Pre-Phase A, NASA defines its stakeholders in Pre-Phase A as NASA Headquarters, NASA Centers, Presidential Directives, NASA advisory committees, the National Academy of Sciences (NASA, 2016). If the ammonia-water thermodynamic power cycle concept were to graduate to the next life cycle, there would be a different set of stakeholders. According to Figure 8 pulled from NASA's System Engineering Handbook, the next stage of defining the principal players is defining customer expectations through needs, goals, objectives, constraints, and success criteria.

5.3.2 Defining Customer Expectations

The literature review revealed that specific customer expectations vary dependent upon mission set (NASA, 2005a; NASA, 2004; Petri et al., 2006; Cataldo & Bozek, 1993). In this analysis, customer expectations are intended to bracket a range of potential lunar mission scenarios and associated power system functionality. The design reference mission will be developed in a following section. Eight customer expectations are developed from the ESAS Figures of Merit (FOM) shown in Table 7 (NASA, 2005a).

1) Flexible, able to use the power system at multiple location on the Lunar surface including the lunar equator, lunar mid latitude, and the lunar pole. Operation during lunar night and day supporting the five mission sets of astronomy, space physics, geology, geophysics, and in-situ resource utilization.

2) Safe to operate including autonomous operations, small keep out zone, graceful degradation, and low site sensitivity

3) Reliable, i.e., high probability of mission success

4) Affordable in technology development cost, facility cost, operation cost, and cost of failure

5) Long operational life, 10 years with minimal maintenance or 20 years with some maintenance

6) Low programmatic risk concerning technology development, cost, schedule, and political issues

7) Minimal launch mass

8) Easily packageable and deliverable system

Table 7: Power System FOMs (NASA, 2005a)

Table 4-28. Power System FOMs FOMs		FSPS	PV/RFC Power System	Hybrid Power System	LRPS Supplemental power source only; not comparable to first three options
Safety and Mission Success		Robust power; autonomous; mass scales well with power; 2-km keep-out zone	Highly site sensitive; Higher mass except under ideal illumination; graceful degradation	Diversity of sources; more graceful degradation; highly site sensitive	Autonomous; smaller keep-out zone
Extensibility/ Flexibility	Lunar Flexibility	Low sensitivity to outpost location	100 kWe mass prohibitive except at ideal site	Low sensitivity to outpost location after FSPS placement	Can be mobile
	Mars Extensibility	Atmosphere will affect outer shell and radiator design	Reduced solar flux yields significantly larger arrays	Atmosphere will affect outer shell and radiator design plus larger solar arrays	Atmosphere will affect outer shell and radiator design
Programmatic Risk	Technology Development Risk	Need to develop infrastructure, system not yet at TRL–6, Many design options	System not yet at TRL–6; alternatives to RFC at even lower TRL	System not yet at TRL–6	System not yet at TRL–6, design options
	Cost Risk	Significant infrastructure cost	Substantially lower DDT&E cost	Significant infrastructure cost	Significant costs in increasing heat source availability
	Schedule Risk	If start FY06	If start FY06	If start FY06	If start FY06
	Political Risk	National Environmental Policy Act (NEPA)	None	NEPA	NEPA
Affordability	Technology Development Cost	High, ground test reactor	Relatively Low	Two concurrent programs	Relatively low
	DDT&E Cost	$3+B class	$2B class	$4+B class	$1+B class
	Facilities Cost	Cost of nuclear infrastructure	Existing facilities may need mods for 1/6th g simulation	Cost of nuclear infrastructure	Cost of nuclear infrastructure
	Operations Cost	Relatively low	100 kWe system requires most launches	Relatively low	NSRP process for multiple launches
	Cost of Failure	High consequences if first reactor fails	High mass for replacement	Diversity of sources gives redundancy	Existing
Legend:	Best	Few challenges	Moderate challenges	Serious challenges	Potential show stopper

5.4 Design Reference Missions

The objective of this step is to use the established customer expectations to develop and define operational scenarios. Operational scenarios allow system baseline functionality to be developed. Power system requirements may vary dependent upon the operational scenario they support. Operational scenarios allow for broad system understanding.

Operational scenarios are developed using Duke's et al. (2003) Lunar Surface Reference Missions. Lunar mission objectives are defined as scientific exploration, astronomical observations, test bed for long-term human lunar stays, test bed for technologies for exploration of Mars and beyond, and technology tests for economical beneficial activities on the moon (Duke et al., 2003). Duke et al. (2003) see photovoltaic as an initial power system followed by nuclear power for larger and longer missions. The ammonia-water thermodynamic power system analyzed by this dissertation will be evaluated against both types of power systems.

Based on Duke's et al. (2003) lunar surface reference mission options, the following three operational scenarios bracket a range of potential lunar mission scenarios and associated power system functionality. The scenarios look to address the customer expectations outlined in the previous section. In the past, NASA has conceptualized numerous strategies for exploring and developing the Moon. Strategies typically include two development occupancy options—permanent occupancy and intermittent occupancy (Petri et al., 2006). However, per the defined scope, these operational concepts are limited to permanency occupancy; stationary power systems (not mobile); two locations including one equatorial and one (1) polar location; 5 mission set power needs (25kW, 100kW, 250kW, 500kW, 1MW).

1) Emplacement Phase (25 kW)

The purpose of the emplacement phase is for outpost operators to gain practical experience constructing and operating a lunar outpost. Unmanned flights will deliver the initial equipment to the selected outpost site, including any site surveying rovers, habitat modules, and initial power systems. This initial phase should allow a crew of 4 to live and work at the outpost for a minimum of 30 days. Activities supported will include performing science activities—small astronomy, space physics, geology, and geophysics experiments—and emplacing additional equipment as it arrives. These activities allow transition to the next phase. After initial habitat and power system installation, a laboratory module along with any additional equipment needed to support a crew of 4 for up to 6 months will be installed. Throughout this phase, the outpost should be able to support small astronaut teams, small science missions, and short EVAs. The emplacement phase is expected to last 3-5 years (Petri et al., 2006).

Based on the data provided by Petri et al. (2006), the power required for daytime operations is 10.8 kW and 9.7 kW during the lunar night. The power during the lunar night will necessitate usage of a power storage system unless utilizing nuclear power. The amount of power or heat storage needed will vary dependent on system location. At the lunar equator, the lunar night and day are both approximately 14 terrestrial days long. A non-nuclear power system at the lunar equator will necessitate energy storage of 14 terrestrial days to operate at during the dark hours. At the lunar pole, the amount of storage needed for a non-nuclear system substantially lower—in some places, virtually zero (Fincannon, 2008).

2) Consolidation Phase (100 kW, 250 kW)

The consolidation phase follows the initial emplacement phase and focuses on three primary objectives which will allow our further understanding of how to operate non-terrestrial outposts. The three objectives are learning to build pre-fabricated habitats, gaining experience with in-situ resource utilization (ISRU), and developing operational techniques which can be used for future Mars missions. To fully realize the three objectives, power systems of up to 100 kW or 250 kW may be required. As a starting point, power on the order of 100 kW will be needed, particularly for ISRU processing plants for a permanent base. The expanded power will be used to support expansion of the habitable volume of the outpost as well as building a lunar-derived liquid oxygen (LOX)/hydrogen pilot plant. The new habitable volume will allow additional crew to live on the lunar surface, increase the science laboratory space, and allow for low gravity end-to-end Mars mission simulation. The construction of the lunar-derived LOX/hydrogen plant will allow engineers to gain valuable insight into operation of such an

ISRU installation. During this phase, mission sets of astronomy, space physics, geology, geophysics, and in-situ resource utilization are supported. This phase is expected to last 5-10 years.

Table 8: 100 kW Consolidation Phase Mission Power Usage (NASA, 2005b)

Load	Requirements			Power System Technology	
	Power, kW	When	How Long	Baseline	Alternative
Habitat Module	15	day/night	10 yr	FSPS	PV / PEM RFC
Lander-Crewed	3.85	day	7 days	PV / Li ion Batt	Prim PEM FC / Li ion Batt (ascent)
Lander-Dormant	1.15	day/night	1-yr	FSPS	adv SRG
Cargo Lander	1.15	day/night	10 yr	Li Ion Batt - FSPS	***
Comm/Nav System	0.9	day/night	10 yr	FSPS	***
Pressurized Rover (w/ or w/o Power Cart)	7	day/night	3-12 day sorties	PEM RFC - FSPS	PV / PEM RFC
Heavy Deployment Rover (ISRU, Logistics Module, etc.)	3.1	day	days	PEM RFC - FSPS	adv SRG
Lunar Unpressurized Rovers	2.15 (crew) / 1.0 (tel)	day	8 hr - sortie	Li ion Batt - LSAM or FSPS	adv SRG
Science Rovers	0.15 each	day	14 day periods	PV / Li ion Batt	***
EVA Suits	0.15	day/night	8 hr - sortie	Li gel-polymer Batt - FSPS	Li ion Batt - FSPS
ISRU Equipment - O2 Plant	15	day or day/night	14 day periods or 10-yr	FSPS	PV / Li ion Batt
ISRU hydrogen/water excavation and extraction	15	day/night	1-2 hr periods	PEM RFC - FSPS	***
ISRU Equipment - Lunar Excavator Hauler	9	day/night	2-4 hr periods	PEM RFC - FSPS	***
Drill Science Equipment	6	day/night	10 yr	adv SRG	FSPS
ISRU Demo Plant	2.25	day	14 day periods	PV / Li ion Batt	***
Science Package 1	0.5	day	14 day periods	PV / Li ion Batt	***
Continuous Ops Science Equipment	0.1 - 0.75	day/night	10 yr	FSPS (local sites)	adv SRG (remote sites)
ISRU Package 1	0.2	day	14 day periods	PV / Li ion Batt	***
ISRU Excavation Demo	0.15	day/night	8 hr periods	Li ion Batt - FSPS	adv SRG

3) Operations Phase (500 kW, 1 MW)

The operations phase will cover the lunar outpost's transition into its permanent phase. In the operations phase, outpost objectives will include expansion of science activities to support actions on the far side of the Moon, increased utilization of local resources, and eventually becoming more self-sufficient. A key ingredient which enables such objectives to be obtained is more available electrical power. Large dynamic power systems should allow enough energy for local food production, an industrial scale LOX/Hydrogen plant, and utilization of other local resources such as titanium and iron. Such a LOX/hydrogen industrial plant should provide enough oxidant and propellant to fuel local LEV flights, as well as support flights to Mars. This phase is the “final” phase of a lunar outpost—meaning the outpost has moved into steady-state operations. During this phase, large astronomy, space physics, geology, geophysics, and in-situ resource utilization missions are supported.

To get a better idea of how all three phases work together, Figure 11 rolls up all three mission phases. Understanding the various phases helps one understand that a lunar architecture will evolve with time. Evolution of architecture may necessitate a change in the lunar power source to stay optimized. The evolution of architecture may impact the answer to the research questions.

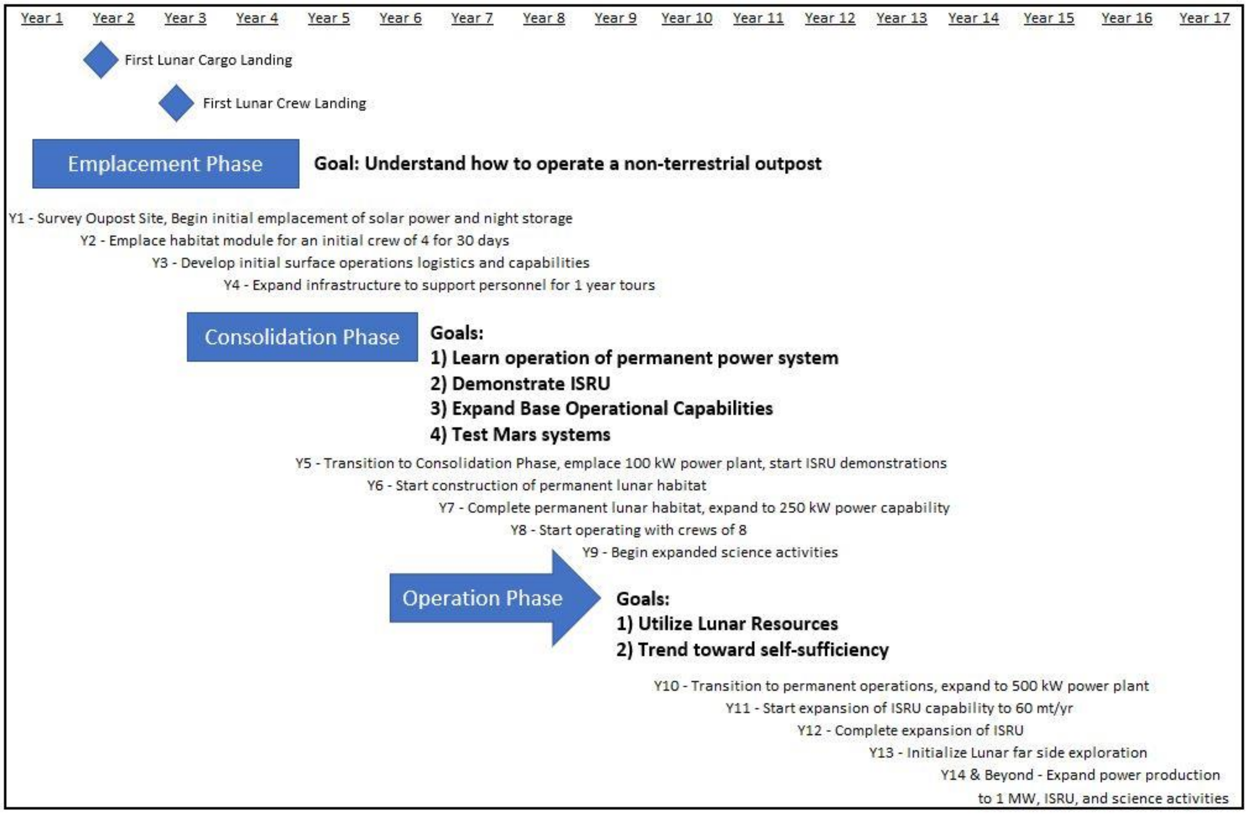

Figure 11: Overall Mission Timeline

5.5 Quantitative Requirements and Constraints

Now that the stakeholders are identified, stakeholder expectations recognized, and a design reference missions setup, three steps are taken to develop the quantitative requirements: a functional analysis is performed, system boundaries and interfaces are defined, and functional requirements developed. Constraints will follow the requirements development.

5.5.1 Quantitative Requirements

5.5.1.1 Functional Analysis

The functional analysis adds definition to the system architecture. The functional requirements are developed from the customer expectations and the operational scenarios. Each of the defined requirements can be traced directly to a customer expectation, PLS constraint, or developed from the operational scenarios. Each of the functional requirements introduced in this step will be further defined in the functional requirement development. Each of the customer expectations are shown in section 5.3.2.

1) Customer Expectation: Flexibility (see first expectation in section 5.3.2)

Functional Requirement: Able to use the power system at multiple location on the Lunar surface including the lunar equator, lunar mid latitude, and the lunar pole. Operation during lunar night and day supporting the five mission sets of astronomy, space physics, geology, geophysics, and in-situ resource utilization.

2) Customer Expectation: Reliability (see second expectation in section 5.3.2)

Functional Requirement: High probability of mission success. Operations will fall under the NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems. The top-level requirement for NASA concerning reliability and maintainability is "to ensure that systems perform as required over their lifecycles to satisfy mission objectives including safety, reliability, maintainability, and quality assurance requirements" (Wilcutt, 2017). For a power system, the top-level NASA requirement is broken down into four sub-requirements.

a. The power system will perform as designed and planned under failed and nominal conditions.

b. The power system is to remain functional for the intended lifetime, environment, operating conditions, and usage.

c. The power system will be tolerant to faults, failures, and anomalous events.

d. The power system is designed in such a way as to satisfy the availability requirement.

3) Customer Expectation: Long Operational Life (see third expectation in section 5.3.2)

Functional Requirement: The power system needs an operational life of at least 10 years with minimal maintenance requirements. Life expectancy of longer than 10 years with some maintenance may be beneficial for reducing replacement system launch costs for permanent base occupation.

4) Customer Expectation: Low Programmatic Risk (see fourth expectation in section 5.3.2)

Functional Requirement: The power system needs to minimize risk associated with technology development, cost, schedule, and the political climate.

5) Customer Expectation: Minimal Launch Mass (see fifth expectation in section 5.3.2)

Functional Requirement: The power system needs to minimize launch mass.

6) Customer Expectation: Easily packageable and deliverable system (see sixth expectation in section 5.3.2)

Functional Requirement: The power system needs to be easily packaged for the trip to the lunar surface and easily deployed with minimal setup.

Table 9: Functional Requirement Summary

Fuctional Requirements	*1.0*		Able to use the power system at multiple location on the Lunar surface including the lunar equator, lunar mid latitude, and the lunar pole Operation during lunar night and day supporting the five mission sets of astronomy, space physics, geology, geophysics, and in-situ resource utilization
	2.0		High probability of mission success
		2.1	The power system will perform as designed and planned under failed and nominal conditions.
		2.2	The power system is to remain functional for the intended lifetime, environment, operating conditions, and usage.
		2.3	The power system will be tolerant to faults, failures, and anomalous events.
		2.4	The power system is designed in such a way as to satisfy the availability requirement.
	3.0		The power system needs to have a long operational life with minimal maintenance requirements.
	4.0		The power system needs to minimize risk associated with technology development, cost, schedule, and the political climate
	5.0		The power system needs to minimize launch mass
	6.0		The power system needs to be easily packaged for the trip to the lunar surface and easily deployed with minimal setup

5.5.1.2 System Boundary and Interface Definition

The system boundaries are outlined in the constraints section 5.5.2.

System interfaces provide direct and indirect inputs and outputs into system functionality. Power system interfaces are developed from the customer expectations and operational scenarios. Section 4G of ESAS, Surface Power Systems, provide an output summary of electrical loads for a 100W requirement. Table 10 shows outputs required from the power system to various lunar base operations as adapted from ESAS, Section 4G (NASA, 2005b) and Petri, Cataldo, and Bozek (2006).

Table 10: Outpost Electrical Loads and Power Requirements Summary

		25 kW Power System, kW	100 kW Power System, kW	250 kW Power System, kW	500 kW Power System, kW	1 MW Power System, kW
Equatorial Operation	Habitat Module	7	6	15	30	60
	Lander-Crewed	1.8	1.54	3.85	7.7	15.4
	Lander-Dormant		0.46	1.15	2.3	4.6
	Cargo Lander		0.46	1.15	2.3	4.6
	Comm/Nav System		0.36	0.9	1.8	3.6
	Pressurized Rover (w/ or w/o Power Cart)	-	2.8	7	14	28
	Heavy Deployment Rover (ISRU, Logistics, Moduel, etc.)	-	1.24	3.1	6.2	12.4
	Lunar Unpressurized Rovers	0.9	1.26	3.15	6.3	12.6
	Science Rovers (ea)	0.1	0.06	0.15	0.3	0.6
	EVA Suits	-	0.06	0.15	0.3	0.6
	ISRU Equipment - O2 Plant		6	15	30	60
	ISRU hydrogen/water excavation and extraction		6	15	30	60
	ISRU Equipment - Lunar Excavator Hauler		3.6	9	18	36
	Drill Science Equipment		2.4	6	12	24
	ISRU Demo Plant	-	0.9	2.25	4.5	9
	Science Package 1		0.2	0.5	1	2
	Continuous Ops Science Equipment	1	0.3	0.75	1.5	3
	ISRU Package 1	-	0.08	0.2	0.4	0.8
	ISRU Excavation Demo	-	0.06	0.15	0.3	0.6
	Charge for Night Operation	14.2	66.22	165.55	331.1	662.2
Polar Operation	Habitat Module	16.2	17.8	44.4	88.8	177.6
	Lander-Crewed	4.2	4.6	11.4	22.8	45.6
	Lander-Dormant	-	1.4	3.4	6.8	13.6
	Cargo Lander	-	1.4	3.4	6.8	13.6
	Comm/Nav System	-	1.1	2.7	5.3	10.7
	Pressurized Rover (w/ or w/o Power Cart)	-	8.3	20.7	41.4	82.9
	Heavy Deployment Rover (ISRU, Logistics, Moduel, etc.)	-	3.7	9.2	18.4	36.7
	Lunar Unpressurized Rovers	2.1	3.7	9.3	18.7	37.3
	Science Rovers (ea)	0.2	0.2	0.4	0.9	1.8
	EVA Suits	-	0.2	0.4	0.9	1.8
	ISRU Equipment - O2 Plant	-	17.8	44.4	88.8	177.6
	ISRU hydrogen/water excavation and extraction	-	17.8	44.4	88.8	177.6
	ISRU Equipment - Lunar Excavator Hauler	-	10.7	26.6	53.3	106.6
	Drill Science Equipment	-	7.1	17.8	35.5	71.0
	ISRU Demo Plant	-	2.7	6.7	13.3	26.6
	Science Package 1	-	0.6	1.5	3.0	5.9
	Continuous Ops Science Equipment	2.3	0.9	2.2	4.4	8.9
	ISRU Package 1	-	0.2	0.6	1.2	2.4
	ISRU Excavation Demo	-	0.2	0.4	0.9	1.8
	Charge for Night Operation	N/A	N/A	N/A	N/A	N/A

5.5.1.3 Functional Requirement Development

Each of the functional requirements introduced in section 5.5.1.1 will be further defined in the functional requirement development. Functional Requirement Section 1 will add definition. Functional Requirement Section 2 will turn the additional definition into quantifiable performance requirements.

5.5.1.3.1 Functional Requirement Definition

In this step, the functional requirements developed in the functional analysis are defined in greater detail. The functional requirements are developed from the customer expectations and the operational scenarios. See section 5.5.1.1 for initial functional requirements development.

1) Flexibility Definition (see 5.5.1.1 for functional requirement)

The flexibility requirement enables any mission set to operate at any location on the lunar surface during the lunar day and night. The requirement will drive architecture design dependent upon location. A well-located site on the lunar pole for a sun-powered system will require minimal energy storage. An equatorial site for a sun-powered system necessitates energy storage for the lunar night of approximately 14 terrestrial days in length. Energy storage for night time operation will also drive system size for sun-powered systems. To store energy for lunar night operation at the equator, a sun-powered power system will need to produce excess power during the lunar day. More power means larger size and mass. A nuclear system has inherent flexibility.

2) Reliability Definition (see 5.5.1.1 for functional requirement)

Operations will fall under the NASA Reliability and Maintainability (R&M) Standard for Spaceflight and Support Systems (Wilcutt, 2017). The top-level requirement for NASA concerning reliability and maintainability is “to ensure that systems perform as required over their lifecycles to satisfy mission objectives including safety, reliability, maintainability, and quality assurance requirements" (Wilcutt, 2017). A full reliability, availability, and maintainability analysis is beyond the scope of this research. However, requirements based on historical analysis will be developed.

Sub-requirements:

a. Sub-requirement: The power system will perform as designed and planned under failed and nominal conditions.

Definition: The power system shall be designed with enough redundant equipment such that a single failed condition will not significantly affect operations. Failed conditions on the lunar surface include solar storms, galactic cosmic radiation, and micrometeorite impacts.

b. Sub-requirement: The power system is to remain functional for the intended lifetime, environment, operating conditions, and usage.

Definition: This sub-requirement hits on the maintainability aspect of the reliability requirement. Barring unusual environmental conditional, the system will operate for the intended lifetime with minimal maintenance or repairs. However, maintainability of the system is important.

c. Sub-requirement: The power system will be tolerant to faults, failures, and anomalous events.

Definition: The power system shall be designed with enough redundant equipment such that a single failure will not significantly affect operations. Redundancy or diversity of systems may be needed to satisfy this requirement.

d. Sub-requirement: The power system is designed in such a way as to satisfy the availability requirement.

Definition: The performance requirements will define the availability standard for a lunar power system. NASA defines operational availability as “the percentage of time that a system or group of systems within a unit are operationally capable of performing an assigned mission and can be expressed as uptime/(uptime+downtime)” (Wilcutt, 2017).

3) Long Operational Life Definition (see 5.5.1.1 for functional requirement)

Long operational life with minimal maintenance will provide a system with high reliability, availability and maintainability. The ability to refurbish at some point in the future may be beneficial for reducing replacement system launch costs for permanent base occupation.

4) Low Programmatic Risk Definition (see 5.5.1.1 for functional requirement)

A full risk assessment for a lunar power system is not within the scope of this research. However, requirements based on historical risk analysis will be developed.

5) Minimal Launch Mass Definition (see 5.5.1.1 for functional requirement)

Lower launch mass means lower cost to get a system to the lunar surface. As this functional requirement gets translated into a performance requirement, the performance requirement will vary based on location—polar or equatorial—and power level. Obviously, higher power systems and systems which requires energy storage will necessitate a higher launch mass.

6) Easily Packageable and Deliverable System Definition (see 5.5.1.1 for functional requirement)

A system which is easy to maximize launch vehicle volume may result in lower cost to get a system to the lunar surface. As this functional requirement gets translated into a performance requirement, the performance requirement will vary based on location—polar or equatorial—and power level. Obviously, higher power systems and systems which requires energy storage will necessitate a higher launch volume.

5.5.1.3.2 Functional Performance Requirement Definition

As described in the methods, a complete functional requirement has two main aspects: basic required capability or function and a quantified performance criterion linked to the basic capability. Each performance criterion is traceable to a supported functional requirement and is defined for each supported function. See section 5.5.1.1 for related functional requirements, and section 5.5.1.3.1 for related functional requirement definition.

1) Performance Requirement: Flexibility (see 5.5.1.1 and 5.5.1.3.1)

Able to use the power system during the lunar day and night at the lunar pole site, Amundsen (88S, 60E), and the lunar equator site, Riccioli (3.5S, 74W).

2) Performance Requirement: Reliability (see 5.5.1.1 and 5.5.1.3.1)

Performance Requirement: See sub-requirements

Sub-requirements:

a. Performance Sub-requirement: The power system will include a 30 percent power margin (see 5.5.1.3.1a).

Definition: Typically, when conditions degrade, productivity of the system diminishes. From a system architecture viewpoint, adding a power margin will assist in the system's ability to perform as designed and planned.

b. Performance Sub-requirement: The components which comprise the power system will allow for field maintenance and replacement (see 5.5.1.3.1b).

Definition: This addresses the maintainability and component design of the system. Maintainability is the probability a failed item will be restored or repaired to a specified condition within a given period of time. A full maintainability analysis is out of scope of this analysis.

c. Performance Sub-requirement: The power system will consist of a primary surface power system with a distribution grid and a secondary, stand-alone, power system (see 5.5.1.3.1c).

Definition: By having a secondary, backup power system, the architecture will be tolerant to faults, failures, and anomalous events. Primary power may consist of a nuclear power source, a solar thermodynamic system, or photovoltaic cells. The primary surface power system will be focus of this research. Conducting trade studies of the distribution grid and secondary power systems is out of scope for this research.

d. Performance Sub-requirement: The overall power system shall be designed to be available for 98% of the time with a 0.995 reliability during critical periods (see 5.5.1.3.1d).

Definition: The values shown are adapted from a 1990 Space Station Freedom Electric Power System Availability Study (Turnquist, 1990).

3) Performance Requirement: Long Operational Life (see 5.5.1.1 and 5.5.1.3.1)

The power system needs to have an operational life of at least 10 years with minimal maintenance requirements. Life expectancy of longer than 10 years with some maintenance may be beneficial for reducing replacement system launch costs for permanent base occupation.

4) Performance Requirement: Low Programmatic Risk (see 5.5.1.1 and 5.5.1.3.1)

Each candidate power system will be graded for risk associated with technology development, cost, schedule, and political climate according to guidance laid out in the NASA Risk Management Handbook (Dezfuli et al., 2011).

A high-level risk analysis will be one of the final steps in providing data to answer the research question. The performance requirements will be analyzed against predicted power system performance. TRL can be analyzed along with projected cost, schedule, and political environment.

5) Performance Requirement: Minimal Launch Mass (see 5.5.1.1 and 5.5.1.3.1)

The power system needs to employ simplicity to minimize launch mass.

Each power system architecture will be compared and contrasted against each other in reference to launch mass. Low launch mass and size equals fewer launches. Fewer launches equal lower cost overall.

6) Performance Requirement: Easily Packaged and Deliverable System (see 5.5.1.1 and 5.5.1.3.1)

The power system shall be sized to fit within the payload envelope of the SpaceX Falcon 9 Heavy. If needed, multiple launches are allowed.

5.5.2 Quantitative Constraints

Quantifiable constraints are now evaluated. The resulting values will guide system analysis and development.

1) Mission Power Set Limitation

a. Description: Five power levels to cover five mission sets will be analyzed (25kW, 100kW, 250kW, 500kW, 1MW).

b. Why: The amount of power required for a lunar base or industrial operation is a big driver in determining cost. Based on the DRMs, the amount of power required for a lunar mission will continually increase. As the system continually increases, the suitability of power schemes may change.

There have been many lunar base architecture studies over the years. One commonality between the studies is a power system which is modular and expandable. A 2005 NASA study summarized many of the previous studies. It summarized the studies as requiring a system of power generation, distribution, and control evolving from early exploration capabilities of 10 kW to longer-term permanent human presence of 1 MW (NASA, 2005a). Potential mission sets of astronomy, space physics, geology, geophysics, and in-situ resource utilization can condense into a single mission as shown in the 1990 study NASA conducted (Petri et al., 1990). Petri et al. (1990) show an incremental base expansion which has a requirement for an increasing power capacity.

Based on the likelihood of lunar base expansion, the power requirements for this analysis are a set of five reference power values. These values cover science missions and resource exploitation, which are the two base level mission types shown in the Petri, Cataldo and Bozek

(1990) study. Early power systems will support science-centric missions. Later mission sets will include resource exploitation. As a reference note, lunar oxygen generation is considered a primary objective of many proposed permanent lunar bases (Crane & Dustin, 1991). A 500 kW power source should be sufficient to cover power needs for a moderate-level oxygen generation plant producing 60,000 kg of lunar oxygen per year. The 500 kW power source would provide 200 kW of power to the oxygen generation plant (Petri et al., 1990).

2) Radiator Emissivity Value

a. Description: Radiator values of emissivity are assumed end of life value of 0.8 and absorptivity of 0.3 (NASA, 1984).

b. Why: Worst case values are used for estimation to properly size the radiator. Worst case is used to bound the mass value to not introduce overly optimistic values into the estimation.

5.6 Chapter Summary

Chapter 5 is focused on the development of requirements for a lunar power system. Although dry in nature, requirements are extremely important for an analysis of alternatives among the variety of lunar power options. A rollup of requirements is shown in the next chapter in section 6.2. Please refer to the available charts and graphs of 6.2 for requirements summarizations.

CHAPTER 6
MISSION CHARACTERIZATION

6.1 Introduction

This chapter concerns selection of equipment based on likely system drivers and requirements. The section 6.2 summarizes requirement and design reference results from previous chapters. The results are used to select appropriate ammonia-water power architecture in section 6.3 and alternate power productions schemes in 6.4. The thermodynamics, mass, volume, and costs resulting from equipment selection are evaluated in the next chapter.

6.2 Likely Power System Drivers and Requirements

The requirements and requirements flow are shown in Table 11 and Figure 13. The requirements cover the Level 1 Technical Requirements and Major Architecture Aspects of Design as defined in the NASA Systems Engineering Handbook (NASA, 2016). The red dashed box in Figure 12 provides additional detail concerning which part of the requirements are developed in this dissertation. Table 12 summarizes the physical characteristic requirements for a lunar power system.

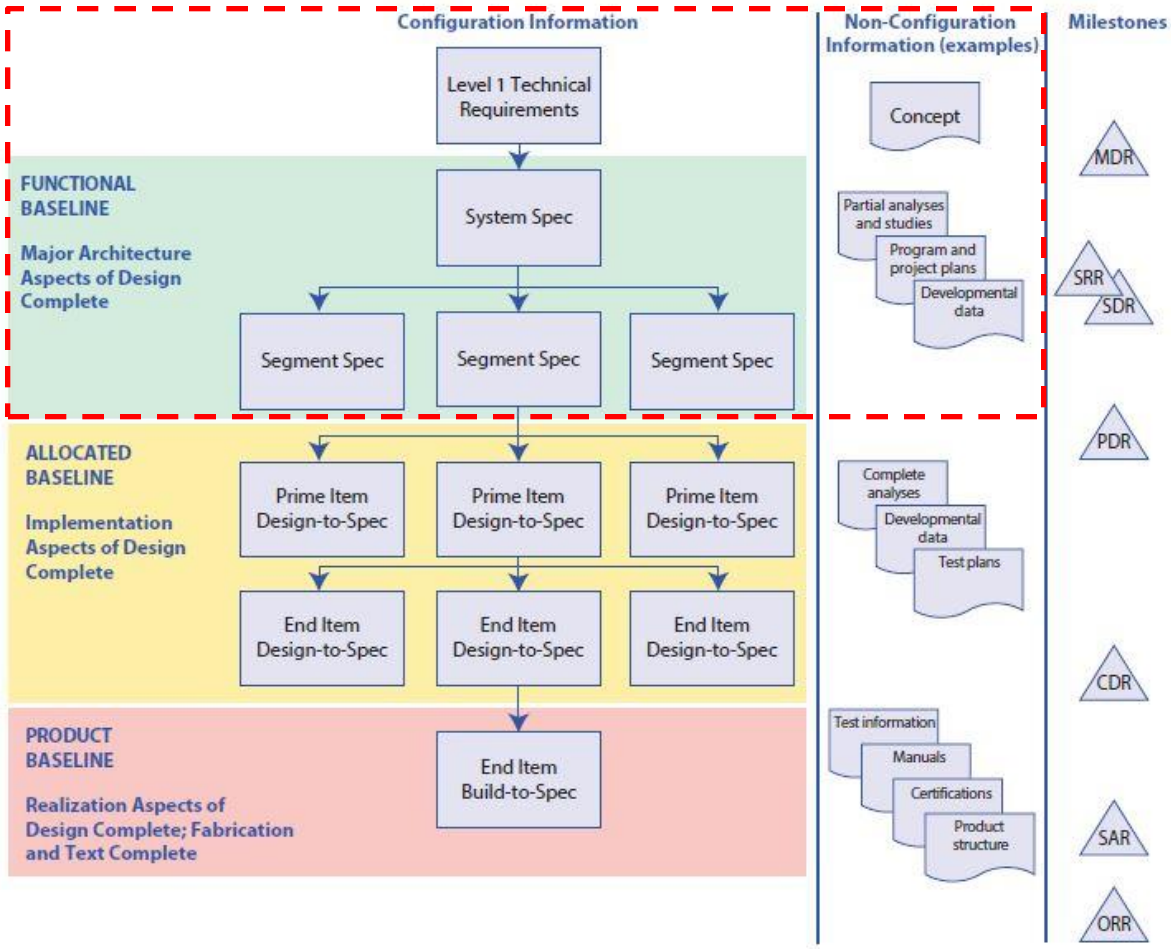

Figure 12: Red Dashed Box Identifies the Relevant Portion of the Systems Engineering Process (NASA, 2016)

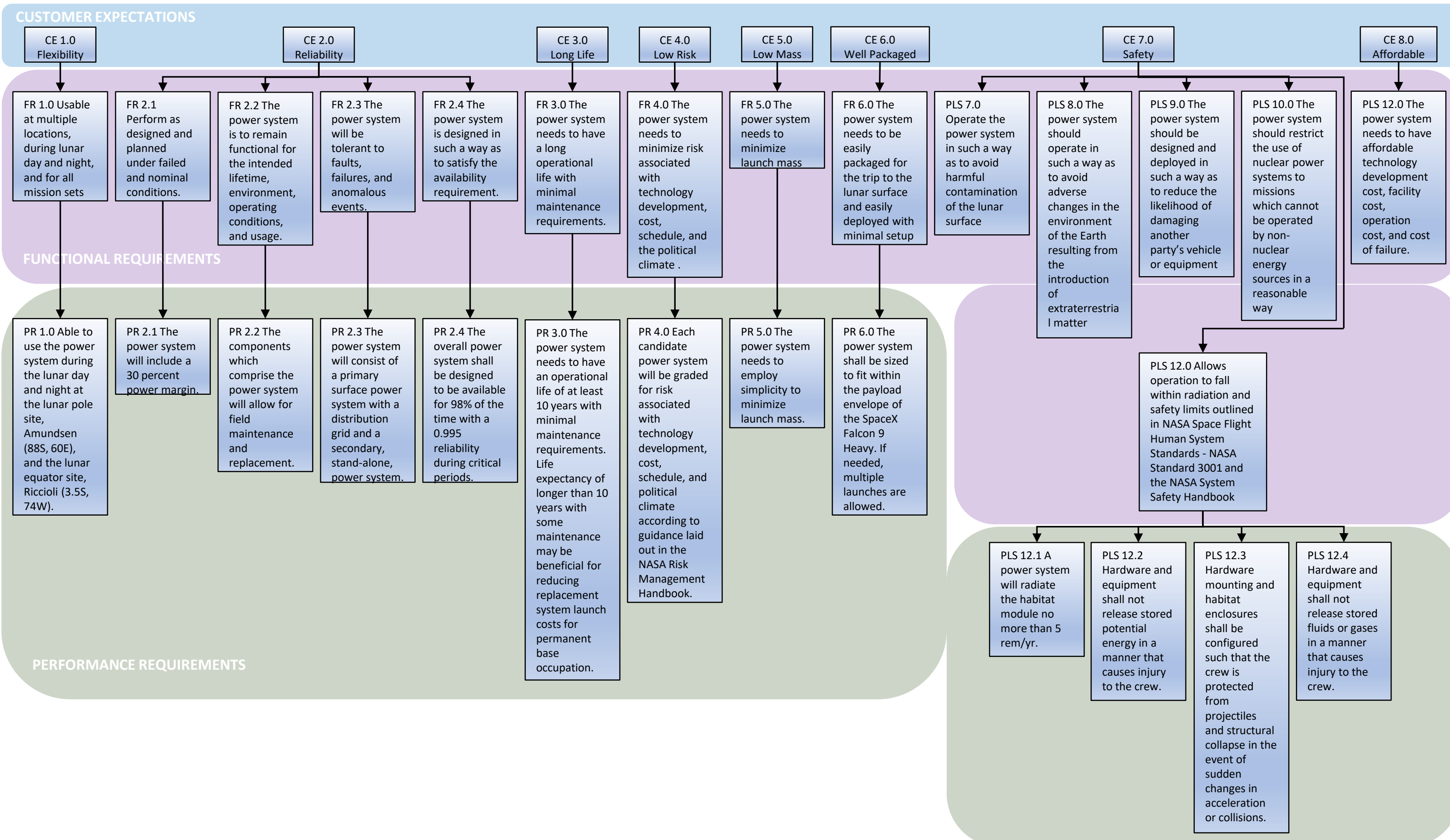

Figure 13: Summary of Lunar Power System Functional Baseline Requirements Flow

Table 11: Lunar Power System Requirements Rollup

Fuctional Requirements	*1.0*		Able to use the power system at multiple location on the Lunar surface including the lunar equator, lunar mid latitude, and the lunar pole Operation during lunar night and day supporting the five mission sets of astronomy, space physics, geology, geophysics, and in-situ resource utilization	Able to use the power system during the lunar day and night at the lunar pole site, Amundsen (88S, 60E), and the lunar equator site, Riccioli (3.5S, 74W).	Performance Requirements
	2.0		High probability of mission success		
		2.1	The power system will perform as designed and planned under failed and nominal conditions.	The power system will include a 30 percent power margin.	
		2.2	The power system is to remain functional for the intended lifetime, environment, operating conditions, and usage.	The components which comprise the power system will allow for field maintenance and replacement.	
		2.3	The power system will be tolerant to faults, failures, and anomalous events.	The power system will consist of a primary surface power system with a distribution grid and a secondary, stand-alone, power system.	
		2.4	The power system is designed in such a way as to satisfy the availability requirement.	The overall power system shall be designed to be available for 98% of the time with a 0.995 reliability during critical periods.	
	3.0		The power system needs to have a long operational life with minimal maintenance requirements.	The power system needs to have an operational life of at least 10 years with minimal maintenance requirements. Life expectancy of longer than 10 years with some maintenance may be beneficial for reducing replacement system launch costs for permanent base occupation.	
	4.0		The power system needs to minimize risk associated with technology development, cost, schedule, and the political climate	Each candidate power system will be graded for risk associated with technology development, cost, schedule, and political climate according to guidance laid out in the NASA Risk Management Handbook.	
	5.0		The power system needs to minimize launch mass	The power system needs to employ simplicity to minimize launch mass.	
	6.0		The power system needs to be easily packaged for the trip to the lunar surface and easily deployed with minimal setup	The power system shall be sized to fit within the payload envelope of the SpaceX Falcon 9 Heavy. If needed, multiple launches are allowed.	
Policy, Legal, and Safety (PLS) Requirements	*7.0*		Operate the power system in such a way as to avoid harmful contamination of the lunar surface		
	8.0		The power system should operate in such a way as to avoid adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter		
	9.0		The power system should be designed and deployed in such a way as to reduce the likelihood of damaging another party's vehicle or equipment		
	10.0		The power system should restrict the use of nuclear power systems to missions which cannot be operated by non-nuclear energy sources in a reasonable way		
	11.0		The power system needs to have affordable technology development cost, facility cost, operation cost, and cost of failure.		
	12.0		Allows operation to fall within radiation and safety limits outlined in NASA Space Flight Human System Standards - NASA Standard 3001 and the NASA System Safety Handbook		
		12.1	A power system will radiate the habitat module no more than 5 rem/yr.		
		12.2	Hardware and equipment shall not release stored potential energy in a manner that causes injury to the crew.		
		12.3	Hardware mounting and habitat enclosures shall be configured such that the crew is protected from projectiles and structural collapse in the event of sudden changes in acceleration or collisions.		
		12.4	Hardware and equipment shall not release stored fluids or gases in a manner that causes injury to the crew.		

Table 12: Physical Characteristic Requirements Summary

	Lunar Location	Lunar Power Demand (kW)
1.0	Amundsen (88S, 60E)	25
2.0		100
3.0		250
4.0		500
5.0		1000
6.0	Riccioli (3.5S, 74W)	25
7.0		100
8.0		250
9.0		500
10.0		1000

All requirements including physical characteristics, such as size and weight, and quality factors, such as reliability and maintainability, are developed from stakeholder requirements. The physical and quality factors developed will be high level. Details relating to the physical characteristics and quality factors are shown in Chapter 5. Physical characteristics and quality factors include reliability, launch mass, and packaging requirements. Reliability covers maintainability, as well as availability. Physical requirements directly impact system availability and cost. At an architecture level, the user interface will be addressed by the policy, legal and safety factors requirements. Safety, cost, and public policy are very important factors in any system design.

Each of the requirements will be applied to choose the appropriate ammonia-water thermodynamic cycle which will operate within the design reference mission constraints. The design reference mission scenarios vary by power demand and lunar location. The requirements will also be used in conjunction with the thermodynamic, mass, volume, and economic analysis to answer the research questions.

6.3 Ammonia-Water Power System Architecture

Kalina cycle development has primarily been for bottoming cycles and geothermal applications (Zhang, 2012). However, a series of papers by a group of Danish researchers provide the basis for a sun-powered Kalina cycle thermodynamic and thermoeconomic analysis. (Knudsen, Clausen, Haglind, & Modi, 2014; Modi & Haglind, 2014; Modi, 2015; Modi et al., 2016).

For terrestrial Kalina cycles, Modi and Haglind (2014) detailed methodology for the development and optimization of high temperature applications. High temperature applications include heat sources which are the reliant on solar energy. Four Kalina-cycle layouts were developed in Modi (2015) with varying recuperator locations and optimizations. The four cycles layouts are adapted with lunar thermal storage and shown in Figures 14 - 17.

Energy storage on the lunar surface can be a battery, fuel cells, or flywheels. To store energy thermally, the cycle would need to be modified to include a thermal storage system where the receiver is located. One would need to add a thermal heat exchanger after the receiver.

Performance analysis has shown a simple Rankine cycle exhibits better performance than the Kalina cycle when a solar receiver is the heat input source alone. The same study showed when using a thermal heat storage system as the primary source of heat input, the Kalina cycle requires a reduction of approximately 1/3 in the heat storage requirement compared to a simple Rankine cycle (Modi & Haglind, 2004). The study also showed other component's exergy destruction is dependent upon the amount of recuperation, turbine inlet pressure, and ammonia mass fraction.

What does this mean for a potential lunar Kalina cycle? As shown in the operation scenarios, any lunar power system has to be moved from the Earth's surface to the lunar surface. Consequently, the mass and size of the system should be as low as possible. Based on the myriad of performance analyses of Kalina cycles, there is no benefit in utilizing the Kalina cycle which utilizes a solar receiver unless the architecture includes a thermal heat storage system. Based on the need, the architecture for the ammonia-water system will include a thermal storage system.

The four systems shown above all have different cycle efficiencies. Cycle efficiencies will feed into component sizing for the energy storage system, solar energy collector, and radiator. Although the more efficient system may have more components—meaning more mass and volume, the higher efficiency may equal lower mass requirements for energy storage, solar energy collection, or radiator. Mass and size will be addressed in Chapter 7.

Each of the four systems shown in Modi (2015) will now be broken down into more detail as the architecture would be on the lunar surface. Component and cycle efficiencies are shown in Table 13. From Figures 14 - 17 and Table 13, the variation in the cycles is based on the location and number of reheaters. Cycle efficiency numbers were initially developed from Modi (2015) and confirmed with the code developed for the thermodynamic analysis shown in Chapter 7. For additional definition for each of the components shown in the following figures, please see section 7.4.1.1.

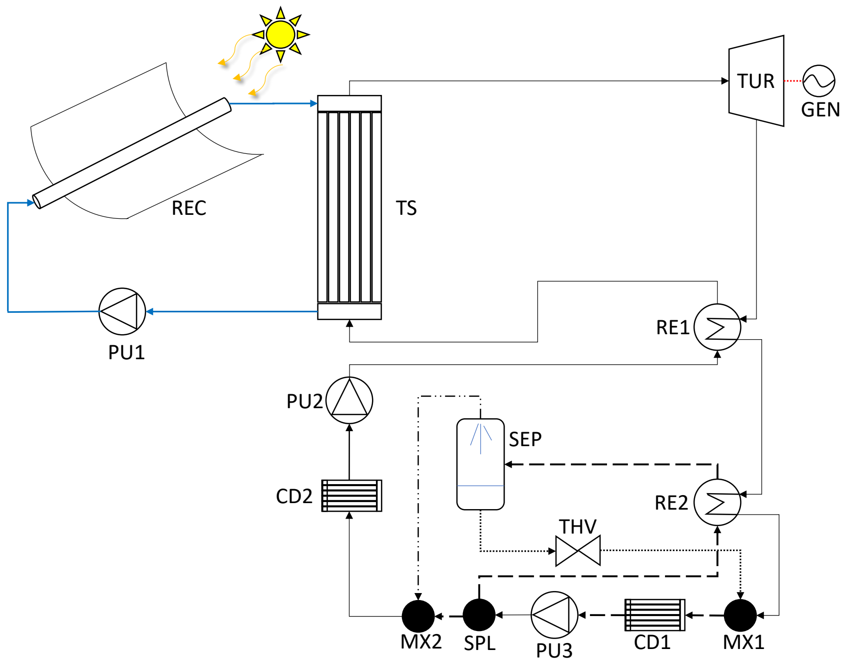

Figure 14: KC12 Cycle with Thermal Storage

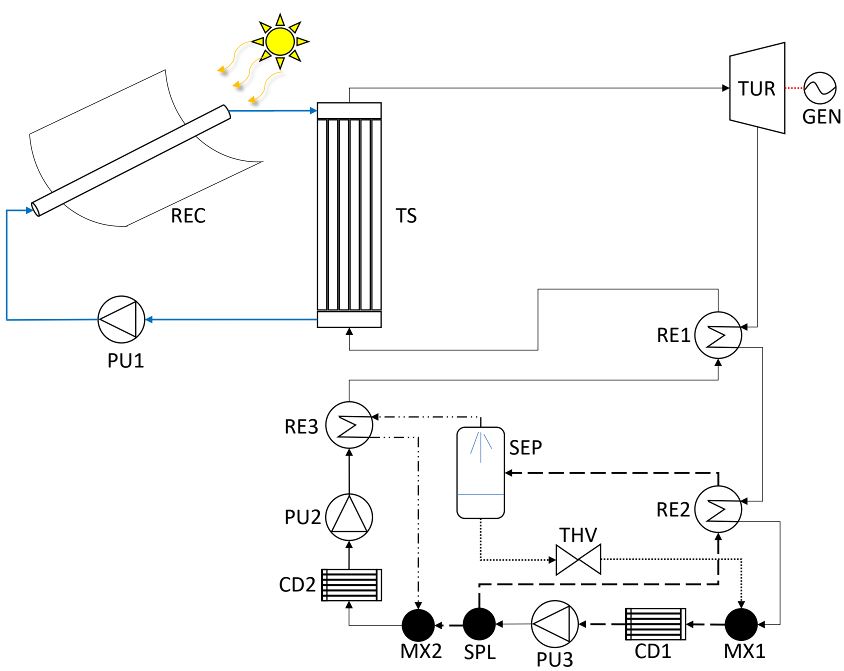

Figure 15: KC123 Cycle with Thermal Storage

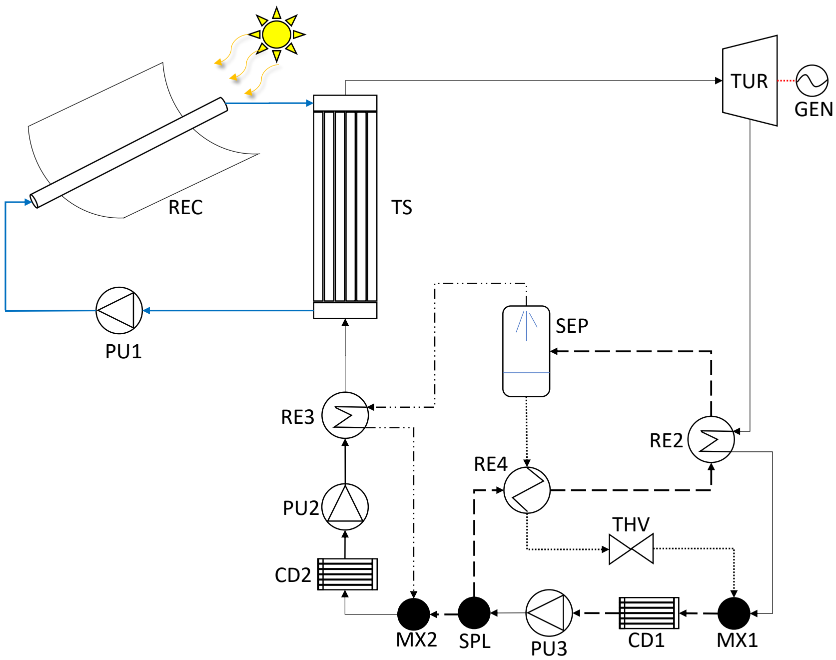

Figure 16: KC234 Cycle with Thermal Storage

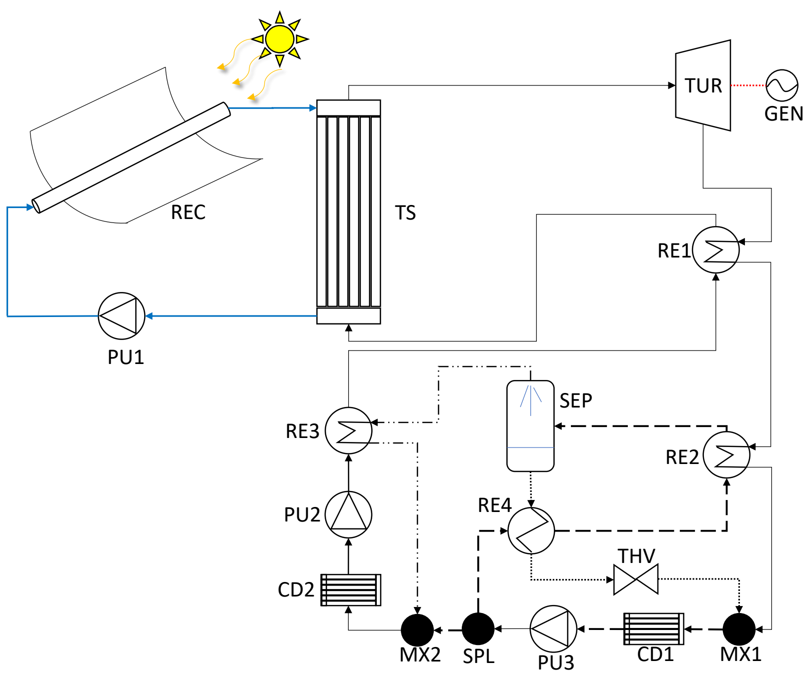

Figure 17: KC1234 Cycle with Thermal Storage

Table 13: Summary of the four KC Components and Efficiencies

	Syst. Eff.	# of REC	# of TS	# of PU	# of TUR	# of RE	# of CD	# of MX	# of SEP	# of THV	# of SPL	# of RAD	# of GEN
KC12	0.314	1	1	3	1	2	2	2	1	1	1	1	1
KC123	0.315	1	1	3	1	3	2	2	1	1	1	1	1
KCS234	0.2975	1	1	3	1	3	2	2	1	1	1	1	1
KCS1234	0.315	1	1	3	1	4	2	2	1	1	1	1	1

What requirements can be used to select the best ammonia-water architecture? Review of requirements shown in Table 11 suggests that the only requirement that differentiates the various KC cycles is Performance Requirement (PR) 5.0., i.e., system simplicity and high efficiency. The simplest of the four systems with the highest efficiency is KC12. KC1234 and KC123 each have virtually the same efficiency but rely on more reheaters than KC12. KCS234 has both a higher number of reheaters and a lower overall thermodynamic efficiency.

In summary, four architecture variations of the Kalina Cycle suitable for a solar heat were chosen from literature. Each of the four equally satisfy the system requirements, except for PR 5.0. KC12 satisfies PR 5.0 best since it has the fewest components and virtually the same high efficiency as the two highest efficiency systems. The life expectancy of a KC12 power system on the lunar surface will be similar to previously analyzed solar dynamic systems. The component similarity is relatively close to a Brayton cycle in that they both share many components. The life expectancy of a KC12 should be approximately 15 years (Mason, 2009). The TRL level of the KC12's use in space is 2. The system has been developed extensively for terrestrial applications. The technology concept and application is formulated in this paper.

6.4 Alternate Mission Power Architecture

There are several base power architecture options which have been proposed over the years for use on the lunar surface: nuclear thermodynamic, solar thermodynamic, and photovoltaic. Each power architecture will be assigned the most recent representative power system which has been analyzed in detail to include hardware development and testing. Appendix 4G of NASA's ESAS study overviews each of these technologies as options for lunar power system powering a base or industrial process (NASA, 2005b).

6.4.1 Nuclear Thermodynamic

In recent years, NASA has been developing a compact nuclear thermodynamic power system, the Kilopower Reactor Using Stirling TechnologY (KRUSTY), which can be used in a wide variety of location. However, that specific system is only designed for up to 10 kWe of power. An older design from the early 1990s, SP-100, is representative of a larger nuclear system of up to 1 MWe (Mason et al., 1989).

6.4.1.1 Nuclear Dynamic (KRUSTY)

Over the past decade, NASA has focused its planetary power system development efforts on smaller nuclear dynamic power schemes. NASA's effort culminated in KRUSTY. A ground test of KRUSTY was completed at the Nevada National Security Site (NNSS) on March 21, 2018 (Gibson et al., 2018). The ground test was a full-scale nuclear demonstration which verified the system design in all stages of operation. The ground test included a space-simulated environment, full-scale components, flight typical component design and off-nominal scenarios. The ground test verified stability and control across a wide range of situations and control scenarios.

KRUSTY is designed for missions ranging from 1 kWe and 10 kWe. The 1 kWe system, shown in Figure 18, has a mass of 400 kg (Gibson, 2018). The 10 kWe system, shown in Figure 19, has a mass of 1804 kg. The power conversion for the 10 kW system is performed by (8) 1,250 We Stirling engines in the dual opposed configuration (Gibson et al., 2017). Since the scenarios being analyzed start at 25 kW, the specific weight value used for KRUSTY is 150 kg/kWe. The life expectancy of KRUSTY is expected to be 12 years (McClure, 2017; Gibson et al., 2017). KRUSTY has a stated TRL level of 5 (Palac et al., 2016).

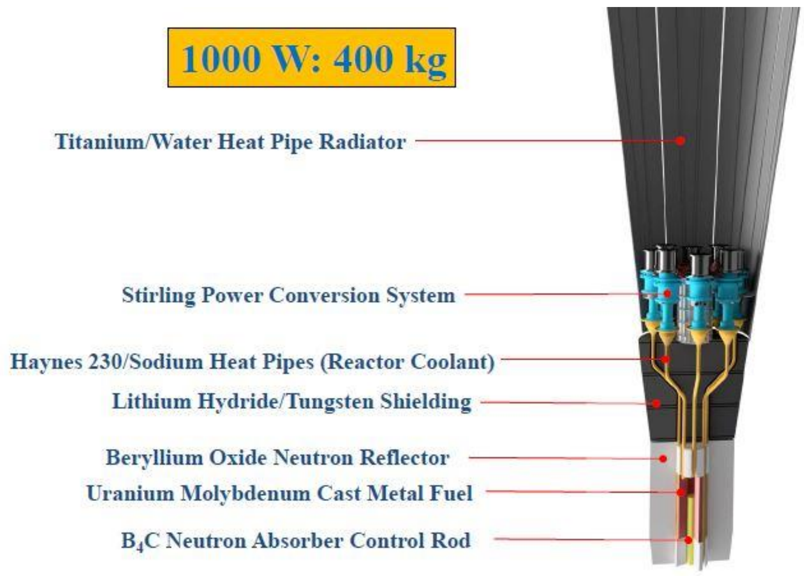

Figure 18: 1 kWe KRUSTY (Gibson, 2018)

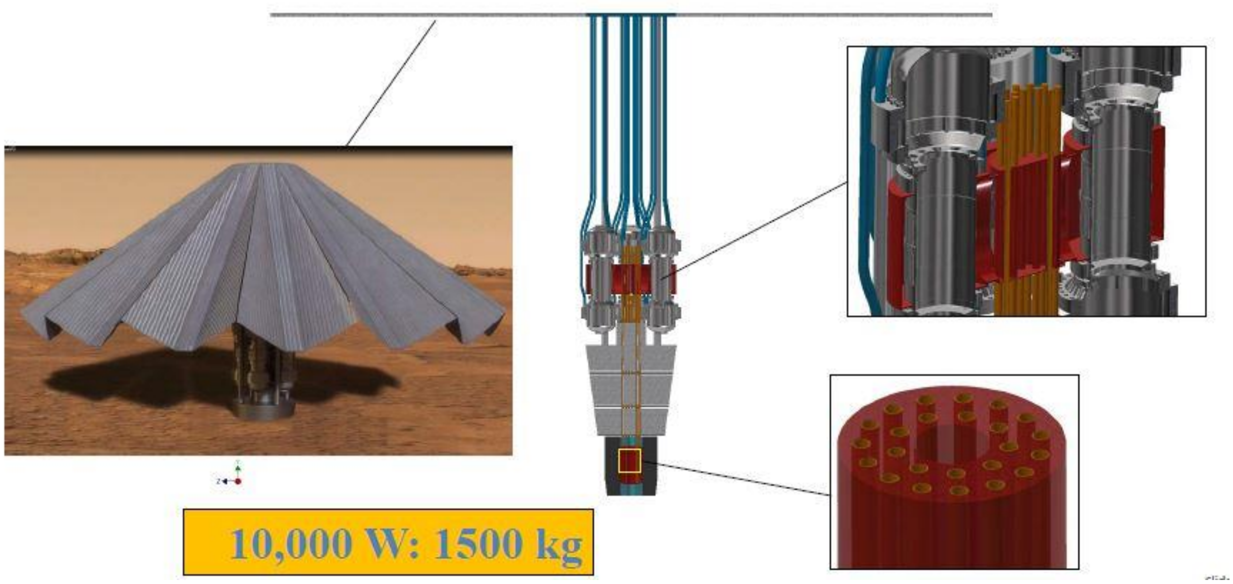

Figure 19: 10 kWe KRUSTY (Gibson, 2018)

6.4.1.2 Nuclear Dynamic (SP-100)

While NASA’s current space power development is focused on small nuclear reactor development, it has not always been so. Starting in 1986 and continuing into the 1990s, NASA’s SP-100 nuclear reactor was evaluated for applications ranging from space propulsion power to lunar base power. Where KRUSTY ranges from 1-10 kWe, SP-100 was designed to produce up to 1 MWe of power. The mass per unit power is lower at higher power levels. Scalability characteristics favor higher power levels due to a minimal reactor size needed to achieve criticality (Marriott & Fujita, 1994). Marriott and Fujita (1994) have mass values of 2000 kg, 2500 kg, and 3500 kg for power levels of 25 kWe, 50 kWe, and 100 kWe, respectively.

Since the focus of this study is lunar base power, SP-100’s design needs to focus on lunar base applications. Mason et al. (1989) provides a conceptual design for the SP-100 for lunar base applications. The lunar base power system mass, volume, and layout are shown in Figures 20, 21, and 22. The SP-100 specific mass for the lunar base is 24.2 kg/kWe. The SP-100 design includes spare standby Stirling engines and associated hardware. The use of advanced technologies and materials would further reduce the mass. The full power lifetime of the reactor is rated for 7 years which does not meet the requirement of 10-year life. Additionally, for the SP-100 system to produce 1 MWe, 7 of 8 engines must operate. The service life expectancy of SP-100 is 7 years (Mason et al., 1989). The TRL level of SP-100 reached 3. Analytical and experimental function along with a proof-of-concept were developed (Mason et al., 1989).

Reactor thermal power, kW	2500
Reactor lifetime (at full power), yr	7
Electrical output (6 of 8 engines), kWe	825
Electrical output/operating engine	137.5
Rated electrical output/engine	150
Percent of full operating capacity, percent	69
Thermal-to-electric efficiency, percent	33
Stirling heater temperature, K	1300
Stirling temperature ratio	2.2
Stirling cooler temperature, K	591
Waste heat to reject, kW	1675
Radiator surface temperature, K	525
Lunar surface temperature (w/apron), K	222
Lunar sky temperature, K	267
Total radiator area, m^2	780

Figure 20: 1 MWe SP-100 Design Point Performance (Mason et al., 1989)

Subsystems and packaging	Mass, kg	Volume, m^3	Stowed configuration, (all dimensions in meters)
Lunear Descent Vehicle (LDV)1			
Reactor bulkhead enclosure	679	19.0	Cylinder (2.4 diam by 4.2 height)
2.5-MWt SP-100 reactor	755		
Instrument shield	931		
Primary Heat transport	342		
Instrumentation and control	359		
Total (1 package)	2 387	9.8	Cylinder (1.8 diam by 3.8 height)
Stirling inlet/outlet manifold	423	2.5	Cylinder (4.0 diam by 0.2 height)
Engine support platform	126		
2 platforms (1 package)	251	2.0	Box (5.4 by 3.1 by 0.1)
Total (4 packages)	1 005	8.0	
Stirling engine[a]	734		
Radiator interface[b]	104		
Power conditioning[c]	206		
1 engine (1 package)	1 044	7.2	Box (3.1 by 2.2 by 1.1)
Total (8 packages)	8 351	57.3	
Lunear Descent Vehicle (LDV)2			
Radiator panel section[d]	156		
5 sections (1 package)	780	11.3	Box (5.0 by 1.0 by 2.3)
Total (8 packages)	6 240	90.2	
Transmission cabling (5 km)	917	3.1	Cylinder (2.0 diam by 1.0 height)
Total (24 packages)	20 004	189.9	

[a]Including hot heat exchanger.
[b]Including piping, electromagnetic pump, and accumulator.
[c]Including ac-dc converter and parasitic load resistor.
[d]Including heat pipes and inlet/outlet manifold.

Figure 21: 1 MWe SP-100 Mass and Volume Breakdown (Mason et al., 1989)

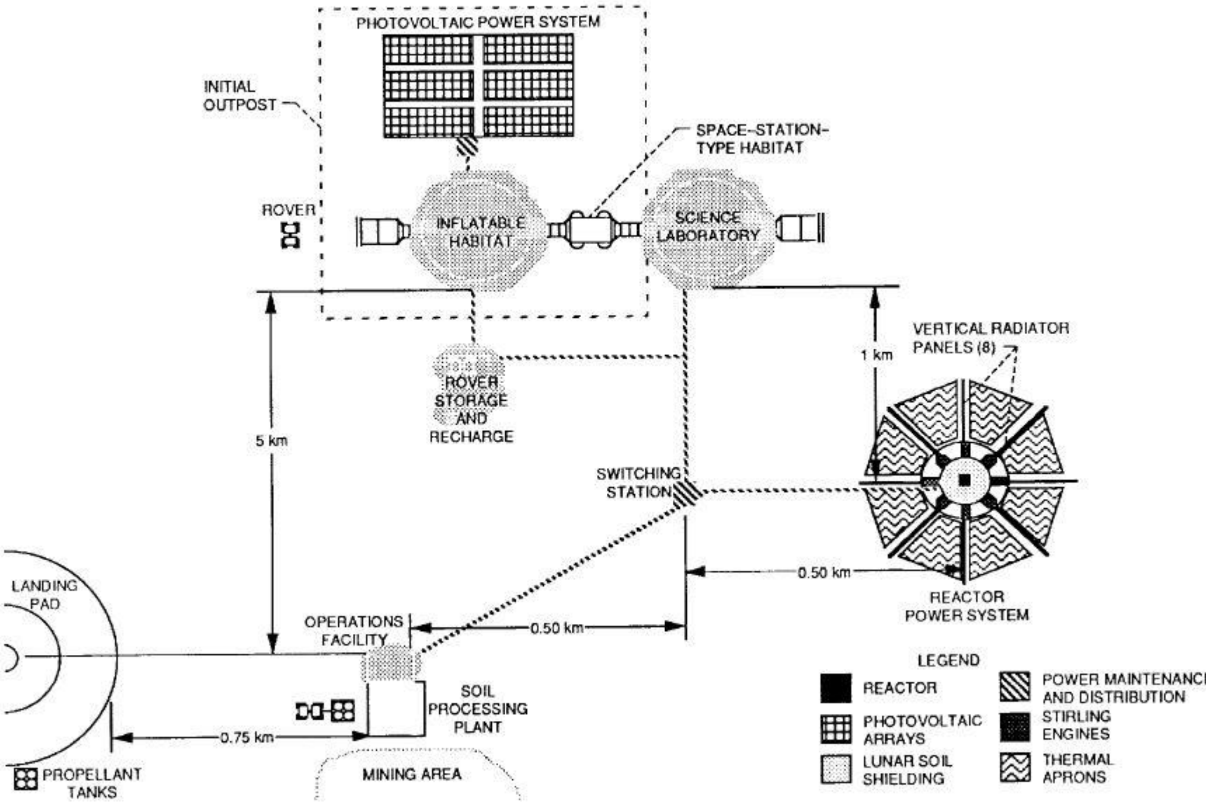

Figure 22: 1 MWe SP-100 Lunar Base Layout (Mason et al., 1989)

6.4.2 Solar Thermodynamic

Due to system complexity and location limitation, solar thermodynamic systems have not been aggressively researched since the 1990s. The most comprehensive development and test of a space based solar dynamic power system was completed in the late 1990s. NASA’s Solar Dynamic Ground Test Demonstration (SDGTDP) accomplished the development of a solar dynamic Brayton cycle power system which operated in a simulated space environment and produced 2 kWe (Alexander, 1997a). An entire power production system was tested including radiator, solar concentrator, Brayton engine, and recuperators. See Figure 23 for the system layout.

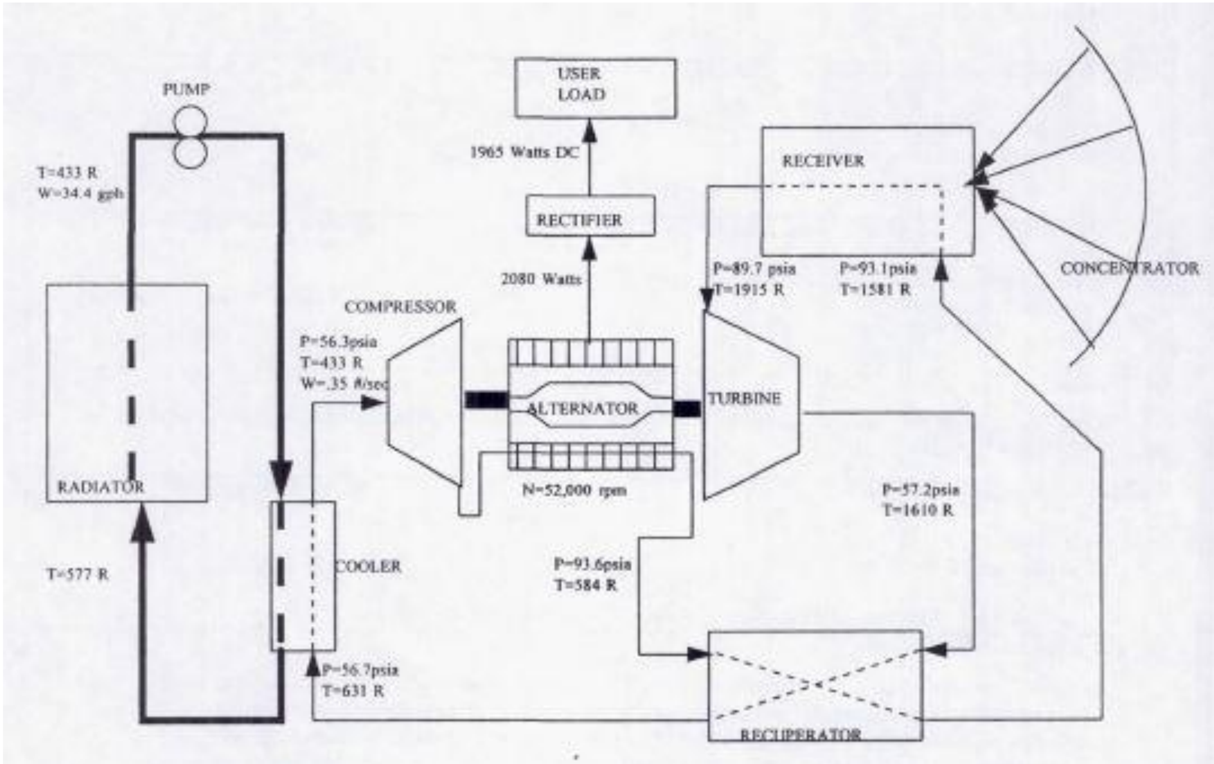

Figure 23: 2 kWe SDGTDP Layout (Alexander, 1997a)

The ground test resulted in cycle efficiencies of almost 30% using 1970's and 1980's component technology. Significant efficiency gains can be realized with better tuned design parameters including the Brayton cycle compressor pressure ratio (CPR), temperature ratio (Tratio), and newer technology. Higher efficiency would reduce solar collection area, translate to a smaller launch vehicle, and, consequently, ease launch vehicle packaging and deployment requirements. However, based on the SDGTDP hardware designs, the system specific power is rated at 21 W/kg. According to Mason (1999), with a reasonable development investment, one can expect 116 W/kg. These numbers are for the power production system and do not include an energy storage system. Details concerning the energy storage system will be covered in section 7.4.1. The energy storage system for a Brayton thermodynamic power cycle will be the same as for an ammonia-water thermodynamic power cycle. Crane evaluated mass for a lunar Brayton thermodynamic cycle with in situ thermal storage. The values are shown in Table 14.

Table 14: 25 kWe Lunar Brayton Thermodynamic Power System with In Situ Thermal Storage (Crane, 1991)

Concentrator	250	kg
TES HX (latent storage)	1066	kg
TES HX (sensible storage)	2737	kg
Brayton Cycle HX	93	kg
Radiation Shields	825	kg
Compressor	10	kg
Engine & Generator	664	kg
Radiator	256	kg
Frame Mass	445	kg
Total Mass (latent storage)	3608	kg
Total Mass (sensible storage)	5279	kg
Specific Weight (latent storage)	144	kg/kW
Specific Weight (sensible storage)	211	kg/kW

For this study, latent storage is evaluated for mass comparison. Also, the mass and sizing of this system is for lunar day and night cycles at the lunar equator. The thermal storage system requirement shrinks 80% when used at the lunar pole.

The expected life of a lunar based solar dynamic system is 15 years. The thermal storage system is expected to be approximately the same but needs verification by experimentation (Mason, 2009). The TRL level of the power cycle itself is 6 due to the hardware development and ground testing of NASA in the late 1990s (Alexander, 1997c). The TRL level of the thermal storage system is 3. Analytical and experimental critical function of the thermal storage was developed by Crane in the early 1990s (Crane, 1991).

6.4.3 Photovoltaic

Solar panels or photovoltaic power is one of the most common technologies used for space applications such as the International Space Station and satellites. One can easily see the direct application of existing satellite photovoltaic technology to provide electricity for a lunar base. Energy storage can be provided through fuel cells (Crane & Dustin, 1991). As stated in the literature review, the current state of the art photovoltaic arrays—without energy storage—is approximately 80-100 W/kg (Beauchamp, 2017).

ESAS baselines the specific mass for a photovoltaic array for both an equatorial landing site and a polar landing site. The calculated end-of-mission solar array peak power specific mass for an equatorial landing site is 82 W/kg. The photovoltaic array specific mass at a polar (85º latitude) landing site is 93 W/kg (NASA, 2005b).

As with all non-nuclear power systems, a photovoltaic system requires energy storage for night operation. ESAS did not view Li-ion battery energy storage as a viable option. For a 25 kWe continuous power system to operate during a 354-hr lunar night period, the calculated battery mass was 53 mT (at 200 Whr/kg) (NASA, 2005b).

NASA states a better option for energy storage is a regenerative fuel cell (RFC). ESAS outlines a system which can provide 100% nighttime power and has three redundant fuel cell stacks, fuel cell ancillaries, electrolyzer stacks, and electrolyzer ancillaries. Hydrogen (H2) and Oxygen (O2) are stored as gas in spherical titanium-lined, Kevlar-overwrapped tanks at a 3,000 psi maximum operating pressure. Tables 15 and 16 outline the mass and volume information for a 25 kWe and 50 kWe system (NASA, 2005b).

Table 15: 25 kWe Regenerative Fuel Cell Mass and Volumes (NASA, 2005b)

	Per Tank Analysis				Total for (2) Tanks		
	Hydrogen	Oxygen			Hydrogen	Oxygen	
Continuous use power level	25	25	kWe		25	25	kWe
Environment Temperature	300.0	300.0	K		300.0	300.0	K
Operation time	354	354	hr		354	354	Hr
Cryogen Mass	210	1677	kg		419	3355	kg
Tank pressure	344.7	344.7	kPa		344.7	344.7	kPa
Tank Diameter	1.92	1.44	m		1.92	1.44	m
Tank Volume	3.71	1.64	m^3		7.41	3.29	m^3
Tank Mass	105	52	kg		211	104	kg
Total Thermal Power	581	468	watt		1162	936	watt
Total Input Power	35	5	kWe		70	10	kWe
Cryo-cooler System Mass	1396	167	kg		2792	334	kg
Total System Wet Mass	1711	1896	kg		3422	3792	kg
Total System Dry Mass	1501	219	kg		3003	438	kg

Table 16: 50 kWe Regenerative Fuel Cell Mass and Volumes (NASA, 2005b)

	Per Tank Analysis				Total for (2) Tanks		
	Hydrogen	Oxygen			Hydrogen	Oxygen	
Continuous use power level	50	50	kWe		50	50	kWe
Environment Temperature	300.0	300.0	K		300.0	300.0	K
Operation time	354	354	hr		354	354	Hr
Cryogen Mass	420	3364	kg		841	6727	kg
Tank pressure	344.7	344.7	kPa		344.7	344.7	kPa
Tank Diameter	2.36	1.85	m		2.36	1.85	m
Tank Volume	6.88	3.32	m^3		13.76	6.63	m^3
Tank Mass	192	102	kg		384	204	kg
Total Thermal Power	1155	938	watt		2310	1876	watt
Total Input Power	70	10	kWe		139	20	kWe
Cryo-cooler System Mass	2599	313	kg		5199	625	kg
Total System Wet Mass	3212	3778	kg		6424	7557	kg
Total System Dry Mass	2791	415	kg		5583	829	kg

Life expectancy for a space-based photovoltaic array is approximately 30 years. The RFC system is estimated to have a life of 15 years before component replacement (Surampudi, 2011).

The TRL level of the solar panels is 9. Photovoltaic arrays are used extensively to power space activities. The regenerative fuel cell energy storage is at a TRL of 5 needing additional development (Jakupca, Bennett, Smith, and Burke, 2018).

6.5 Power System Hardware Definition

Nuclear, solar dynamic, and photovoltaic power system have shared common hardware components as well unique components. Each common and unique system component will be defined in this section. The information introduced here lays important groundwork for the analysis of Chapter 7.

6.5.1 Thermal Energy Storage

Terrestrially, a solar dynamic system will store thermal energy in LiF-based salt phase change materials which is turned to a specific melting point matching power converter requirements (Reddy, 2013). During a 354-hour lunar night, NASA estimates 135 mT of LiF-CaF2 salt is required for production of 25 kWe which requires 30 MWt-hr of thermal energy (NASA, 2005b). According to ESAS, the mass requirement of a LiF-CaF2 thermal storage system make its employment unaffordable.

Multiple literature sources stated the mass and volume of thermal storage required by a dynamic heat engine is best served by utilizing local resources. Reductions in energy storage mass by utilizing local lunar resources can be as high as 67% (Colozza, 1991; Crane & Dustin, 1991; Crane, 1991). The size of thermal storage is greatly dependent upon the size of the system it supports. A big drawback to approach is the low technical readiness level.

Crane (1991) conducted a detailed analysis of a Thermal Energy Storage (TES) system shown in Figure 24. The regolith thermophysical properties were evaluated as to how they impact the utilization of lunar regolith as a thermal heat storage device. Crane's concept utilizes coils of pipe collapsed down to their elastic limit at standard temperature for launch to the lunar surface. The coils are then augured into the lunar regolith and connected to a sun-powered thermodynamic system. Crane evaluated both sensible and latent heating with the concept. Based on Crane's research, a value of 9.43×10^{-6} $kg/kJ_{thermal}$ for a latent thermal storage system can be used for estimation values.

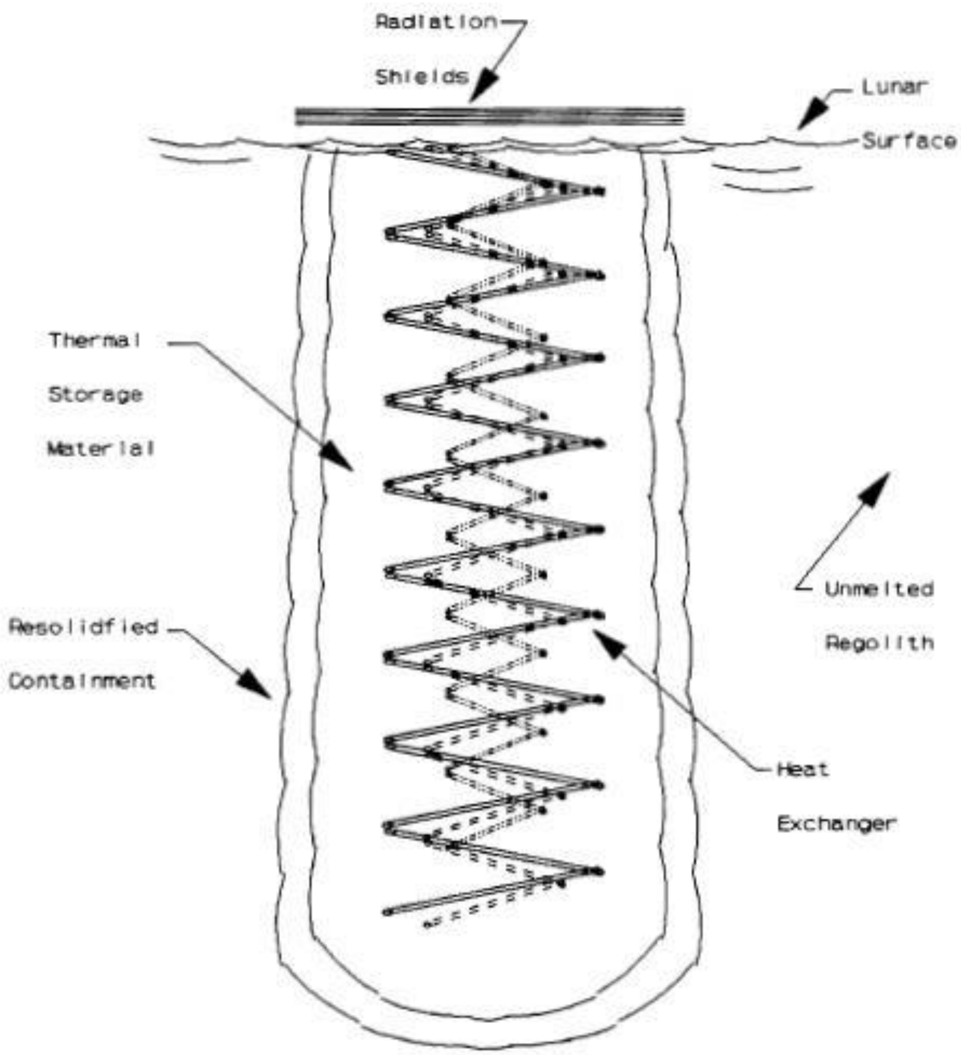

Figure 24: Proposed in-situ TES Arrangement (Crane, 1991)

6.5.2 Heat Rejection Assembly (Radiators and Condensers)

Radiative heat rejection relies heavily upon temperature differential between the radiator and the thermal sink. Although not typically used in terrestrial applications, a heat pump rejection system is necessary due to the relatively low temperature of the working fluid at the heat rejection point of the cycle. For a space Kalina cycle, an actively managed heat pump thermal rejection system like what will be used to cool lunar habitats can be used. Sridhar, Gottmann, and Nanjundan (1993) proposed a heat rejection system designed to reject heat at relatively low temperatures on a lunar base. Their system is shown in Figure 25. It works similarly to common domestic cooling systems with a heat exchanger, compressor, and expansion valve. A big difference between the system shown in Figure 25 and a terrestrial domestic cooling system is how the heat is rejected. A domestic terrestrial system rejected heat primarily through convection and conduction. The lunar system rejects heat primarily through radiation. Based on existing hardware estimates, the specific mass of the heat rejection assembly to include all hardware and plumbing is 30 $kg/kW_{thermal}$ (Sridhar et al., 1993).

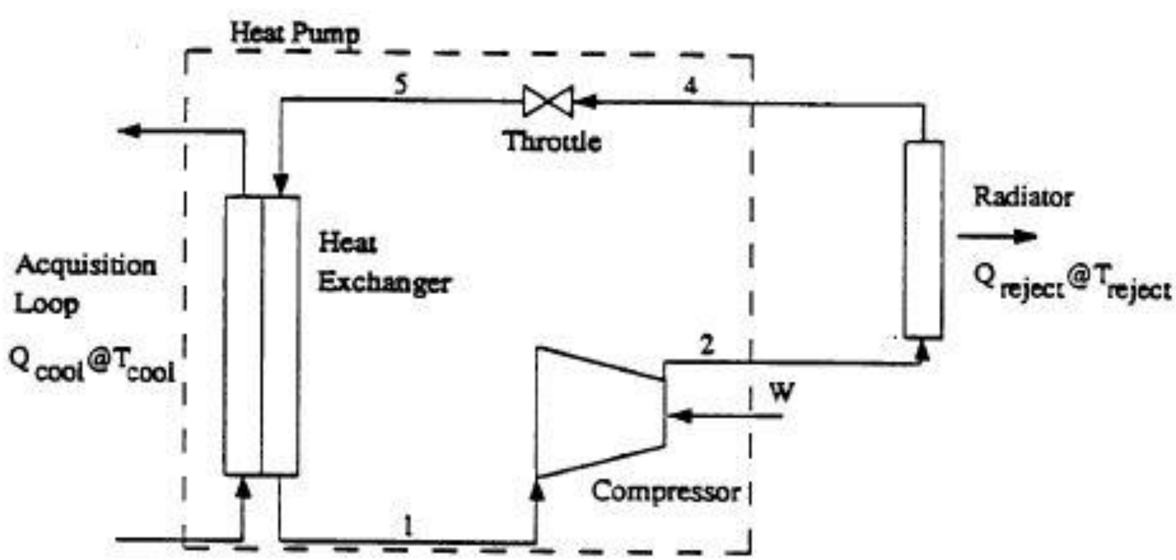

Figure 25: Proposed Heat Rejection Arrangement (Sridhar et al., 1993)

6.5.3 Solar Energy Concentrator

One of the visually dominant pieces of any solar dynamic system is the solar concentrator. There are multiple ways for the sun’s thermal emissions to be concentrated, to include parabolic troughs, mirrors, or arrays of mirrors. NASA has spent quite a bit of effort over the years developing solar concentrators. A solar dynamic power system was proposed for the International Space Station’s design predecessor, Space Station Freedom. As shown in Figure 26, a concentrator design which is light and easily packaged for transport was designed and tested (Alexander, 1997a,b,c).

Figure 26: Proposed Space Station Freedom Heat Concentrator Arrangement (Knasel & Ehresman, 1989)

The concentrator in Figure 26 was the result of the Solar Concentrator Advanced Development Project. It resulted in an erectable structure designed to be assembled by astronauts. An offset parabolic reflector system is comprised of multiple reflective surfaces, support structures, and a gimballed pointing mechanism. Although the ISS design eventually used a simpler photovoltaic system, the hardware design was fully developed and tested. The resulting specific power of such a system is 3.5 $kg/kW_{thermal}$ (Crane & Dustin, 1991).

6.5.4 Power Conversion Unit

The power conversion unit is the heart of any solar dynamic system. It includes the power turbine, alternator, recuperators, ducting, and equipment management. The power conversion unit does not take up a large amount of mass when compared to the heat rejection, heat collection, and storage systems. Mason (1999) estimates a Brayton conversion system to be 0.2 kg/kWe. Since the Brayton and Rankine hardware is similar, a conservative mass estimate for a space ammonia-water power conversion system is set at 0.3 kg/kWe.

6.5.5 Solar Receiver

The receiver is the second part of the solar dynamic process. It is located near the focal point of the solar concentrator. For previously proposed space Brayton cycles, the receiver is a cavity lined axially with tubes through which the gaseous working fluid of the Brayton cycle flows (Labus et al., 1989). Based on hardware values expected in the near term, Mason places the specific weight of a receiver at 0.12 kg/kWe (Mason, 1999).

6.6 Chapter Summary

This chapter started with a summary of the requirements for a space power system. The requirements were used to select KC12 as the candidate ammonia-water thermodynamic power system. Four comparison systems were chosen to include KRUSTY, SP-100, SDGTDP, and a photovoltaic power scheme with fuel cell energy storage. Thermodynamic system component specific power values from literature were introduced. The systems and mass properties shown in this chapter are used in conjunction with the thermodynamic analysis of the next chapter to produce mass and cost estimates for each candidate system.

CHAPTER 7
MISSION EVALUATION

7.1 Introduction

This chapter transitions from the analysis of alternatives background development into the analysis itself. First, step 3 of the SMART method will identify importance attributes culminating in a value tree. Step 4 will assign values for each attribute for each of the power systems. Step 4 will include performance assessments to include a thermodynamic analysis of the identified Kalina cycle (KC12) and an economic analysis for all identified power system candidates. Steps 5 through 7 will assign and aggregate weights and values. The final part of this chapter will be Step 8, i.e., the sensitivity analysis.

7.2 Step 3: Identification of the attributes which are relevant to the decision problem

The previously developed system requirements are the foundation of the value tree. To transition requirements to value tree attributes, one takes the 18 requirements and sub-requirements and apply the five criteria used to judge a value tree. The five criteria used to judge a value tree are completeness, operationality, decomposability, absence of redundancy, and minimum size. Of the five criteria, the entire requirements list passes the first four. The fifth criterion, minimum size, will be addressed. The fifth criterion asks whether one can eliminate any attributes which do not distinguish between the various power options. Table 17 summarizes the resulting requirements/attributes for use in the value tree. Utilizing the results from Table 17, one can construct a value tree. To simplify the value tree further, the attributes are renamed based on the full requirement definition. Renaming is shown in Table 18. The resulting value tree is shown in Figure 27.

Table 17: Reduction of Requirements to Key Attributes

	Attribute	Distinguishing Attribute (Yes or No)	Explanation
1.0	Able to use the power system during the lunar day and night at the lunar pole site, Amundsen (88S, 60E), and the lunar equator site, Riccioli (3.5S, 74W).	No	All Systems are designed to operate during lunar day and night at both locations
2.1	The power system will include a 30 percent power margin.	No	All Systems are designed with power margin
2.2	The components which comprise the power system will allow for field maintenance and replacement.	Yes	Certain portions of nuclear systems do not allow for field maintenance
2.3	The power system will consist of a primary surface power system with a distribution grid and a secondary, stand-alone, power system.	No	Out of scope of this dissertation
2.4	The overall power system shall be designed to be available for 98% of the time with a 0.995 reliability during critical periods.	No	All systems are designed for this level of reliability; analysis of this level is out of scope of dissertation
3	The power system needs to have an operational life of at least 10 years with minimal maintenance requirements. Life expectancy of longer than 10 years with some maintenance may be beneficial for reducing replacement system launch costs for permanent base occupation.	Yes	Systems vary on life expectancy
4.0	Each candidate power system will be graded for risk associated with technology development, cost, schedule, and political climate according to guidance laid out in the NASA Risk Management Handbook.	No	Out of scope of this dissertation
5	The power system needs to employ simplicity to minimize launch mass.	Yes	Each system will vary in mass
6.0	The power system shall be sized to fit within the payload envelope of the SpaceX Falcon 9 Heavy. If needed, multiple launches are allowed.	No	All systems will be able to be launch in the payload envelope
7	Operate the power system in such a way as to avoid harmful contamination of the lunar surface	Yes	Nuclear systems can cause contamination
8.0	The power system should operate in such a way as to avoid adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter	No	All systems are designed and launched in a way to avoid impact to Earth environment
9.0	The power system should be designed and deployed in such a way as to reduce the likelihood of damaging another party's vehicle or equipment	No	All systems are designed and launched in a way to avoid damaging other party's vehicles or equipment
10	The power system should restrict the use of nuclear power systems to missions which cannot be operated by non-nuclear energy sources in a reasonable way	Yes	There are two nuclear systems evaluated
11	The power system needs to have affordable technology development cost, facility cost, operation cost, and cost of failure.	Yes	The systems vary in development costs
12.1	A power system will radiate the habitat module no more than 5 rem/yr.	No	Location and configuration of nuclear power system allows adherence to this requirement
12.2	Hardware and equipment shall not release stored potential energy in a manner that causes injury to the crew.	No	Location and configuration of power systems allows adherence to this requirement
12.3	Hardware mounting and habitat enclosures shall be configured such that the crew is protected from projectiles and structural collapse in the event of sudden changes in acceleration or collisions.	No	Location and configuration of power systems allows adherence to this requirement
12.4	Hardware and equipment shall not release stored fluids or gases in a manner that causes injury to the crew.	No	Location and configuration of power systems allows adherence to this requirement

Table 18: Attribute Name to Requirement Correlation

	Requirement	Attribute Name
2.2	The components which comprise the power system will allow for field maintenance and replacement.	Ease of Maintenance
3	The power system needs to have an operational life of at least 10 years with minimal maintenance requirements. Life expectancy of longer than 10 years with some maintenance may be beneficial for reducing replacement system launch costs for permanent base occupation.	Long Operational Life
5	The power system needs to employ simplicity to minimize launch mass.	Low Mass
7	Operate the power system in such a way as to avoid harmful contamination of the lunar surface	Surface Contamination Avoidance
10	The power system should restrict the use of nuclear power systems to missions which cannot be operated by non-nuclear energy sources in a reasonable way	Non-nuclear System Preference
11	The power system needs to have affordable technology development cost, facility cost, operation cost, and cost of failure.	Low Developmental, Facility, and Operational Costs

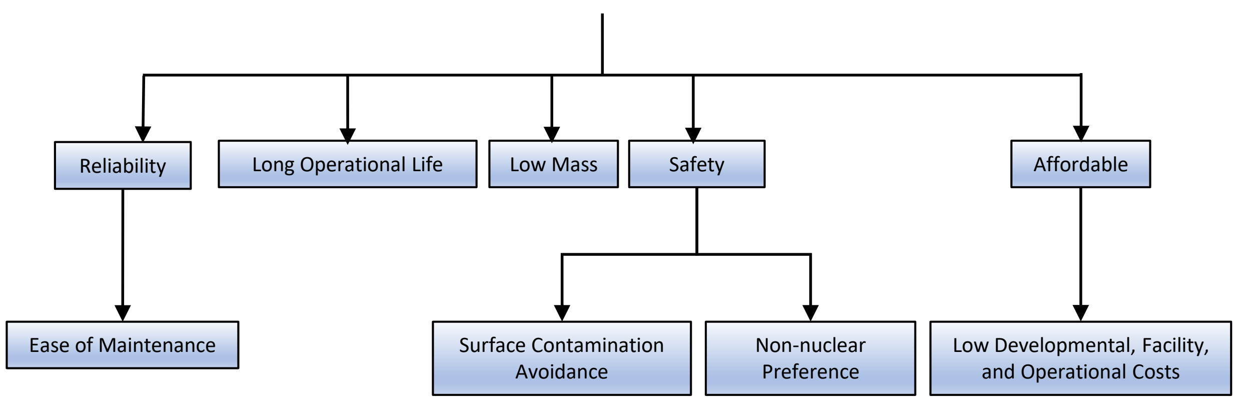

Figure 27: Value Tree

7.3 Step 4: Assignment of Value to Measure Performance of the Attributes

This step has several parts: defining what a good value is for each attribute, assigning and justifying attribute values, and inserting values into the scoring chart.

7.3.1 Attribute Function Definition

Step 3 produced six attributes. The six attribute values are shown in Table 18. The values may vary depending on lunar location—polar vs. equatorial site. Each location will be addressed within the section. As overviewed in the Methods chapter, attribute value is developed from attribute functions.

7.3.1.1 Ease of Maintenance

Ease of maintenance attribute came from the requirement for the power system to allow for field maintenance and replacement. Each of the systems have already been broken out into subsystems. The number of subsystems which can be repaired ($N_{repairable}$) in the field compared to the number of total subsystems ($N_{totalsyst}$) will be the basis for the value. The attribute value for Ease of Maintenance ($AV_{Ease\ of\ Maintenance}$) is developed from equation 7.1.

Table 19 shows the number of subsystems each power scheme has and what they are. The attribute value will be based on repairable subsystems. Each of the power systems will have at least one repairable subsystem—PMAD. Since all systems have PMAD, to determine $AV_{EaseofMaintenance}$ the subsystem total is adjusted to take out PMAD for calculation purposes.

Table 19: Power Scheme Subsystems

Power System	SubSystem Totals	Adjusted Subsystem Total	SubSystems
KRUSTY	2	1	1) Power System designed to be a single unit, not to be repaired, 2) PMAD
SP-100	2	1	1) Power System designed to be a single unit, not to be repaired, 2) PMAD
SDGTDP	6	5	1) Concentrator, 2) Receiver, 3) Thermodynamic Cycle, 4) Radiators, 5) Thermal Storage, 6) PMAD
Photovoltaic	3	2	1) Panel Array, 2) PMAD, 3) Regen Fuel Cell System
Kalina	6	5	1) Concentrator, 2) Receiver, 3) Thermodynamic Cycle, 4) Radiators, 5) Thermal Storage, 6) PMAD

There is not a difference in number of repairable subsystems depending on Lunar and Equatorial locations or power output.

The resulting function for Ease of Maintenance is

$$AV_{\text{Ease of Maintenance}} = (PS_{\text{AdjustedSubsystemTotal}} - 1)\ \frac{\mathbf{100}}{\mathbf{4}} \tag{7.2}$$

Following attribute development, further definition of system scoring is outlined in the upcoming SMART steps.

7.3.1.2 Long Operational Life

The requirement of long operational life was based on a value of 10 years. The long operational life attribute value function will be based on the lowest and highest of system life expectancy. Figure 28 aggregates the life values for each of the five power system schemes as outlined in Step 2.

Power System	Life Expectancy (yrs)	Reference
KRUSTY	12	McClure, 2017; Oleson, Poston and McClure, 2017
SP-100	7	Mason and Poston, 1989
SDGTDP	15	Mason, 2009
Photovoltaic	30	Surampudi, 2011
KC12	15	Mason, 2009

Figure 28: Power Scheme Life Expectancies

The bounding values of life expectancies are 7 and 30 years. Thus, the value functions for bounding values are…

$$v(30) = 100$$

$$v(7) = 0$$

The resulting equation for the attribute value for life expectancy ($AV_{\text{Life Expectancy}}$) based on each power schemes life expectancy ($LE_{\text{Power System}}$) is…

$$AV_{\text{Life Expectancy}} = (LE_{\text{Power System}} - 7)\ \frac{\mathbf{100}}{\mathbf{23}} \qquad (7.2)$$

It is assumed, due to the lunar environment, there is not a difference in life expectancy between the lunar equator and polar sites. See chapter 2 for additional information regarding the assumption. The life expectancy will also be the same for each power level of each system.

7.3.1.3 Low Mass

Due to the high cost of launching mass from the Earth to any extraterrestrial location, lower mass means lower emplacement costs. As previously mentioned, the research associated with this dissertation is iterative. To get a proper value function, one needs to have the system mass for each of the five candidate systems. The mass of each system is determined in step 5. However, to complete this step, the values will be pulled forward to develop the attribute value function. Due to the variation in energy storage requirements, the attribute value will vary for each of the bounding lunar locations and each power levels. Table 20 shows the bounding power system scheme masses used to determine the attribute value function.

Table 20: Lunar Power Scheme(s) Mass Bounding Values

	Polar Mass (kg)			Equator Mass (kg)		
Power	min	max	Δminmax	min	max	Δminmax
25	1712	3750	2038	2000	7519	5519
100	3500	15000	11500	3500	30076	26576
250	6050	37500	31450	6050	75190	69140
500	12100	75000	62900	12100	150380	138280
1000	24200	150000	125800	24200	300760	276560

Lunar Equator Location

Each of the five power levels has a different value function based on mass for the lunar equatorial location.

$$AV_{EquatorMass25kW} = 100 - [(m_{Power\ System} - 2000)\ \frac{\mathbf{100}}{\mathbf{5519}}] \tag{7.3}$$

$$AV_{EquatorMass100kW} = 100 - [(m_{Power\ System} - 3500)\ \frac{\mathbf{100}}{\mathbf{26576}}] \tag{7.4}$$

$$AV_{EquatorMass250kW} = 100 - [(m_{Power\ System} - 6050)\ \frac{\mathbf{100}}{\mathbf{69140}}] \tag{7.5}$$

$$AV_{EquatorMass500kW} = 100 - [(m_{Power\ System} - 12100)\ \frac{\mathbf{100}}{\mathbf{138280}}] \tag{7.6}$$

$$AV_{EquatorMass1000kW} = 100 - [(m_{Power\ System} - 24200)\ \frac{\mathbf{100}}{\mathbf{276560}}] \tag{7.7}$$

Lunar Pole Location

Each of the five power levels has a different value function based on mass for the lunar pole location.

$$AV_{PolarMass25kW} = 100 - [(m_{Power\ System} - 2000)\ \frac{\mathbf{100}}{\mathbf{2038}}] \tag{7.8}$$

$$AV_{PolarMass100kW} = 100 - [(m_{Power\ System} - 3500)\ \frac{\mathbf{100}}{\mathbf{11500}}] \tag{7.9}$$

$$AV_{PolarMass250kW} = 100 - [(m_{Power\ System} - 6050)\ \frac{\mathbf{100}}{\mathbf{31450}}] \tag{7.10}$$

$$AV_{PolarMass500kW} = 100 - [(m_{Power\ System} - 12100)\ \frac{\mathbf{100}}{\mathbf{62900}}] \tag{7.11}$$

$$AV_{PolarMass1000kW} = 100 - [(m_{Power\ System} - 24200)\ \frac{\mathbf{100}}{\mathbf{125800}}] \tag{7.12}$$

7.3.1.4 Surface Contamination Avoidance

Surface contamination avoidance means not releasing stored fluids, gases, energy, or radiation in such a matter as to permanently alter the lunar surface. This attribute is a yes or no attribute. Yes, means the system alters the surface thus gets 0 points. No, means the system does not alter the surface and receives 100 points. Two of the analyzed systems will abandon a portion of their equipment—the thermal storage system. Remediation will also be required to remove equipment—resulting in a score 50 points. The surface contamination preference does not delineate between power levels or lunar location.

7.3.1.5 Non-nuclear Preference

Non-nuclear preference means not utilizing nuclear material which will need to be abandoned in place at the end of life. This attribute is a yes or no attribute. Yes, means the system has nuclear material thus gets 0 points. No, means the system does not have nuclear material and receives 100 points. The nuclear preference does not delineate between power levels or lunar location.

7.3.1.6 Low Developmental, Facility, and Operational Cost

The current technology readiness level (TRL) is used as the quantitative value to differentiate the developmental, facility, and operation costs. The TRL level for each system is defined in Step 3 located in chapter 6 and summarized in Table 21.

Table 21: Lunar Power Scheme(s) TRL Values

Power System	TRL
KRUSTY	5
SP-100	3
SDGTDP	3
Photovoltaic	5
Kalina	2

Using the TRL levels in Table 21, one can develop the equation for attribute value (AV_{TRL}).

$$AV_{TRL} = (TRL_{Power\ System} - 2)\,\frac{100}{3} \tag{7.13}$$

The system TRL level is not subject to differences due to lunar location or power level. The TRL is for basic space power scheme technology readiness.

7.3.2 Attribute Value Assignment

Each of the attributes for each system are calculated and shown in Tables 50 and 51 located in Appendix 3. For detailed calculations please see Appendix 2 Attribute Calculations.

7.3.3 Scoring Chart Update

Based on the calculated attribute value, the scoring chart is update as shown in Tables 50 and 51 located in Appendix 3.

7.4 Performance Assessments and System Trades

To evaluate system performance of the ammonia-water thermodynamic power system in reference to the other power production schemes, two types of analysis are required. The first analysis is a thermodynamic study of the lunar ammonia-water thermodynamic power architecture. The second analysis estimates system sizes and masses by applying the results of the thermodynamic study and data from historic space power systems. From these analyses, scoring for mass of each of the candidate systems can be created.

7.4.1 Thermodynamic Analysis

The thermodynamic analysis presentation is broken into several parts. The thermodynamic analysis equations, constants, and processes for each system component are presented first. The resulting calculated values with variations in mass flow for several power output levels for KC12 are shown second. The calculated mass flows and heat values are used in the following mass estimation section.

7.4.1.1 Thermodynamic Analysis Equations and Processes

Each component of the Ammonia-Water (Kalina) system is analyzed thermodynamically. The analysis involves equations required to evaluate the system at a component level. Component level analysis will allow solving of the unknown parameter of the system and allow the determination of mass and volume values.

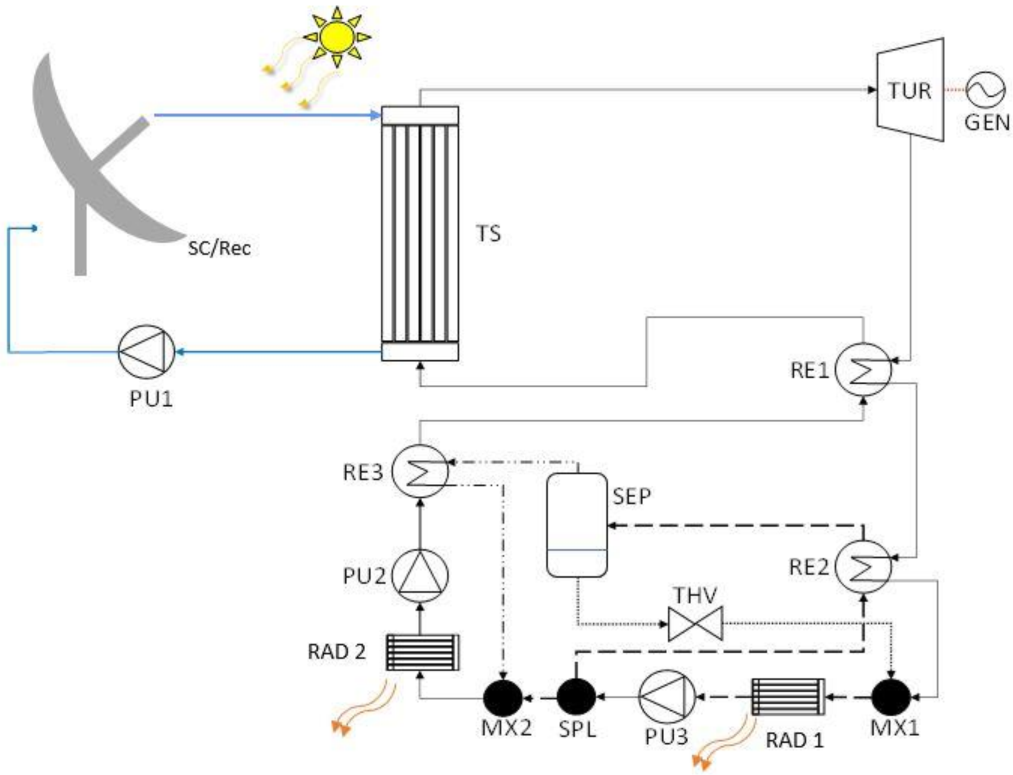

Figure 29: Lunar KC12 Concept

7.4.1.1.1 Thermal Heat Concentrator and Receiver (REC)

A very visible and important part of the power system is the concentrator and receiver. The optical concentrator focuses solar energy onto the receiver which transfers the heat into a working fluid. Since the system is working in a vacuum (air convection is not an issue as on Earth), the main losses involved is thermal emission. Several items influence the amount of useful energy the receiver absorbs: surface absorptivity and emissivity, optical concentration ratio, optical efficiency, and surface temperature (Duffie & Beckman, 1980).

For analysis purposes, the losses are put together into one efficiency number. Over the years, NASA has modeled and developed solar concentrators and receivers. The solar concentrator and receiver efficiency value ($\alpha_{Con\&Rec}$) is based on NASA's research and development activity (Colozza, 2009).

$$\alpha_{Con\&Rec} = 0.81 \quad (7.14)$$

One of the important evaluation factors this analysis seeks to uncover is the size of the thermal concentrator and receiver. The area and mass estimate can be developed mathematically. The total heat collected (Qabs) by the solar concentrator is expressed as

$$Q_{abs} = \alpha I_{sc} A_{eff} \quad (7.15)$$

where α is efficiency of the solar collector, Isc is solar constant at 1 AU or the solar radiation that strikes the receiver, and Aeff is the concentrator area. Concentrator area is shown as

$$A_{eff} = \frac{\pi * d2}{4} \quad (7.16)$$

where d is receiver diameter. The solar constant at 1 AU is (Duffie & Beckman, 1980)

$$I_{sc} = 4871 \text{ kJ/m}^2\text{hr} \quad (7.17)$$

Combining the equations together, one can calculate the needed area of the concentrator

$$A_{eff} = [Q_{period} / [I_{sc} * \alpha * 3600(\text{sec/hr})] \quad (7.18)$$

where Q_{period} is the amount of heat needed by the process.

7.4.1.1.2 Thermal Storage (TS)

Operation of a sun powered electrical generation system on the lunar surface both day and night demand the use of an energy storage system. The long lunar night dictates a large energy storage system. If one analyzes the use of batteries or transportation for an entire thermal energy storage system to the lunar surface, the mass of the systems will be prohibitively high

(Crane & Dustin, 1991; Barna & Johnson, 1968; Tillotson, 1992). Utilizing the lunar regolith as a thermal storage medium minimizes the transportation cost of a sun-powered system. This analysis utilizes Crane's 1991 study of in-situ thermal energy storage in the Lunar surface (Crane, 1991). Detailed analysis of the thermal energy storage system is out of scope of this dissertation. Determining how the launch mass and volume of the thermal energy storage components are impacted by an ammonia-water thermodynamic heat engine is the focus of this portion of research. Three areas need to be analyzed to determine launch mass and volume: lunar regolith properties at the two locations to be analyzed, Crane's Thermal Energy Storage (TES) concept, and the thermal heat properties that will feed the overall thermodynamic analysis.

The lunar regolith properties drive the mass and size of a TES system, i.e., the heat the regolith can store dictates how many thermal wells are needed to support a continuously operating thermodynamic power system. The two bounding lunar locations chosen are Riccioli and Amundsen. Riccioli is located near the lunar equator and geologically consists of mare basalts. Apollo 11, 12, and 15 probed near side mare depth and composition. Regolith depths ranged from 3-6 meters (Crane, 1991). Amundsen is located at the lunar south pole has mature, highlands regolith which does not have any mare basalt resources to include ilmenite (Morrison, 1990a). According to Mest (2011), Amundsen's mineralogy should be an intermediate between mafic and felsic. Apollo 16 was able to probe regolith depth and consistency in a highland region (Crane, 1991). The minerology is a result of mixing upper mantle and lower crustal material with feldspathic highlands material (Mest, 2011). Table 22 shows are the chemical compositions of the lunar regolith at the various Apollo landing sites.

Table 22: Regolith Composition at Apollo Sites (Crane, 1991)

	Apollo 11	Apollo 12	Apollo 14	Apollo 15	Apollo 16
SiO_2	42.04	46.40	47.93	46.61	44.94
TiO_2	7.48	2.66	1.74	1.36	0.58
Al_2O_3	13.92	13.50	17.60	17.18	26.71
FeO	15.74	15.50	10.37	11.62	5.49
MgO	7.90	9.73	9.24	10.46	5.96
CaO	12.01	10.50	11.19	11.64	15.57
Na_2O	0.44	0.59	0.68	0.46	0.48
K_2O	0.14	0.32	0.55	0.20	0.13
P_2O_5	0.12	0.40	0.53	0.19	0.12
MnO	0.21	0.21	0.14	0.16	0.07

These values were used by Colozza to develop a correlation for an average specific heat value (c_p) over a range of temperatures (Crane, 1991).

$$C_p = -1.8485 + 1.04741 \log(T) \text{ (kJ/kgK)} \quad (7.19)$$

Using Colozza's equation, across the range of temperatures of 250K to 1350K, one gets an average specific heat of regolith of 1.44 kJ/kg K. Using this value, Crane's thermal storage which utilizes latent heat needs 9.433 x 10^{-6} $kg/kJ_{thermal}$, and sensible heat needs 2.38 x 10^{-5} $kg/kJ_{thermal}$ (Crane, 1991).

How exactly does the thermal storage fit into the electrical generation scheme? Climent et al. (2014) develops the model used for this dissertation. Energy from sunlight concentrated by the solar concentrator is absorbed by a medium and transported to the energy storage subsystem. A separate transportation system sends needed heat to the thermodynamic engine. Excess heat is transported to a radiator/heat rejection unit.

7.4.1.1.3 Ammonia-Water Thermodynamic Engine (Kalina Cycle)

The various Kalina cycle heat engine components are now be shown in equation form.

7.4.1.1.3.1 Turbine (TUR) (with Generator)

The power produced from the turbine can be calculated using:

$$\dot{W}_{Turb} = \dot{m}_1 (h_2 - h_1) \tag{7.20}$$

The isentropic efficiency of the turbine can be shown as:

$$\eta_{Turb,i} = \frac{h_2 - h_1}{h_2 - h_{1s}} \tag{7.21}$$

Isentropic efficiency values can range from 79% to 90% (Nag & Gupta, 1998). The value of 85% is assumed for this study.

The electrical power output of the generator is calculated using:

$$\dot{W}_{Gen} = \dot{W}_{Turb}\, \eta_{Turb,m}\, \eta_{Gen} \tag{7.22}$$

Where the mechanical turbine efficiency ($\eta_{Turb,m}$) is assumed to be 98%. Mechanical turbine efficiency includes bearing and other mechanical system losses. The generator efficiency (η_{Gen}) is assumed to be 98% also.

7.4.1.1.3.2 Pumps (PU)

The work required by each pump can be calculated using:

$$\dot{W}_{PU1} = \dot{m}_6 (h_7 - h_6) \tag{7.23}$$

$$\dot{W}_{PU2} = \dot{m}_{15} (h_{16} - h_{15}) \tag{7.24}$$

The isentropic efficiency of each pump can be shown as:

$$\eta_{PU1} = \frac{h_7 - h_6}{h_7 - h_{6s}} \tag{7.25}$$

$$\eta_{PU2} = \frac{h_{16} - h_{15}}{h_{16} - h_{15s}} \tag{7.26}$$

Pump efficiencies typically range between 60% and 85% (Nag & Gupta, 1998). As with previous studies of solar powered Kalina cycles, a value of 70% is assumed for this study (Modi, 2015).

7.4.1.1.3.3 Reheaters (RE)

The energy balance equations in the reheaters are:

$$\dot{m}_2 (h_2 - h_3) = \dot{m}_{16} (h_{17} - h_{16}) \tag{7.27}$$

$$\dot{m}_3 (h_3 - h_4) = \dot{m}_9 (h_{10} - h_9) \tag{7.28}$$

The heat exchange effectiveness is estimated to be approximately 80%.

7.4.1.1.3.4 Radiator System (RAD)

The heat rejection system is covered in more depth in 7.4.1.1.4. For the purposes of this portion of analysis calculations and equations, the energy balance equations for the heat rejection are modeled as:

$$\dot{m}_5 (h_5 - h_6) = \dot{m}_{cw,rad1}\, c_{p,cw} (T_{cw,out} - T_{cw,in}) \tag{7.29}$$

$$\dot{m}_{14} (h_{14} - h_{15}) = \dot{m}_{cw,rad2}\, c_{p,cw} (T_{cw,out} - T_{cw,in}) \tag{7.30}$$

7.4.1.1.3.5 Mixers (MX)

The energy balance equations for the mixers are:

$$\dot{m}_5 h_5 = \dot{m}_4 h_4 + \dot{m}_{13} h_{13} \tag{7.31}$$

$$\dot{m}_{14} h_{14} = \dot{m}_8 h_8 + \dot{m}_{11} h_{11} \tag{7.32}$$

7.4.1.1.3.6 Separator (SEP)

The energy balance equation for the separator is:

$$\dot{m}_{10} h_{10} = \dot{m}_{11} h_{11} + \dot{m}_{12} h_{12} \tag{7.33}$$

7.4.1.1.3.7 Splitter (SPL)

The energy balance equations for the splitters are:

$$h_8 = h_7 \tag{7.34}$$

$$h_9 = h_7 \tag{7.35}$$

7.4.1.1.3.8 Throttling Valve (THV)

The energy balance equation for the throttling valve is:

$$h_{12} = h_{13} \tag{7.36}$$

7.4.1.1.4 Radiator System (RAD) Details

The heat rejection system for a relatively low temperature power cycle has unique challenges to operate on the lunar surface. A heat rejection similar to a system used to reject heat from lunar base habitation and science modules is utilized. One needs to determine the rejected heat values required from the system.

Radiators are governed by the following equation:

$$Q_{out} = \varepsilon\sigma(T^4_{rad} - T^4_{sink}) \tag{7.37}$$

where Q_{out} is the rejected heat in W/m^2, ε is the emissivity of the radiator(s), σ is the Stefan-Boltzmann constant which is 5.6697×10^{-8} W/m^2K^4, T_{rad} is the temperature of the radiator, and T_{sink} is the sink temperature (Simonsen, DeBarro, & Farmer, 1992). The sink temperature is based on the methodology presented in Dallas, Diaguila, & Saltsman (1971) and includes IR flux from the lunar surface, solar flux, and the effects of cold space. The radiator equation suggests that the temperature of the radiator plays a big part in heat rejection. For a low temperature thermodynamic cycle such as the Kalina cycle, heat rejection by radiation alone poses a unique problem since terrestrial thermodynamic cycles typically have condensers to reject heat. Terrestrial condensers typically rely upon water or air cooling through convection and conduction (Moran & Shapiro, 2004). The problem is remedied through the use of a compressor which compresses the working fluid prior to sending it to the radiator thus driving up the working fluid's temperature in the radiator. The working fluid is put through an expansion valve lowering the working fluid's temperature allowing it to pull sufficient thermal energy from the thermodynamic cycle (Sridhar et al., 1993). A high-level schematic of the system is shown in Figure 30.

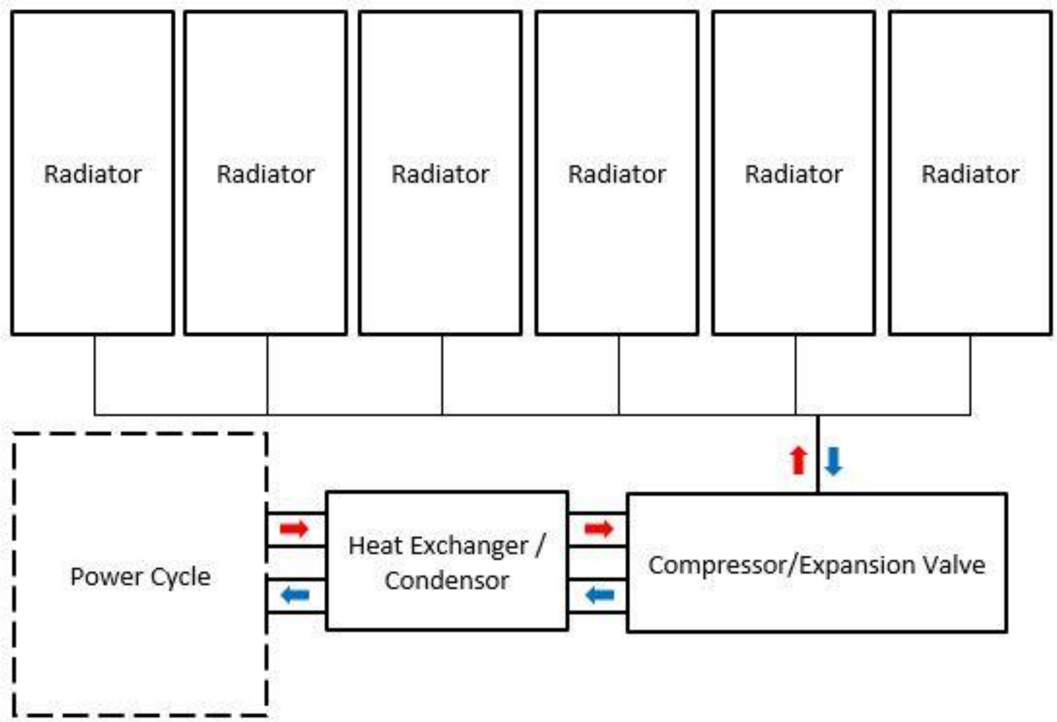

Figure 30: Low Temperature Thermal Control for Power Cycle (Sridhar et al., 1993)

The heat needed to be rejected by the lunar thermodynamic system drives the size and mass of the heat rejection system. For a heat rejection system, which includes piping, radiators, heat pumps, and heat exchangers, system mass and surface area is 30 kg/kW_t and 2.23 m^2/kW_t, respectively (Sridhar et al., 1993; Simonsen et al., 1992).

7.4.1.1.5 Mass Flow and Ammonia Fractions

One of the unique aspects of utilizing a binary cycle is determining mixture and quantity of ammonia during the cycle. As shown in chapter 6, the Kalina cycle 12 has been analyzed by multiple engineers as ideal for a sun-powered, high-temperature, e.g., an Ammonia/Water, thermodynamic cycle. Different ammonia mixture concentrations have been analyzed and graphed at the turbine inlet to show for the Kalina cycle 12 the ideal mass fraction is 0.8 (Modi

& Haglind, 2014). The resulting equations for mass flow rates based on mixture and amount of ammonia are:

$$\dot{m}_1 = \dot{m}_8 + \dot{m}_{13} \tag{7.38}$$

$$\dot{m}_1 \, x_1 = \dot{m}_8 \, x_8 + \dot{m}_{11} \, x_{11} \tag{7.39}$$

$$\dot{m}_5 = \dot{m}_1 + \dot{m}_{12} \tag{7.40}$$

$$\dot{m}_5 = \dot{m}_1 + \dot{m}_{12} \tag{7.41}$$

$$\dot{m}_5 \, x_5 = \dot{m}_1 \, x_1 + \dot{m}_{12} \, x_{12} \tag{7.42}$$

$$\dot{m}_8 = \dot{m}_5 \tag{7.43}$$

$$\dot{m}_{10} = \dot{m}_{11} + \dot{m}_{12} \tag{7.44}$$

$$\dot{m}_{10} \, x_{10} = \dot{m}_{11} \, x_{11} + \dot{m}_{12} \, x_{12} \tag{7.45}$$

$$\dot{m}_{11} = \dot{m}_{10} \, X_{10} \tag{7.46}$$

$$x_5 = x_8 = x_{10} \tag{7.47}$$

where x is the ammonia mass fraction, X is vapor quality, and $\dot{m}$ is mass flow rate.

7.4.1.2 Thermodynamic Analysis Results

For the ammonia-water power cycle, Table 23 shows the results for the calculated thermodynamic values for five different power requirements.

Table 23: Values for Lunar KC12

Stream	T (°C)	T (K)	p (bar)	1 MWe m_{DOT} (kg/s)	500 kWe m_{DOT} (kg/s)	250 kWe m_{DOT} (kg/s)	100 kWe m_{DOT} (kg/s)	25 kWe m_{DOT} (kg/s)	x	h (kJ/kg)
1	500	773.15	140	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	2902.4
2	183.9	457.05	6.04	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	2190.9
3	93	366.15	6.04	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	1658.8
4	38.6	311.75	6.04	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	1024.7
5	43.4	316.55	6.04	2.3575	1.1788	0.5894	0.2358	0.0589	0.6795	699
6	24	297.15	6.04	2.3575	1.1788	0.5894	0.2358	0.0589	0.6795	132.7
7	24.1	297.25	8.2	2.3575	1.1788	0.5894	0.2358	0.0589	0.6795	133.1
8	24.1	297.25	8.2	0.9000	0.4500	0.2250	0.0900	0.0225	0.6795	133.1
9	24.1	297.25	8.2	1.4575	0.7288	0.3644	0.1458	0.0364	0.6795	133.1
10	56	329.15	8.2	1.4575	0.7288	0.3644	0.1458	0.0364	0.6795	769.9
11	56	329.15	8.2	0.5635	0.2818	0.1409	0.0564	0.0141	0.9925	1728.4
12	56	329.15	8.2	0.8940	0.4470	0.2235	0.0894	0.0224	0.4823	166
13	47.8	320.95	6.04	0.8940	0.4470	0.2235	0.0894	0.0224	0.4823	166
14	34.3	307.45	8.2	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	747.2
15	27	300.15	8.2	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	259.8
16	31	304.15	152.17	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	289.3
17	134.2	407.35	152.17	1.4635	0.7318	0.3659	0.1464	0.0366	0.8	821.3

Table 24 shows the calculated heat in, heat out, and heat storage for the ammonia-water power cycle. These values will be used to estimate mass and volume for the power cycle.

Table 24: Calculated Heat Values from KC12

		1 MWe	500 kWe	250 kWe	100 kWe	25 kWe
Heat In	Q_{in} (kW_t)	3045.69	1522.845	761.4225	304.569	76.14225
	Q_{Period} (kJ)	7.76E+09	3.88E+09	1.94E+09	7.76E+08	1.94E+08
	$Q_{50\%Storage}$ (kJ)	3.88E+09	1.94E+09	9.7E+08	3.88E+08	97035679
	$Q_{90\%Storage}$ (kJ)	7.76E+08	3.88E+08	1.94E+08	77628543	19407136
Heat Out	Q_{out1} (kW_t)	1335.052	667.5261	333.7631	133.5052	33.37631
	Q_{out2} (kW_t)	713.3099	356.655	178.3275	71.33099	17.83275

7.4.2 Mass and Volume Analysis

Mass and volume of any system sent to support activities on the lunar surface will directly impact system costs. The sizing of the solar concentrator and receiver, heat rejection system, and thermal storage will drive mass and volume numbers. These three system component sizes can be estimated with values from the thermodynamic analysis. The thermodynamic analysis shows how much sunlight needs to be collected (Q_{in}), how much heat needs to be rejected (Q_{out}), and how much heat needs to be stored ($Q_{Storage}$). The design reference mission scenarios developed are utilized. As shown in Tables 25 and 26, the polar location will demand a different sized system than the equatorial location. The specific weight values developed in Chapter 6 are used to develop Table 27. The values from Tables 28 and 29 will feed into the economic estimates of the next section.

Table 25: Calculated Area and Mass Values from Lunar KC12 at Equatorial Location

		1 MWe	**500 kWe**	**250 kWe**	**100 kWe**	**25 kWe**
Riccioli (50/50)	$A_{Collector}$ (m^2)	5557.955	2778.977	1389.489	555.7955	138.9489
	$m_{Collector}$ (kg)	21771.4	10885.7	5442.849	2177.14	544.2849
	$A_{Radiator1}$ (m^2)	2980.796	1490.398	745.199	298.0796	74.5199
	$A_{Radiator2}$ (m^2)	1592.62	796.3102	398.1551	159.262	39.81551
	$m_{Radiator1}$ (kg)	40051.57	20025.78	10012.89	4005.157	1001.289
	$m_{Radiator2}$ (kg)	21399.3	10699.65	5349.824	2139.93	534.9824
	$m_{LatTherStor}$ (kg)	36615.94	18307.97	9153.985	3661.594	915.3985
	$m_{SenTherStor}$ (kg)	92377.97	46188.98	23094.49	9237.797	2309.449

Table 26: Calculated Area and Mass Values from Lunar KC12 at Polar Location

		1 MWe	**500 kWe**	**250 kWe**	**100 kWe**	**25 kWe**
Amundsen (90/10)	$A_{Collector}$ (m^2)	3087.753	1543.876	771.9382	308.7753	77.19382
	$m_{Collector}$ (kg)	12095.22	6047.61	3023.805	1209.522	302.3805
	$A_{Radiator1}$ (m^2)	2980.796	1490.398	745.199	298.0796	74.5199
	$A_{Radiator2}$ (m^2)	1592.62	796.3102	398.1551	159.262	39.81551
	$m_{Radiator1}$ (kg)	40051.57	20025.78	10012.89	4005.157	1001.289
	$m_{Radiator2}$ (kg)	21399.3	10699.65	5349.824	2139.93	534.9824
	$m_{LatTherStor}$ (kg)	7323.188	3661.594	1830.797	732.3188	183.0797
	$m_{SenTherStor}$ (kg)	18475.59	9237.797	4618.898	1847.559	461.8898

Table 27: Combined Calculated and Estimated Mass Values for Lunar KC12

		Mass (kg)				
		1 MWe	*500 kWe*	*250 kWe*	*100 kWe*	*25 kWe*
Riccioli (50/50)	*Concentrator*	21771	10886	5443	2177	544
	TES HX (latent storage)	36616	18308	9154	3662	915
	Receiver	120	60	30	12	3
	KC Conversion (0.2 kg/kWe)	300	150	75	30	8
	Radiator	61451	30725	15363	6145	1536
	PMAD	1000	500	250	100	25
	Total Mass	**121258**	**60629**	**30315**	**12126**	**3031**
Amundsen (90/10)	*Concentrator*	12095	6048	3024	1210	302
	TES HX (latent storage)	7323	3662	1831	732	183
	Receiver	120	60	30	12	3
	KC Conversion (0.2 kg/kWe)	300	150	75	30	8
	Radiator	61451	30725	15363	6145	1536
	PMAD	1000	500	250	100	25
	Total Mass	**82289**	**41145**	**20572**	**8229**	**2057**

Table 28: Calculated Mass Values from Lunar Power Systems at Polar Location

Lunar Location	Lunar Power Demand (kW)	Power System Type	Specific Power (kg/kWe)	Mass (kg)
Amundsen (88S, 60E)	25	KRUSTY	150	3750
		SP-100	80	2000
		SDGTDP	144	3600
		Photovoltaic	300.76	7519
		KC12	121.24	3031
	100	KRUSTY	150	15000
		SP-100	35	3500
		SDGTDP	144	14400
		Photovoltaic	300.76	30076
		KC12	121.35	12135
	250	KRUSTY	150	37500
		SP-100	24.2	6050
		SDGTDP	144	36000
		Photovoltaic	300.76	75190
		KC12	121.26	30315
	500	KRUSTY	150	75000
		SP-100	24.2	12100
		SDGTDP	144	72000
		Photovoltaic	300.76	150380
		KC12	121.258	60629
	1000	KRUSTY	150	150000
		SP-100	24.2	24200
		SDGTDP	144	144000
		Photovoltaic	300.76	300760
		KC12	121.258	121258

Table 29: Calculated Mass Values from Lunar Power Systems at Equator Location

Lunar Location	Lunar Power Demand (kW)	Power System Type	Specific Power (kg/kWe)	Mass (kg)
Riccioli (3.5S, 74W)	25	KRUSTY	150	3750
		SP-100	80	2000
		SDGTDP	136	3400
		Photovoltaic	68.48	1712
		KC12	82.28	2057
	100	KRUSTY	150	15000
		SP-100	35	3500
		SDGTDP	136	13600
		Photovoltaic	68.48	6848
		KC12	82.29	8229
	250	KRUSTY	150	37500
		SP-100	24.2	6050
		SDGTDP	136	34000
		Photovoltaic	68.48	17120
		KC12	82.288	20572
	500	KRUSTY	150	75000
		SP-100	24.2	12100
		SDGTDP	136	68000
		Photovoltaic	68.48	34240
		KC12	82.29	41145
	1000	KRUSTY	150	150000
		SP-100	24.2	24200
		SDGTDP	136	136000
		Photovoltaic	300.76	68480
		KC12	82.289	82289

Note: Only the nuclear-powered systems do not need energy storage for night operation. The photovoltaic array and solar thermodynamic power systems are estimated to need energy storage for 10% of the time for operation at the lunar pole.

7.5 Mission Utility Evaluation

Does a thermodynamic power cycle such as a Kalina power cycle provide a lower transport mass to the lunar surface when compared to other power generation schemes? Is the footprint of the photovoltaic power system smaller than a thermodynamic system? By answering these questions and questions such as these, one can begin to provide answers the research questions.

7.5.1 Launch Cost Analysis

For this analysis, the base costs per launch of a Falcon 9 and Falcon Heavy are used. Jones (2017) calculated the $/kg for lunar surface emplacement utilizing these two vehicles. NASA's Space Launch System (SLS) was initially considered, but there are not any reliable NASA estimates for the SLS average costs per flight. NASA's William H. Gerstenmaier said, "[per mission] costs must be derived from the data and are not directly available" (Berger, 2017).

The values determined for volume and mass numbers shown in Tables 28 and 29 feed launch vehicle requirements. Note: for every kilogram of mass placed on the lunar surface, 6.98 kg mass of the rocket and rocket fuel must also be placed in low earth orbit (BVAD, 2004).

Table 30: Lunar Surface Emplacement Cost (Jones, 2017)

System	Shuttle actual	Shuttle planned	Falcon 9	Falcon Heavy	Reusable Falcon 9	Reusable Falcon Heavy
Cost per launch, $M	1,200	400	62	90	6	9
Payload in LEO, k kg	16	16	22.8	54.4	14.8	35.4
Launch cost to LEO, $k/kg	75	25	2.72	1.65	0.40	0.25
Lunar surface emplacement cost, $k/kg	524	175	19.0	11.5	2.83	1.78

Based on the values from Table 30, Falcon 9 can deliver 3,266 kg and a Falcon Heavy can deliver 7,793 kg to the lunar surface. The calculated launches and launch costs are shown in Table 31.

Table 31: Estimated Power System Lunar Emplacement Cost

Lunar Location	Lunar Power Demand (kWe)	Power System Type	Mass (kg)	Falcon 9 Heavy Cost	Falcon 9 Heavy Reusable Cost
Amundsen (88S, 60E)	25	KRUSTY	3750	$43,125,000	$6,675,000
		SP-100	2000	$23,000,000	$3,560,000
		SDGTDP	3600	$41,400,000	$6,408,000
		Photovoltaic	7519	$86,468,500	$13,383,820
		Kalina	3031	$34,856,500	$5,395,180
	100	KRUSTY	15000	$172,500,000	$26,700,000
		SP-100	3500	$40,250,000	$6,230,000
		SDGTDP	14400	$165,600,000	$25,632,000
		Photovoltaic	30076	$345,874,000	$53,535,280
		Kalina	12135	$139,552,500	$21,600,300
	250	KRUSTY	37500	$431,250,000	$66,750,000
		SP-100	6050	$69,575,000	$10,769,000
		SDGTDP	36000	$414,000,000	$64,080,000
		Photovoltaic	75190	$864,685,000	$133,838,200
		Kalina	30315	$348,622,500	$53,960,700
	500	KRUSTY	75000	$862,500,000	$133,500,000
		SP-100	12100	$139,150,000	$21,538,000
		SDGTDP	72000	$828,000,000	$128,160,000
		Photovoltaic	150380	$1,729,370,000	$267,676,400
		Kalina	60629	$697,233,500	$107,919,620
	1000	KRUSTY	150000	$1,725,000,000	$267,000,000
		SP-100	24200	$278,300,000	$43,076,000
		SDGTDP	144000	$1,656,000,000	$256,320,000
		Photovoltaic	300760	$3,458,740,000	$535,352,800
		Kalina	121258	$1,394,467,000	$215,839,240
Riccioli (3.5S, 74W)	25	KRUSTY	3750	$43,125,000	$6,675,000
		SP-100	2000	$23,000,000	$3,560,000
		SDGTDP	3400	$39,100,000	$6,052,000
		Photovoltaic	1712	$19,688,000	$3,047,360
		Kalina	2057	$23,655,500	$3,661,460
	100	KRUSTY	15000	$172,500,000	$26,700,000
		SP-100	3500	$40,250,000	$6,230,000
		SDGTDP	13600	$156,400,000	$24,208,000
		Photovoltaic	6848	$78,752,000	$12,189,440
		Kalina	8229	$94,633,500	$14,647,620
	250	KRUSTY	37500	$431,250,000	$66,750,000
		SP-100	6050	$69,575,000	$10,769,000
		SDGTDP	34000	$391,000,000	$60,520,000
		Photovoltaic	17120	$196,880,000	$30,473,600
		Kalina	20572	$236,578,000	$36,618,160
	500	KRUSTY	75000	$862,500,000	$133,500,000
		SP-100	12100	$139,150,000	$21,538,000
		SDGTDP	68000	$782,000,000	$121,040,000
		Photovoltaic	34240	$393,760,000	$60,947,200
		Kalina	41145	$473,167,500	$73,238,100
	1000	KRUSTY	150000	$1,725,000,000	$267,000,000
		SP-100	24200	$278,300,000	$43,076,000
		SDGTDP	136000	$1,564,000,000	$242,080,000
		Photovoltaic	68480	$787,520,000	$121,894,400
		Kalina	82289	$946,323,500	$146,474,420

7.5.2 Cost Analysis Conclusions

The objective of this portion of the study is to determine whether an ammonia-water thermodynamic cycle, called a Kalina cycle, can provide lower launch costs benefits over the power generation schemes of photovoltaic, nuclear thermodynamic and sun-powered Brayton cycles on the lunar surface for powering a large lunar base or lunar industrial process. The answer is yes, but not in all situations and scenarios. A Kalina cycle is lower cost to launch than a photovoltaic system for large lunar bases. Photovoltaic has lower launch cost for smaller applications, but as a base's power demand increases, photovoltaic rapidly gets to be larger compared to thermodynamic systems. When comparing a Kalina cycle with a solar powered Brayton cycle, the benefits are somewhat marginal until power demand starts getting large. Most of the cost savings is from a smaller thermal heat sink requirement. Cost savings from a thermal heat sink start to be realized around a 250 kW system size. Compared to all other power production systems at the higher power output requirement, the nuclear-powered thermodynamic system is much lower in cost for a medium length mission. The benefit that a solar powered thermodynamic system has over a nuclear-powered system is heat source life. A nuclear-powered system only lasts 12-15 years before needing a new nuclear core. Replacing a core in space may be tricky and has not been done before. If one has bases which last decades, the monetary launch costs will mount with a nuclear power system.

All in all, a thermodynamic Kalina cycle can provide lower launch cost benefits over nuclear thermodynamic, solar Brayton thermodynamic, and photovoltaic for the right mission set. If launch costs continue to decline, the economic benefits and power system choice will be impacted.

7.6 Step 5: Attribute Weight Determination

Now that the mass and cost estimations are complete, we can use these results and switch back to the SMART method. Attribute weight determination has two parts: ranking the attributes from least to most important base on priority found in literature and assigning weights through the Rank Order Centroid (ROC) weights.

7.6.1 Attribute Importance Determination

Attributes will now be put into order of importance based on available literature from NASA and the space community. Three lunar power system requirements documents are used to determine the attribute importance. The first document is Appendix 4G of ESAS followed by Petri, Cataldo, and Bozek's (2006) Power System Requirements and Definition for Lunar and Mars Outposts and, finally, Cataldo and Bozek's (1993) Power Requirements for the First Lunar Outpost (FLO).

7.6.1.1 ESAS, Appendix 4G Attribute Importance

ESAS has its attributes defined as figures of merit (FOM). The FOMs for ESAS—in descending order of importance—are identified as Lunar Flexibility, Safety and Mission Success, Programmatic Risk, and Affordability. The question remains how do these FOMs relate to this dissertation's defined attributes. As shown in ESAS Appendix 4G, Lunar Flexibility is heavily dependent upon system mass. Long Operational Life and Ease of Maintenance are both key components of Safety and Mission Success. Surface Contamination Avoidance and Non-nuclear preference are addressed as programmatic risks. However, as a nuclear system is the top choice of ESAS, surface contamination avoidance is placed above non-nuclear preference. Low Developmental, Facility, and Operational Expenses are addressed as affordability issues (NASA, 2005b). Table 32 summarizes the ranking ESAS, Appendix 4G has for the attributes named in this dissertation.

Table 32: ESAS, Appendix 4G Attribute Equivalent

Rank	Attribute	ESAS FOM Equivalent
1	Low Mass	Lunar Flexibility
2 tie	Long Operational Life	Safety and Mission Success
2 tie	Ease of Maintenance	Safety and Mission Success
4	Surface Contamination Avoidance	Programatic Risk
5	Non-nuclear preference	Programatic Risk
6	Low Developmental, Facility, and Operational Expenses	Affordability

7.6.1.2 Petri, Cataldo, and Bozek's Attribute Importance

Petri, Cataldo, and Bozek (2006) have primary design driver system requirements for power systems as mass allocation per flight, safety, reliability, maintainability, telerobotic or self-deployment and commonality. Mass is defined as the key discriminator for surface power systems due to it not only affecting initial emplacement scheme, but limiting maintenance, servicing and replacement. Systems which have Long Operational Life are important due keeping launch mass low. Ease of Maintenance is considered key due to a verifiable component of system viability. Low Developmental, Facility, and Operational Expenses is considered a side benefit of reliability and maintainability, not a key component. Surface contamination avoidance and non-nuclear preference are not mentioned. However, a nuclear system is proposed as one option thus non-nuclear preference is not seen as highly important (Petri et al., 2006).

Table 33: Petri, Cataldo, & Bozek (2006) Attribute Equivalent

Rank	Attribute	Petri, Cataldo, and Bozek, 2006 Equivalent
1	Low Mass	Low Mass
2	Long Operational Life	Long Life Reduces Mass
3	Ease of Maintenance	Maintenance is key item to be verified
4	Low Developmental, Facility, a	Keeping costs low considered a side benefit of reliability and maintainability
5	Surface Contamination Avoid	Not directly mentioned
6	Non-nuclear preference	Nuclear systems proposed

7.6.1.3 Cataldo and Bozek's Attribute Importance

The 1993 study by Cataldo and Bozek has low mass and volume as an "obvious" most salient design feature. Reliability and system lifetime—matching up with long operational life and ease of maintenance—are defined as critical. Low Developmental, Facility, and Operational Expenses are shown as having a significant impact to mission success but not defined as critical. Surface contamination avoidance and non-nuclear preference are not mentioned. However, as will all the other requirement studies, a nuclear system is proposed as one option, thus non-nuclear preference is not seen as highly important (Cataldo & Bozek, 1993).

Table 34: Cataldo, and Bozek (1993) Attribute Equivalent

Rank	Attribute	Cataldo and Bozek, 1993 Equivalent
1	Low Mass	Low mass and volume most saliet design feature
2 tie	Long Operational Life	Reliability and lifetimes are critical
2 tie	Ease of Maintenance	Reliability and lifetimes are critical
4	Low Developmental, Facility, and Operational Expenses	Life Cycle costs have a significant impact on mission success
5	Surface Contamination Avoidance	Not directly mentioned
6	Non-nuclear preference	Nuclear systems proposed

7.6.1.4 Attribute Importance Summary

There are two places where the three studies do not match. ESAS has life cycle costs as below surface contamination and non-nuclear preference. However, the other two studies have it ranked 4. ESAS's preference is not strong, therefore the ultimate ranking of life cycle costs will be 4. A tie between operational life and ease of maintenance exists in ESAS and Cataldo and Bozek (1993). Petri, Cataldo, and Bozek (2006) delineate between the two, thus breaking the tie. The final ranking is shown in Table 35.

Table 35: Final Attribute Ranking

Rank	Attribute
1	Low Mass
2	Long Operational Life
3	Ease of Maintenance
4	Low Developmental, Facility, and Operational Expenses
5	Surface Contamination Avoidance
6	Non-nuclear preference

7.6.2 Placing Weight Values into Score Matrix

Based on the rankings shown in Table 35, the ROC values from Table 5 are applied to the score chart. The resulting charts are shown in Tables 52 and 53 located in Appendix 3.

7.7 Step 6: Multiplication of the Weight with Attribute Value to Determine Final System Score

The following charts and graphs show the final scores for each of the systems. The scores are shown at the polar and equatorial locations. The ROC values and attribute scores are multiplied together in each column and aggregated together for a final score. Tables 36 and 37 along with Figures 31 and 32 display the final scoring of all systems in all DRMs.

Table 36: Final Polar Location Score Chart

Lunar Power Demand (kW)	Power System Type	Value Dimensions: Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	35.11	0.00	0.00	3.39	38.51
	SDGTDP	15.83	8.46	6.94	3.06	2.78	3.39	40.46
	Photovoltaic	15.83	24.17	40.83	6.11	2.78	10.28	100.00
	KC12	15.83	8.46	33.89	3.06	2.78	0.00	64.01
100	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	25.31	3.06	2.78	3.39	58.83
	Photovoltaic	15.83	24.17	35.52	6.11	2.78	10.28	94.69
	KC12	15.83	8.46	33.48	3.06	2.78	0.00	63.61
250	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	3.06	2.78	3.39	58.01
	Photovoltaic	15.83	24.17	34.30	6.11	2.78	10.28	93.47
	KC12	15.83	8.46	32.26	3.06	2.78	0.00	62.38
500	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	3.06	2.78	3.39	58.01
	Photovoltaic	15.83	24.17	34.30	6.11	2.78	10.28	93.47
	KC12	15.83	8.46	32.26	3.06	2.78	0.00	62.38
1000	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	3.06	2.78	3.39	58.01
	Photovoltaic	15.83	24.17	34.30	6.11	2.78	10.28	93.47
	KC12	15.83	8.46	32.26	3.06	2.78	0.00	62.38

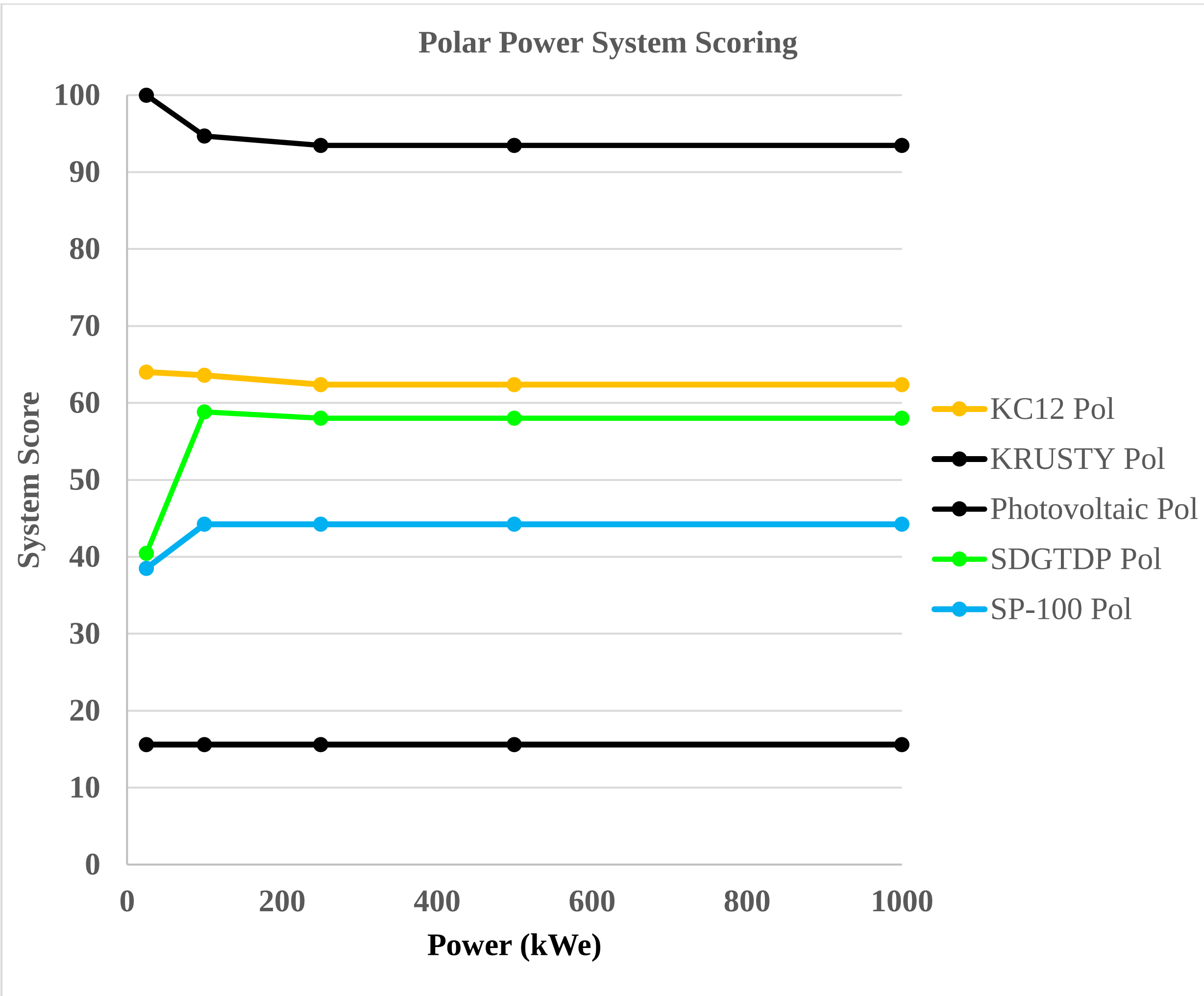

Figure 31: Final Pole Location Score Graph

Table 37: Final Equatorial Location Score Chart

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	27.76	0.00	0.00	10.28	43.36
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	28.99	3.06	2.78	3.39	62.51
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	33.07	3.06	2.78	0.00	63.20
100	KRUSTY	0.00	5.32	23.27	0.00	0.00	10.28	38.87
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.09	3.06	2.78	3.39	57.61
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	27.76	3.06	2.78	0.00	57.89
250	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	3.06	2.78	3.39	56.79
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	26.54	3.06	2.78	0.00	56.66
500	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	3.06	2.78	3.39	56.79
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	26.54	3.06	2.78	0.00	56.66
1000	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	3.06	2.78	3.39	56.79
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	26.54	3.06	2.78	0.00	56.66

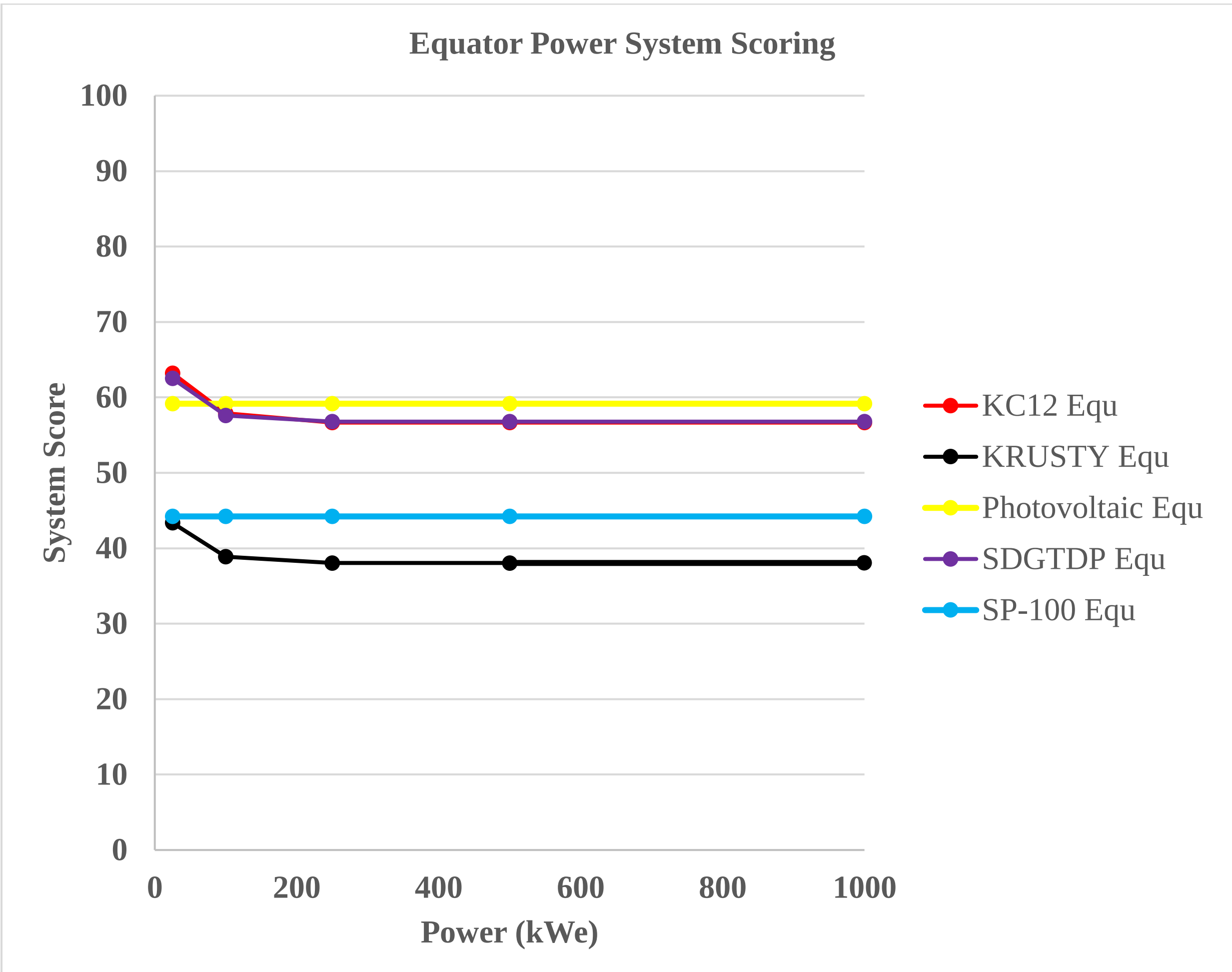

Figure 32: Final Equatorial Location Score Graph

7.8 Step 7: Provisional Determinations

Based on Tables 36 and 37 in Step 6, there is a clear difference between the scores the power systems have at the equator and the polar locations. The polar location strongly favors a photovoltaic/regenerative fuel cell system. The favoring of the photovoltaic at the poles can be traced to several technological and environmental reasons. The lunar surface has a much higher illumination level at the poles which favors sun-powered systems. The photovoltaic system is at a higher technological development than sun-power thermodynamic, is the simplest system, and does not significantly or permanently impact the lunar environment. The equatorial location has much closer scoring. The aggregate scores for the equatorial location do show a preference to solar-powered systems. The scoring between the solar systems is very close. The thermodynamic systems have a clear advantage with mass. The photovoltaic system has a clear advantage with maintenance and length of life.

7.9 Step 8: Sensitivity Analysis

The sensitivity analysis is broken into two parts. The first will look at the polar location. The second will look at the equatorial location.

7.9.1 Polar Location Sensitivity

7.9.1.1 Mass = 0

Table 38: Polar Low Mass = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
100	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
250	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
500	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
1000	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12

Zeroing out the mass score for the polar location does not change the system with the highest scoring. Photovoltaic still has the highest scoring for all systems. This sensitivity analysis does point out the impact of mass on the scoring as power demand is changed. Each system has the same scoring regardless of power demand when mass is taken out of the equation. The second and third ranked systems are swapped when mass is removed. KC12 drops to third, and SDGTDP moves up to second. The swap is due to KC12's higher complexity resulting in a higher efficiency and lower mass. When the mass advantage is removed, the complexity risk linked to maintenance becomes a bigger issue.

7.9.1.2 Long Operational Life = 0

Table 39: Polar Long Operational Life = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	0.00	0.00	0.00	0.00	10.28	10.28
	SP-100	0.00	0.00	35.11	0.00	0.00	3.39	38.51
	SDGTDP	15.83	0.00	6.94	3.06	2.78	3.39	32.00
	Photovoltaic	15.83	0.00	40.83	6.11	2.78	10.28	75.83
	KC12	15.83	0.00	33.89	3.06	2.78	0.00	55.55
100	KRUSTY	0.00	0.00	0.00	0.00	0.00	10.28	10.28
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	25.31	3.06	2.78	3.39	50.37
	Photovoltaic	15.83	0.00	35.52	6.11	2.78	10.28	70.52
	KC12	15.83	0.00	33.48	3.06	2.78	0.00	55.15
250	KRUSTY	0.00	0.00	0.00	0.00	0.00	10.28	10.28
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	24.50	3.06	2.78	3.39	49.56
	Photovoltaic	15.83	0.00	34.30	6.11	2.78	10.28	69.30
	KC12	15.83	0.00	32.26	3.06	2.78	0.00	53.92
500	KRUSTY	0.00	0.00	0.00	0.00	0.00	10.28	10.28
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	24.50	3.06	2.78	3.39	49.56
	Photovoltaic	15.83	0.00	34.30	6.11	2.78	10.28	69.30
	KC12	15.83	0.00	32.26	3.06	2.78	0.00	53.92
1000	KRUSTY	0.00	0.00	0.00	0.00	0.00	10.28	10.28
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	24.50	3.06	2.78	3.39	49.56
	Photovoltaic	15.83	0.00	34.30	6.11	2.78	10.28	69.30
	KC12	15.83	0.00	32.26	3.06	2.78	0.00	53.92

Taking the Long Operational Life to zero does not changed the rank order of power systems at the polar location.

7.9.1.3 Ease of Maintenance = 0

Table 40: Polar Ease of Maintenance = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	35.11	0.00	0.00	3.39	38.51
	SDGTDP	0.00	8.46	6.94	3.06	2.78	3.39	24.63
	Photovoltaic	0.00	24.17	40.83	6.11	2.78	10.28	84.17
	KC12	0.00	8.46	33.89	3.06	2.78	0.00	48.18
100	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	25.31	3.06	2.78	3.39	43.00
	Photovoltaic	0.00	24.17	35.52	6.11	2.78	10.28	78.86
	KC12	0.00	8.46	33.48	3.06	2.78	0.00	47.78
250	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	24.50	3.06	2.78	3.39	42.18
	Photovoltaic	0.00	24.17	34.30	6.11	2.78	10.28	77.64
	KC12	0.00	8.46	32.26	3.06	2.78	0.00	46.55
500	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	24.50	3.06	2.78	3.39	42.18
	Photovoltaic	0.00	24.17	34.30	6.11	2.78	10.28	77.64
	KC12	0.00	8.46	32.26	3.06	2.78	0.00	46.55
1000	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	24.50	3.06	2.78	3.39	42.18
	Photovoltaic	0.00	24.17	34.30	6.11	2.78	10.28	77.64
	KC12	0.00	8.46	32.26	3.06	2.78	0.00	46.55

By removing maintenance from the value dimensions, the relative score of the nuclear systems increases as compared to the sun power systems. The SP-100 system marginally outscores the SDGTDP for all the power demand schemes.

7.9.1.4 Low Developmental, Facility, and Operational Costs = 0

Table 41: Polar Low Developmental, Facility, and Operational Costs = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	0.00	0.00	0.00	0.00	5.32
	SP-100	0.00	0.00	35.11	0.00	0.00	0.00	35.11
	SDGTDP	15.83	8.46	6.94	3.06	2.78	0.00	37.07
	Photovoltaic	15.83	24.17	40.83	6.11	2.78	0.00	89.72
	KC12	15.83	8.46	33.89	3.06	2.78	0.00	64.01
100	KRUSTY	0.00	5.32	0.00	0.00	0.00	0.00	5.32
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	25.31	3.06	2.78	0.00	55.44
	Photovoltaic	15.83	24.17	35.52	6.11	2.78	0.00	84.41
	KC12	15.83	8.46	33.48	3.06	2.78	0.00	63.61
250	KRUSTY	0.00	5.32	0.00	0.00	0.00	0.00	5.32
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	24.50	3.06	2.78	0.00	54.62
	Photovoltaic	15.83	24.17	34.30	6.11	2.78	0.00	83.19
	KC12	15.83	8.46	32.26	3.06	2.78	0.00	62.38
500	KRUSTY	0.00	5.32	0.00	0.00	0.00	0.00	5.32
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	24.50	3.06	2.78	0.00	54.62
	Photovoltaic	15.83	24.17	34.30	6.11	2.78	0.00	83.19
	KC12	15.83	8.46	32.26	3.06	2.78	0.00	62.38
1000	KRUSTY	0.00	5.32	0.00	0.00	0.00	0.00	5.32
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	24.50	3.06	2.78	0.00	54.62
	Photovoltaic	15.83	24.17	34.30	6.11	2.78	0.00	83.19
	KC12	15.83	8.46	32.26	3.06	2.78	0.00	62.38

Taking the Developmental Costs to zero does not change the rank order of power systems at the polar location.

7.9.1.5 Surface Contamination Avoidance = 0

Table 42: Polar Surface Contamination Avoidance = 0 Sensitivity Values

		Value Dimensions							
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	35.11	0.00	0.00	3.39	38.51
	SDGTDP	15.83	8.46	6.94	0.00	2.78	3.39	37.40
	Photovoltaic	15.83	24.17	40.83	0.00	2.78	10.28	93.89
	KC12	15.83	8.46	33.89	0.00	2.78	0.00	60.96
100	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	25.31	0.00	2.78	3.39	55.78
	Photovoltaic	15.83	24.17	35.52	0.00	2.78	10.28	88.58
	KC12	15.83	8.46	33.48	0.00	2.78	0.00	60.55
250	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	0.00	2.78	3.39	54.96
	Photovoltaic	15.83	24.17	34.30	0.00	2.78	10.28	87.36
	KC12	15.83	8.46	32.26	0.00	2.78	0.00	59.33
500	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	0.00	2.78	3.39	54.96
	Photovoltaic	15.83	24.17	34.30	0.00	2.78	10.28	87.36
	KC12	15.83	8.46	32.26	0.00	2.78	0.00	59.33
1000	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	0.00	2.78	3.39	54.96
	Photovoltaic	15.83	24.17	34.30	0.00	2.78	10.28	87.36
	KC12	15.83	8.46	32.26	0.00	2.78	0.00	59.33

By removing surface contamination avoidance from the value dimensions, the relative score of the nuclear systems increases as compared to the sun power systems. The SP-100 system marginally outscores the SDGTDP for all the power demand schemes.

7.9.1.6 Non-nuclear System Preference = 0

Table 43: Polar Non-nuclear System Preference = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	35.11	0.00	0.00	3.39	38.51
	SDGTDP	15.83	8.46	6.94	3.06	0.00	3.39	37.68
	Photovoltaic	15.83	24.17	40.83	6.11	0.00	10.28	97.22
	KC12	15.83	8.46	33.89	3.06	0.00	0.00	61.23
100	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	25.31	3.06	0.00	3.39	56.05
	Photovoltaic	15.83	24.17	35.52	6.11	0.00	10.28	91.91
	KC12	15.83	8.46	33.48	3.06	0.00	0.00	60.83
250	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	3.06	0.00	3.39	55.23
	Photovoltaic	15.83	24.17	34.30	6.11	0.00	10.28	90.69
	KC12	15.83	8.46	32.26	3.06	0.00	0.00	59.60
500	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	3.06	0.00	3.39	55.23
	Photovoltaic	15.83	24.17	34.30	6.11	0.00	10.28	90.69
	KC12	15.83	8.46	32.26	3.06	0.00	0.00	59.60
1000	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.50	3.06	0.00	3.39	55.23
	Photovoltaic	15.83	24.17	34.30	6.11	0.00	10.28	90.69
	KC12	15.83	8.46	32.26	3.06	0.00	0.00	59.60

By removing non-nuclear preference from the value dimensions, the relative score of the nuclear systems increases as compared to the sun power systems in one instance. The SP-100 system marginally outscores the SDGTDP for the 25 kWe the power demand scheme.

7.9.2 Equatorial Location Sensitivity

7.9.2.1 Mass = 0

Table 44: Equatorial Low Mass = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
100	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
250	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
500	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12
1000	KRUSTY	0.00	5.32	0.00	0.00	0.00	10.28	15.60
	SP-100	0.00	0.00	0.00	0.00	0.00	3.39	3.39
	SDGTDP	15.83	8.46	0.00	3.06	2.78	3.39	33.52
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	10.28	59.17
	KC12	15.83	8.46	0.00	3.06	2.78	0.00	30.12

Zeroing out the mass score for the equatorial location does not change the system with the highest scoring. Photovoltaic still has the highest scoring for all systems. This sensitivity analysis does point out the impact of mass on the scoring as power demand is changed. The scoring at the equator and polar location are the same when mass is taken out of the equation.

7.9.2.2 Long Operational Life = 0

Table 45: Equatorial Long Operational Life = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	0.00	27.76	0.00	0.00	10.28	38.04
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	28.99	3.06	2.78	3.39	54.05
	Photovoltaic	15.83	0.00	0.00	6.11	2.78	10.28	35.00
	KC12	15.83	0.00	33.07	3.06	2.78	0.00	54.74
100	KRUSTY	0.00	0.00	23.27	0.00	0.00	10.28	33.55
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	24.09	3.06	2.78	3.39	49.15
	Photovoltaic	15.83	0.00	0.00	6.11	2.78	10.28	35.00
	KC12	15.83	0.00	27.76	3.06	2.78	0.00	49.43
250	KRUSTY	0.00	0.00	22.46	0.00	0.00	10.28	32.74
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	23.27	3.06	2.78	3.39	48.33
	Photovoltaic	15.83	0.00	0.00	6.11	2.78	10.28	35.00
	KC12	15.83	0.00	26.54	3.06	2.78	0.00	48.20
500	KRUSTY	0.00	0.00	22.46	0.00	0.00	10.28	32.74
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	23.27	3.06	2.78	3.39	48.33
	Photovoltaic	15.83	0.00	0.00	6.11	2.78	10.28	35.00
	KC12	15.83	0.00	26.54	3.06	2.78	0.00	48.20
1000	KRUSTY	0.00	0.00	22.46	0.00	0.00	10.28	32.74
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	0.00	23.27	3.06	2.78	3.39	48.33
	Photovoltaic	15.83	0.00	0.00	6.11	2.78	10.28	35.00
	KC12	15.83	0.00	26.54	3.06	2.78	0.00	48.20

For the equatorial location, removing long operational life dramatically impacts several of the systems scores. The photovoltaic system's score drops by almost 50% dropping its ranking to second to last in all instances. The sun powered thermodynamic schemes still score higher than the closest nuclear systems; however, the SP-100 draws within 4 points of the sun power thermodynamic systems when the long operational life is removed.

7.9.2.3 Ease of Maintenance = 0

Table 46: Equatorial Ease of Maintenance = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	27.76	0.00	0.00	10.28	43.36
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	28.99	3.06	2.78	3.39	46.68
	Photovoltaic	0.00	24.17	0.00	6.11	2.78	10.28	43.34
	KC12	0.00	8.46	33.07	3.06	2.78	0.00	47.37
100	KRUSTY	0.00	5.32	23.27	0.00	0.00	10.28	38.87
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	24.09	3.06	2.78	3.39	41.78
	Photovoltaic	0.00	24.17	0.00	6.11	2.78	10.28	43.34
	KC12	0.00	8.46	27.76	3.06	2.78	0.00	42.06
250	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	23.27	3.06	2.78	3.39	40.96
	Photovoltaic	0.00	24.17	0.00	6.11	2.78	10.28	43.34
	KC12	0.00	8.46	26.54	3.06	2.78	0.00	40.83
500	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	23.27	3.06	2.78	3.39	40.96
	Photovoltaic	0.00	24.17	0.00	6.11	2.78	10.28	43.34
	KC12	0.00	8.46	26.54	3.06	2.78	0.00	40.83
1000	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	0.00	8.46	23.27	3.06	2.78	3.39	40.96
	Photovoltaic	0.00	24.17	0.00	6.11	2.78	10.28	43.34
	KC12	0.00	8.46	26.54	3.06	2.78	0.00	40.83

When ease of maintenance at the equatorial lunar site is taken to zero, the values of all systems tighten and draw very close to each other. All values draw within 6 points of each other is all instances. Ease of maintenance is highlighted as an important delineator for the equatorial site.

7.9.2.4 Low Developmental, Facility, and Operational Costs = 0

Table 47: Equatorial Low Developmental, Facility, and Operational Costs = 0 Sensitivity Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	27.76	0.00	0.00	0.00	33.08
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	28.99	3.06	2.78	0.00	59.11
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	0.00	48.89
	KC12	15.83	8.46	33.07	3.06	2.78	0.00	63.20
100	KRUSTY	0.00	5.32	23.27	0.00	0.00	0.00	28.59
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	24.09	3.06	2.78	0.00	54.21
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	0.00	48.89
	KC12	15.83	8.46	27.76	3.06	2.78	0.00	57.89
250	KRUSTY	0.00	5.32	22.46	0.00	0.00	0.00	27.77
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	23.27	3.06	2.78	0.00	53.40
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	0.00	48.89
	KC12	15.83	8.46	26.54	3.06	2.78	0.00	56.66
500	KRUSTY	0.00	5.32	22.46	0.00	0.00	0.00	27.77
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	23.27	3.06	2.78	0.00	53.40
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	0.00	48.89
	KC12	15.83	8.46	26.54	3.06	2.78	0.00	56.66
1000	KRUSTY	0.00	5.32	22.46	0.00	0.00	0.00	27.77
	SP-100	0.00	0.00	40.83	0.00	0.00	0.00	40.83
	SDGTDP	15.83	8.46	23.27	3.06	2.78	0.00	53.40
	Photovoltaic	15.83	24.17	0.00	6.11	2.78	0.00	48.89
	KC12	15.83	8.46	26.54	3.06	2.78	0.00	56.66

The developmental costs removal pushes the thermodynamic systems ahead of the photovoltaic systems. This highlights the photovoltaic systems reliance on its heritage of space system development in the scoring. The scores implies if sun-powered thermodynamic systems are further developed the efficiency advantages will show.

7.9.2.5 Surface Contamination Avoidance = 0

Table 48: Equatorial Surface Contamination Avoidance = 0 Sensitivity Values

		Value Dimensions							
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	27.76	0.00	0.00	10.28	43.36
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	28.99	0.00	2.78	3.39	59.45
	Photovoltaic	15.83	24.17	0.00	0.00	2.78	10.28	53.06
	KC12	15.83	8.46	33.07	0.00	2.78	0.00	60.14
100	KRUSTY	0.00	5.32	23.27	0.00	0.00	10.28	38.87
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.09	0.00	2.78	3.39	54.55
	Photovoltaic	15.83	24.17	0.00	0.00	2.78	10.28	53.06
	KC12	15.83	8.46	27.76	0.00	2.78	0.00	54.83
250	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	0.00	2.78	3.39	53.74
	Photovoltaic	15.83	24.17	0.00	0.00	2.78	10.28	53.06
	KC12	15.83	8.46	26.54	0.00	2.78	0.00	53.61
500	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	0.00	2.78	3.39	53.74
	Photovoltaic	15.83	24.17	0.00	0.00	2.78	10.28	53.06
	KC12	15.83	8.46	26.54	0.00	2.78	0.00	53.61
1000	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	0.00	2.78	3.39	53.74
	Photovoltaic	15.83	24.17	0.00	0.00	2.78	10.28	53.06
	KC12	15.83	8.46	26.54	0.00	2.78	0.00	53.61

By removing surface contamination avoidance, the thermodynamic systems once again rise above the photovoltaic. If, during the development of in situ thermal storage, engineers can mitigate or determine how to avoid surface contamination, thermodynamic systems show some advantage.

7.9.2.6 Non-nuclear System Preference = 0

Table 49: Equatorial Non-nuclear System Preference = 0 Sensitivity Values

		Value Dimensions							
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0.00	5.32	27.76	0.00	0.00	10.28	43.36
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	28.99	3.06	0.00	3.39	59.73
	Photovoltaic	15.83	24.17	0.00	6.11	0.00	10.28	56.39
	KC12	15.83	8.46	33.07	3.06	0.00	0.00	60.42
100	KRUSTY	0.00	5.32	23.27	0.00	0.00	10.28	38.87
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	24.09	3.06	0.00	3.39	54.83
	Photovoltaic	15.83	24.17	0.00	6.11	0.00	10.28	56.39
	KC12	15.83	8.46	27.76	3.06	0.00	0.00	55.11
250	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	3.06	0.00	3.39	54.01
	Photovoltaic	15.83	24.17	0.00	6.11	0.00	10.28	56.39
	KC12	15.83	8.46	26.54	3.06	0.00	0.00	53.88
500	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	3.06	0.00	3.39	54.01
	Photovoltaic	15.83	24.17	0.00	6.11	0.00	10.28	56.39
	KC12	15.83	8.46	26.54	3.06	0.00	0.00	53.88
1000	KRUSTY	0.00	5.32	22.46	0.00	0.00	10.28	38.05
	SP-100	0.00	0.00	40.83	0.00	0.00	3.39	44.22
	SDGTDP	15.83	8.46	23.27	3.06	0.00	3.39	54.01
	Photovoltaic	15.83	24.17	0.00	6.11	0.00	10.28	56.39
	KC12	15.83	8.46	26.54	3.06	0.00	0.00	53.88

Removing non-nuclear system preference does tighten the relative system scoring but does not change the ranking.

7.9.3 Sensitivity Analysis Conclusion

The sensitivity analysis points out several important facts. The attribute, mass, with the highest weighting does not impact the system ranking when zeroed out for either the polar or equatorial location. The second highest weight attribute, long operational life, only impacts the scoring at the equatorial location. The second attribute makes up approximately half of the photovoltaic systems scoring at the equatorial location. Removing the second attribute, vaults the sun powered thermodynamic systems well above the photovoltaic system. Removal of the third highest attribute, ease of maintenance, results in all the systems drawing very close to each other scoring wise. The nuclear systems even take a lead in some instances. The fourth highest attribute weight, developmental cost, only impacts scoring at the equatorial location. The photovoltaic system has such a large advantage at the polar location, the impact of removing developmental system advantage is minimal. Removing the either of the two lowest scoring attributes, raises the competitiveness of nuclear systems. This indicates system designers for ESAS and other NASA systems give less weight to these two parameters than given here since nuclear systems are frequently recommended above all other power production schemes (NASA, 2005b).

7.10 Chapter Summary

This chapter covers steps 3-8 of the SMART method. These steps include a system thermodynamic analysis and mass estimation. A numeric score based of the identified attributes is assigned to each of the candidate systems. The results are used in the next chapter to answer the research questions and validate or invalidate each of the hypothesis.

CHAPTER 8
RESULTS AND CONCLUSIONS

8.1 Introduction

The final chapter of this dissertation is dedicated to directly applying research results to the hypothesis. Recommended future work is also touched upon followed by final concluding remarks.

8.2 Results and Hypotheses

8.2.1 Hypothesis 1: An ammonia-water thermodynamic power cycle located at a lunar pole location can operate at lower policy or monetary cost when compared to a nuclear thermodynamic power production scheme.

Hypothesis 1 is accepted. The scoring values for KC12, an ammonia-water thermodynamic cycle, is as much as 4 times higher than small nuclear systems and 50% higher than large nuclear systems at the lunar pole location. Nuclear systems have a clear advantage with initial mass placement values which result in lower initial emplacement cost. However, the initial emplacement cost savings are mitigated by several facts. Outer space policy and law clearly prefer non-nuclear systems to be used when technically feasible. Also, nuclear systems have lower life-spans resulting in sun-powered systems having significantly lower operational expenses. Lower lifetime replacements costs—the systems do not need replacing as often and easier maintenance—no nuclear material to mitigate also push the KC12 to a higher score than either of the nuclear systems evaluated.

8.2.2 Hypothesis 2: An ammonia-water thermodynamic power cycle located at a lunar pole location can operate at lower policy or monetary cost when compared to a solar Brayton thermodynamic power production scheme.

Hypothesis 2 is accepted. The scoring values for KC12, an ammonia-water thermodynamic cycle, is 50 % higher for a 25-kW system and approximately 10% higher for larger power demands than the evaluated Brayton cycle. The advantage comes from mass savings. The KC12's estimated mass is lower than the SDGTDP system. Mass is the highest weighted scoring parameter which gives the KC12 the higher score. Much of the Brayton cycle and KC12 major components are similar. Thus, the maintenance, life, and other factors are minimal in differentiating the systems.

8.2.3 Hypothesis 3: An ammonia-water thermodynamic power cycle located at a lunar pole location can operate at lower policy or monetary cost when compared to a photovoltaic power production scheme.

Hypothesis 3 is refuted. The advantage of photovoltaic systems at the lunar pole is clear. Photovoltaic systems are relatively simple compared to thermodynamic systems which results in longer life, easier maintenance, and lower surface contamination. Thermodynamic systems still have a slight mass advantage resulting in lower initial emplacement costs. However, due to all the other factors, photovoltaic systems have a strong advantage at the polar location. The scoring for the ammonia-water system is typically about 30% lower than a photovoltaic system at the polar location.

8.2.4 Hypothesis 4: An ammonia-water thermodynamic power cycle located at a lunar equatorial location can operate at lower policy or monetary cost when compared to a nuclear thermodynamic power production scheme.

Hypothesis 4 is accepted. The scoring values for KC12 at the lunar equator, an ammonia-water thermodynamic cycle, is closer than at the pole when compared to small nuclear powered thermodynamic systems. On average, the scoring for KC12 is approximately 30-50% higher when compared to both small and large nuclear systems. Nuclear systems have an even larger initial mass placement advantage over sun powered systems due to higher energy storage needs at the equator as compared to the lunar pole. However, the initial emplacement cost savings are still mitigated by non-nuclear preference and lower life cycle costs. The sensitivity analysis does indicate scoring reliance on surface contamination and non-nuclear preference. However, as demonstrated in the attribute development process (pp. 64-71), these policy issues do merit consideration when evaluating systems.

8.2.5 Hypothesis 5: An ammonia-water thermodynamic power cycle located at a lunar equatorial location can operate at lower policy or monetary cost when compared to a solar Brayton thermodynamic power production scheme.

Hypothesis 5 is refuted. The scoring values for KC12, an ammonia-water thermodynamic cycle, are equivalent to the evaluated Brayton cycle at the equatorial location. Minimal differentiation come from mass savings. The maintenance, life, and other factors are minimal in differentiating the systems. The scoring for each of the system types are within 1-2% of each other for all power cases.

8.2.6 Hypothesis 6: An ammonia-water thermodynamic power cycle located at a lunar equatorial location can operate at lower policy or monetary cost when compared to a photovoltaic power production scheme.

Hypothesis 6 is very marginally refuted, within 1-3% higher in 4 of the five power demand cases. In the 25 kWe power demand case, KC12, the ammonia-water thermodynamic cycle, has a small score advantage. The scoring results for the equatorial location does show promise for thermodynamic power cycles. The long life and TRL level of photovoltaic systems push it to have higher score than thermodynamic systems. If thermodynamic systems are developed further, a clear advantage for thermodynamic systems should emerge for use at the lunar equator. Higher efficiency systems equal lower mass and lower emplacement costs.

8.3 Final Conclusions

An ammonia water thermodynamic power cycle does have promise for use for electric power production on the lunar surface. Nuclear power systems have mass advantage in all scenarios. Sun-powered thermodynamic and photovoltaic systems have longer operational lives, lower surface contamination, and are easier to maintain. The ammonia-water thermodynamic system, KC12, shows best promise of use at the lunar equator. This is primarily due to lower storage mass requirements due to higher efficiency over a photovoltaic system. Photovoltaic still scores marginally higher in most cases, but the scores are extremely close. Future development of solar thermodynamic systems for use at the lunar equator and possibly up to the mid-latitudes warrant further analysis and hardware development.

8.4 Recommended Future Work

The research analysis conducted in this dissertation has shed light upon several areas for further development. Recommended future work will be identified and briefly described.

8.4.1 Recommendation 1: The utilization of the analyzed ammonia-water power cycle as a bottoming cycle for lunar industrial processes.

Lunar industrial processes—to include reduction of ilmenite to produce usable raw materials such as iron, titanium, and oxygen—require large amounts of heat (Eagle Engineering, 1988). The need for large amount of heat is common in terrestrial industrial applications as well. The Kalina cycle is often used terrestrially as a bottoming cycle to extract energy in the form of electricity from industrial waste heat. A thorough analysis on applying terrestrial bottoming cycles to future lunar industrial processes is recommended.

8.4.2 Recommendation 2: Hardware Demonstration for Solar Dynamic Process

NASA conducted ground testing of a Brayton solar dynamic power production scheme in the 1990s (Alexander, 1997a, b, c). The next step is to test the hardware in space or on the lunar surface. Future research could further develop and refine solar dynamic hardware which could dramatically impact lunar and space operations. Many components can be shared between a variety of solar dynamic processes such as concentrators, radiators and energy storage. It is also not unusual for thermodynamic processes to have one or two pieces of unique equipment such as the Kalina cycle's separator and the Brayton cycle's turboalternator-compressor. Each of the hardware should be tested in the space environment to ensure proper operation and to discover any operationally unique phenomenon.

8.4.3 Recommendation 3: Development of ground and space test of in situ lunar thermal storage

Crane (1991) analyzed in situ lunar thermal storage. Hardware development and demonstration would allow system architects to add a useful energy storage option to the available lunar energy architecture options.

8.4.4 Recommendation 4: Expand evaluated locations to create a lunar power system map of the surface.

In this study, lunar locations were limited to bounding locations. As stated before, the location of a base on the lunar surface will influence power system design. However, there are many unique locations such as crater rims and valleys which will impact systems which rely upon solar illumination. One big attraction of nuclear systems is their universal application. One system design can be used virtually anywhere with very minor installation adjustments. Mapping the lunar surface in reference to solar power system usability could assist lunar base architects to apply the best power system to specific locations. A map similar to Fincannon's (2008) polar illumination map across the entire lunar surface would be useful.

8.4.5 Recommendation 5: Expand evaluated power levels

Lunar reference missions were limited to values from 25-1000 kWe. Systems have been proposed requiring tens of megawatts. Evaluating systems which can support tens of megawatts could dramatically change how we view specific power production schemes. More analysis is warranted.

8.4.6 Recommendation 6: Reliability Analysis

A full RAM analysis was not conducted. A full RAM analysis typically requires extensive analysis by teams of subject matter experts. It is recommended that future analysis could explore impacts of RAM on design.

8.4.7 Recommendation 7: Risk Assessment

A full risk assessment was not conducted. It is recommended that a future risk analysis of all power production schemes should be conducted to explore impacts of risk and risk mitigation on design.

8.4.8 Recommendation 8: Higher fidelity model development

The model used for mass estimation is high level. A higher fidelity model would be useful to further understand specific component mass impacts to help future researchers understand where efforts should be focused on to reduce mass and system emplacement costs.

APPENDIX 1

Applicable Space Law and Policy Impacting Lunar Power Systems

1) Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty)

Probably the most important of all space law is the Outer Space Treaty. The Outer Space Treaty, specifically its provisions on environmental protection of space and celestial objects, presents interesting discussions when one is evaluating the use of power for a space station, planetary base, or industrial operations. Any manned space station or lunar base will require the establishment of a power system to support mission requirements. More than likely, power requirements will grow as stations or bases continue operations. Initially, power requirements will be in the tens of kilowatt level which can be covered by photovoltaic panels and batteries. Eventually, megawatts of power may be required. Megawatts will necessitate a concentrated solar or nuclear power source. If a nuclear power source is used, the Outer Space Treaty is not highly specific concerning operation. The Outer Space Treaty does establish the base level law which one can use to evaluate nuclear power use. Article IX of the Outer Space Treaty requires States operating in outer space to "conduct exploration of them so as to avoid their harmful contamination" and avoid any "adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter." How one goes about avoiding harmful contamination is not specifically identified. What the Outer Space Treaty does delve into is who is responsible for damages, liabilities associated, and who is responsible for mitigation of harmful contamination. Geologically, a nuclear system would be somewhat invasive to a planetary surface. Such a system will require burying to insulate the local area from radioactive contamination. A space-based system will need heavy shielding. These additional steps will result in secondary effects such as irradiated soil around the nuclear reactor site or radiated material surrounding a reactor. The soil around a buried reactor will also be disturbed or excavated resulting permanent alternation from its natural state. Photovoltaic or sun-powered thermodynamic systems will not have radioactive material to worry with. However, they are not completely free of impacting local environments. Leakage of working fluid may contaminate the local environment. If there is leakage in buried pipes or pipes above ground which are carrying the working fluid, the local environment may be permanently altered from its natural state. In the vacuum environment, much of the fluid may instantly freeze, sublimate, or evaporate. In other words, the material will litter the surrounding ground or dissipate to space. Sites will be disturbed for emplacement of systems. It may be tricky to remediate nuclear radiation in a space environment or planetary surface. To date, there has not been any analysis on the difference between soil irradiated from a man-made nuclear device as compared to the radiation that the lunar surface receives naturally from the Sun and galactic cosmic radiation. Determining what exactly the Outer Space Treaty means by harmful contamination is key to determining what type of mitigation is necessary (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 1967).

2) Convention on International Liability for Damage Caused by Space Objects (Liability Convention)

The primary source of international law which addresses liabilities for damage cause by space objects is the Liability Convention. There are several articles which apply to space power systems. Article I defines “space object” to include component parts of a space objects and its associated parts. Although not directly mentioned, a space power system and its associated components will be covered by this convention. The Liability Convention imposes absolute liability on the launching State—defined as the State who launches or procures the launching of a space object or from whose territory or facility the object is launched from. Basically, if any liability needs to be assigned to the space object, the launching state is liable. It is important for requirements to appropriately reflect that if a space power system were to damage another party's vehicle or equipment, the launching state will be liable. Damage could be caused by radiation, explosion, or numerous other means. Absolute liability applies only when the damage done is between two or more States and on the surface or airspace of the Earth. In outer space, damages only apply between States when there is fault. Fault is challenging to determine. When constructing power systems on a celestial body, States need use their best efforts to prevent damage to other States. Best effort results in a solid defense against claims of fault-based damage coming from an injured State. (Convention on International Liability for Damage Caused by Space Objects, 1972).

3) The Principles Relevant to the Use of Nuclear Power Sources (NPS) in Outer Space

The NPS principles are only relevant if a power system has nuclear fuel as its heat source. The UN General Assembly recognized that some space missions require the use of NPS. NPS are compact with relatively long life. The principles emphasize the need for thorough risk analysis and safety assessments. These Principles are not legally binding in the strictest sense, though they are persuasive. The Principles are a UN General Assembly resolution not an international treaty. For the most part, the NPS Principles restate existing law found in the OST, the Liability convention, and other general member duties, such as notification of NPS objects re-entry from outer space. That being said, there are several principles which should be kept in mind when developing requirements. Principle 3 (Guidelines and criteria for safe use) states "In order to minimize the quantity of radioactive material in space and the risks involved, the use of nuclear power sources in outer space shall be restricted to those space missions which cannot be operated by non-nuclear energy sources in a reasonable way." Although this is not binding law, the principle 3 guideline should be kept in mind (United Nations, 1993).

4) National Environmental Policy Act (NEPA)

NASA and government contracted US space companies, identified customers for space power systems, will need to comply with the National Environmental Policy Act. The reason for NEPA is Congress's identification of its "continuing responsibility . . . to use all practicable means, consistent with other essential considerations of national policy, to improve and coordinate Federal plans, functions, programs, and resources" to protect renewable resources and the environment (National Environmental Policy Act, 2000). NEPA mandates a federal agency anticipating taking any major actions which will significantly impact the human environment to develop an Environmental Impact Statement (EIS). An EIS need is determined by an Environmental Assessment (EA). If a federal agency planning a change such as building a space port or making a major modification to a current federal building determines that change is insubstantial through the EA, then no EIS will be needed. If the agency determines the environmental change will be substantial, then an EIS will be required to follow the EA.

That being said, NEPA only applies to the government. Since most space companies working with the government to conduct launches, that connection will sometimes necessitate efforts to comply with NEPA. According to the law, an EIS must include: the environmental impact of the proposed action, unavoidable adverse environmental effects resulting from the action, what alternative actions are available, short term and long term effects, and any irreversible and irretrievable resource commitments (National Environmental Policy Act, 2000). An example of litigation involving a NASA space power system is Cassini's RTG. The court found in both the final EIS and supplemental EIS, NASA noted the need to use an RTG instead of solar panels because the Sun's intensity at Saturn is only 1 percent of the intensity available to Earth. This demonstrated that solar power was not feasible and an RTG is necessary (Hawaii County Green Party v Clinton, 1997). This case implies—due to radiating the local environment on the surface of the moon—a nuclear power system should be used sparingly and only if other power systems are not technically feasible. An operator of a lunar power system must consider potential health risks and accident scenarios.

5) Safety Framework for Nuclear Power Source Application in Outer Space

This framework was endorsed by the Committee on the Peaceful Uses of Outer Space at its fifty-second session and contained in A/AC.105/934. The framework is a recommendation and not binding law. The framework recognizes the need for NPS use in outer space where non-nuclear power sources are not realistic. High-level guidance in the form of a model safety framework is given by the guidelines. The guidelines can be used as reference when developing safety of NPS system but is not binding law.

6) Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space

These guidelines were endorsed by the Committee on the Peaceful Uses of Outer Space at its fiftieth session and contained in A/62/20, annex. The framework is a recommendation and not binding law. However, while not strictly binding, these recommendations are highly respected internationally, and for some States that have essentially become law or regulation. For example, the USA uses these in part to form the foundation of their NASA Policy Directives and US Government Orbital Debris Mitigation Guidelines. Although geared toward orbital systems, applicable guidelines are guidelines 1, 4, and 5. Guideline 1 directs the limitation of debris released during normal operations. Guideline 4 seeks to avoid intentional destruction and other harmful activities. Guideline 5 looks to minimize potential for post-mission break-ups resulting from stored energy. Although not binding law, these guidelines help mission architects develop requirements which will show the international community the space power system places on the lunar surface is designed and operated in an environmentally conscious way.

7) U.S. Space Resource Exploration and Utilization Act of 2015

Due to vague international space laws, the U.S. Congress took it upon themselves to provide a better framework for U.S. companies to understand property rights through the passage of the Space Act. The Space Act outlines the property rights of U.S. citizens over asteroid and space resources. Foster (2016) does well summarizing the pros and cons. The pros revolve around the law's clarifying aspect which increases investor's confidence. Most of the cons revolve around fears of violating the OST. The OST is written so broadly that there is need to fear violation. The United States is leading the way with this legislation and has the opportunity to set legal precedent which will set the standard for future resource utilization. Some states may take issue with a U.S. company mining asteroid resources since the mined material's freedom of access will be removed. However, the U.S. can defend its corporations by coming back with the argument that the Space Act and companies following it are not seizing rights over the body itself and thus are following international law.

Space resource utilization directly impacts space power systems. Space power systems are required for all systems which will be utilized in space—without power, systems which gather material or analyze the local geology could not function. Understanding the U.S.'s stance on resource utilization impacts how system are designed and function.

8) The 1979 Agreement Governing the Activities of States on the Moon and other Celestial Bodies

The 1979 Agreement Governing the Activities of States on the Moon and other Celestial Bodies (Moon Treaty) is considered generally to be of non-consequence. No major space power has signed it (Sattler, 2005). However, while the major space powers are not States Party to this Agreement, there are some States that have ratified it. The Moon Treaty States Party are bound to its more stringent environmental regulations. The Moon Treaty's Article 7 prohibits States from making a large change to the environment of the space environment. The article is important to the States Party since power production systems frequently impact local environmental conditions (Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 1979).

9) Environmental issues which may result from the utilization of power schemes for a lunar base or industrial operation

These eight are lunar surface manipulation and intrusion, vapor deposits of leaked material on lunar regolith, leaking of working fluids into lunar regolith, decrease in vacuum environment due to low temperature gas leakage, subterranean nuclear contamination, increased soil temperature, microbial contamination from Earth, and disposal issues of end-of-life and damaged equipment. Each of the eight will be analyzed and discussed in the context of policy recommendations.

The first potential environmental issue is lunar surface manipulation and intrusion. Virtually any utilizations of the lunar surface will result in manipulation of the surface layer. Just walking on the lunar surface or driving a rover will cause tracks and disturb the surface. There are those who espouse the ecocentric environmental view of the lunar surface who say that outer space, including the lunar surface, deserved to be preserved in its original ‘pristine’ state. The reasoning for this is for its own sake and for future generations to enjoy (Schafer, 1988). If a policy was placed to have the entirety of space as a wilderness preserve then this would prevent others from utilizing space for personal use. Reynolds (2004) notes that this simply an “aesthetic view masquerading as a religious one.” In other words, the view puts one person’s aesthetic preference above the preferences of others and above the wellbeing of the human race. Reynolds argues the wellbeing of the human species on an individual level as well as a societal level is bettered by an increase in available resource utilization. Current policy and law does not prohibit simple manipulation and intrusion.

The second potential environmental issue is vapor deposits of leaked material on lunar regolith. This issue results from potential leaks from pipes and their contained working fluids. This will not be an issue if a system is properly designed. Common causes of leaks on high pressure, high temperature systems result from impurities in the working fluid, incompatible component materials, and faulty seals. A properly designed system operating in a high vacuum environment should have very little corrosion that would not be a known issue which is mitigated with a sacrificial anode. If a spill or leak happens, material will quickly freeze or sublimate and not ‘seep’ into the soil. Ways to mitigate spills and leaks are remedial in nature. Operators should properly clean up materials as soon as a leak is found. Cold traps should be installed at the location similar in concept to runoff management on a terrestrial parking lot. If a material freezes in the lunar night and sublimates in the lunar day, over time the material could eventually make it to the natural cold traps which are on the lunar surface. The natural cold traps are prime locations to mine water and helium-3. Contamination from a power system working fluid, assuming the fluid is not water or other materials found in the cold trap such as ammonia, could degrade the ability to mine these resources and necessitate additional processing. The downside to a remediation step is increased site preparation for planetary power and industrial operations. Extra site preparation will cost time and money to emplace but will allow for other resources to not be contaminated by processed material.

The third potential environmental issue is leaking of working fluids into lunar regolith. Scenarios which have leaking fluids which stay fluid after leaking will be in an enclosed pressurized environment. This means in a building or underground. Once again, mitigation is remedial in nature. Operators should properly clean up materials as soon as a leak is found. Cold traps should be installed to catch any vaporized material.

The fourth potential environmental issue is a decrease in vacuum environment due to low temperature gas leakage. Due to the vacuum conditions on the lunar surface, a leaking gas may be difficult to see. The best way to detect a leak in a closed cycle such as a closed thermodynamic power cycle is to monitor the pressure at various locations. If the pressure drops unexpectedly, the likely culprit is a loss of material in the system. Mitigation can include sensors and detectors on any system with a working fluid to alert the operators of potential leaks. The downside to this mitigation could be increased system cost.

The fifth potential environmental issue is subterranean nuclear contamination. Literature overviewing the extent of irradiation of the soil shielding of a nuclear reactor was minimal. Additional analysis needs to be conducted to thoroughly understand any economic impact of a reactor on the local lunar environment. That being said, the literature I did find showed the amount of radiation the lunar regolith receives from the reactor does not appear to be more than what the top of the lunar surface receives naturally. Since this process does not consume any local material, the issue of conservation of resources does not apply with this system. We do not have any operational experience of the extent of nuclear contamination on the lunar surface from a buried reactor. There is a small risk that the system will contaminate more soil or create a situation that we cannot foresee.

The sixth potential environmental issue is an increase in soil temperature. This issue can be environmentally significant from several angles. First, heat could impact any life which may be present. This issue should not be a problem on the lunar surface since no life has been detected. Second, heat could release gases from the regolith. Outgassing may be an issue in a surface mining region which may rely on regolith gases as a product. However, the area of heated soil will be a small but necessary footprint to provide power to such an operation. The temperature increase area will be regulated the small footprint of the power reactor or heat storage devices. As with the nuclear contamination, there is a small risk that the system will create a negative situation that we cannot foresee.

The seventh potential environmental issue is microbial contamination from Earth. This is one of the few issues which already has policy in place. The Outer Space Treaty says that the signatories “shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination”. (Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, 1967). The major countries which have space launch and operation capability are signatories of the Outer Space Treaty and have active planetary protection programs. For example, NASA has an Office of Planetary Protection which deals with policy creation such as microbial decontamination. The European Space Agency (ESA) has a planetary protection officer and policy documents associated with microbial examination and control.

The eighth potential environmental issue is disposal of end-of-life and damaged equipment. This issue is one of the most difficult to manage. There is a precedent of leaving hardware in place once it reaches end-of-life or fails for one reason or another. The only space hardware which is removed from space to be disposed of are some of the more recent satellites. Due to orbital crowding, many satellites are deorbited when they reach their end-of-life in order to make way for new satellites. Other satellites are boosted into a less useful graveyard orbit. The Inter-Agency Space Debris Coordination Committee (IADC) is an international forum of national space agencies such as NASA, ESA, JAXA, and Roscosmos for the coordination of activities related to the issues of manmade and natural debris in space (IADC, 2018). The IADC's purpose is to facilitate information exchange related to research activities between member space agencies and to identify debris mitigation options. (IADC, 2018). The IADC has developed good guidelines for mitigating and managing orbital space debris. Debris and refuse on planetary bodies have not become a problem due to the low volume.

APPENDIX 2

Attribute Calculations (Step 4)

Each of the five power schemes are scored referencing the six attributes according to the developed attribute types. The calculations are shown for each system.

A. <u>KRUSTY AV Calculations</u>

1. *Ease of Maintenance*

$$AV_{\text{Ease of Maintenance}} = (1 - 1)\ \frac{\mathbf{100}}{\mathbf{4}} = 0 \qquad \text{(A4.1)}$$

2. *Long Operational Life*

$$AV_{\text{Life Expectancy}} = (12 - 7)\ \frac{\mathbf{100}}{\mathbf{23}} = 22 \qquad \text{(A4.2)}$$

3. *Low Mass*

Location and power production are important for this attribute. Each location and system power are assigned individual attribute value.

4. *Lunar Equator AV Calculations*

$$AV_{\text{EquatorMass25kW}} = 100 - [(3750 - 2000)\ \frac{\mathbf{100}}{\mathbf{5519}}] = 68 \qquad \text{(A4.3)}$$

$$AV_{\text{EquatorMass100kW}} = 100 - [(15000 - 3500)\ \frac{\mathbf{100}}{\mathbf{26576}}] = 57 \qquad \text{(A4.4)}$$

$$AV_{\text{EquatorMass250kW}} = 100 - [(37500 - 6050)\ \frac{\mathbf{100}}{\mathbf{69140}}] = 55 \qquad \text{(A4.5)}$$

$$AV_{\text{EquatorMass500kW}} = 100 - [(75000 - 12100)\ \frac{\mathbf{100}}{\mathbf{138280}}] = 55 \qquad \text{(A4.6)}$$

$$AV_{\text{EquatorMass1000kW}} = 100 - [(150000 - 24200)\ \frac{\mathbf{100}}{\mathbf{276560}}] = 55 \qquad \text{(A4.7)}$$

5. Lunar Pole Location

$$AV_{PolarMass25kW} = 100 - [(3750 - 1712)\ \frac{\mathbf{100}}{\mathbf{2038}}] = 0 \qquad (A4.8)$$

$$AV_{PolarMass100kW} = 100 - [(15000 - 3500)\ \frac{\mathbf{100}}{\mathbf{11500}}] = 0 \qquad (A4.9)$$

$$AV_{PolarMass250kW} = 100 - [(37500 - 6050)\ \frac{\mathbf{100}}{\mathbf{31450}}] = 0 \qquad (A4.10)$$

$$AV_{PolarMass500kW} = 100 - [(75000 - 12100)\ \frac{\mathbf{100}}{\mathbf{62900}}] = 0 \qquad (A4.11)$$

$$AV_{PolarMass1000kW} = 100 - [(150000 - 24200)\ \frac{\mathbf{100}}{\mathbf{125800}}] = 0 \qquad (A4.12)$$

6. Surface Contamination Avoidance

$$AV_{SurfaceContamination} = 0 \qquad (A4.13)$$

The end-of-life plans for nuclear systems are to abandon in place. Abandoning nuclear material in place permanently contaminates the lunar surface.

7. Non-nuclear Preference

$$AV_{Non\text{-}NuclearPreference} = 0 \qquad (A4.14)$$

KRUSTY is a nuclear system.

8. Low Developmental, Facility, and Operational Costs

$$AV_{TRL} = (5 - 2)\ \frac{\mathbf{100}}{\mathbf{3}} = 100 \qquad (A4.15)$$

B. <u>SP-100 AV Calculations</u>

1. Ease of Maintenance

$$AV_{\text{Ease of Maintenance}} = (1 - 1)\ \frac{\mathbf{100}}{\mathbf{4}} = 0 \quad \text{(A4.16)}$$

2. Long Operational Life

$$AV_{\text{Life Expectancy}} = (7 - 7)\ \frac{\mathbf{100}}{\mathbf{23}} = 0 \quad \text{(A4.17)}$$

3. Low Mass

Location and power production are important for this attribute. Each location and system power are assigned individual attribute value.

4. Lunar Equator AV Calculations

$$AV_{\text{EquatorMass25kW}} = 100 - [(2000 - 2000)\ \frac{\mathbf{100}}{\mathbf{5519}}] = 100 \quad \text{(A4.18)}$$

$$AV_{\text{EquatorMass100kW}} = 100 - [(3500 - 3500)\ \frac{\mathbf{100}}{\mathbf{26576}}] = 100 \quad \text{(A4.19)}$$

$$AV_{\text{EquatorMass250kW}} = 100 - [(6050 - 6050)\ \frac{\mathbf{100}}{\mathbf{69140}}] = 100 \quad \text{(A4.20)}$$

$$AV_{\text{EquatorMass500kW}} = 100 - [(12100 - 12100)\ \frac{\mathbf{100}}{\mathbf{138280}}] = 100 \quad \text{(A4.21)}$$

$$AV_{\text{EquatorMass1000kW}} = 100 - [(24200 - 24200)\ \frac{\mathbf{100}}{\mathbf{276560}}] = 100 \quad \text{(A4.22)}$$

5. Lunar Pole Location

$$AV_{\text{PolarMass25kW}} = 100 - [(2000 - 1712)\ \frac{\mathbf{100}}{\mathbf{2038}}] = 86 \quad \text{(A4.23)}$$

$$AV_{\text{PolarMass100kW}} = 100 - [(3500 - 3500)\ \frac{\mathbf{100}}{\mathbf{11500}}] = 100 \quad \text{(A4.24)}$$

$$AV_{\text{PolarMass250kW}} = 100 - [(6050 - 6050)\ \frac{\mathbf{100}}{\mathbf{31450}}] = 100 \quad \text{(A4.25)}$$

$$AV_{\text{PolarMass500kW}} = 100 - [(12100 - 12100)\ \frac{\mathbf{100}}{\mathbf{62900}}] = 100 \quad \text{(A4.26)}$$

$$AV_{PolarMass1000kW} = 100 - [(24200 - 24200)\frac{100}{125800}] = 100 \quad (A4.27)$$

6. Surface Contamination Avoidance

$$AV_{SurfaceContamination} = 0 \quad (A4.28)$$

The end-of-life plans for nuclear systems are to abandon in place. Abandoning nuclear material in place permanently contaminates the lunar surface.

7. Non-nuclear Preference

$$AV_{Non\text{-}NuclearPreference} = 0 \quad (A4.29)$$

SP-100 is a nuclear system.

8. Low Developmental, Facility, and Operational Costs

$$AV_{TRL} = (3 - 2)\frac{100}{3} = 33 \quad (A4.30)$$

C. <u>SDGTDP AV Calculations</u>

1. Ease of Maintenance

$$AV_{Ease\ of\ Maintenance} = (5 - 1)\frac{100}{4} = 100 \quad (A4.31)$$

2. Long Operational Life

$$AV_{Life\ Expectancy} = (15 - 7)\frac{100}{23} = 35 \quad (A4.32)$$

3. Low Mass

Location and power production are important for this attribute. Each location and system power are assigned individual attribute value.

4. Lunar Equator AV Calculations

$$AV_{EquatorMass25kW} = 100 - [(3600 - 2000)\,\frac{100}{5519}] = 71 \quad (A4.33)$$

$$AV_{EquatorMass100kW} = 100 - [(14400 - 3500)\,\frac{100}{26576}] = 59 \quad (A4.34)$$

$$AV_{EquatorMass250kW} = 100 - [(36000 - 6050)\,\frac{100}{69140}] = 57 \quad (A4.35)$$

$$AV_{EquatorMass500kW} = 100 - [(72000 - 12100)\,\frac{100}{138280}] = 57 \quad (A4.36)$$

$$AV_{EquatorMass1000kW} = 100 - [(144000 - 24200)\,\frac{100}{276560}] = 57 \quad (A4.37)$$

5. Lunar Pole Location

$$AV_{PolarMass25kW} = 100 - [(3400 - 1712)\,\frac{100}{2038}] = 17 \quad (A4.38)$$

$$AV_{PolarMass100kW} = 100 - [(13600 - 3500)\,\frac{100}{11500}] = 62 \quad (A4.39)$$

$$AV_{PolarMass250kW} = 100 - [(34000 - 6050)\,\frac{100}{31450}] = 60 \quad (A4.40)$$

$$AV_{PolarMass500kW} = 100 - [(68000 - 12100)\,\frac{100}{62900}] = 60 \quad (A4.41)$$

$$AV_{PolarMass1000kW} = 100 - [(136000 - 24200)\,\frac{100}{125800}] = 60 \quad (A4.42)$$

6. Surface Contamination Avoidance

$$AV_{SurfaceContamination} = 50 \quad (A4.43)$$

The end-of-life plans for the thermal storage system does require abandoning material in place due to molten regolith solidifying around the heat exchanger. Abandoning a portion of the overall system in place permanently contaminates the lunar surface.

7. Non-nuclear Preference

$$AV_{Non\text{-}NuclearPreference} = 100 \quad (A4.44)$$

SDGTDP is not a nuclear system.

8. *Low Developmental, Facility, and Operational Costs*

$$AV_{TRL} = (3 - 2)\,\frac{100}{3} = 33 \quad (A4.45)$$

D. <u>Photovoltaic AV Calculations</u>

1. *Ease of Maintenance*

$$AV_{Ease\ of\ Maintenance} = (3 - 1)\ \frac{100}{2} = 100 \quad (A4.46)$$

2. *Long Operational Life*

$$AV_{Life\ Expectancy} = (30 - 7)\,\frac{100}{23} = 100 \quad (A4.47)$$

3. *Low Mass*

Location and power production are important for this attribute. Each location and system power are assigned individual attribute value.

4. *Lunar Equator AV Calculations*

$$AV_{EquatorMass25kW} = 100 - [(7519 - 2000)\,\frac{100}{5519}] = 0 \quad (A4.48)$$

$$AV_{EquatorMass100kW} = 100 - [(30076 - 3500)\,\frac{100}{26576}] = 0 \quad (A4.49)$$

$$AV_{EquatorMass250kW} = 100 - [(75190 - 6050)\,\frac{100}{69140}] = 0 \quad (A4.50)$$

$$AV_{EquatorMass500kW} = 100 - [(150380 - 12100)\,\frac{100}{138280}] = 0 \quad (A4.51)$$

$$AV_{EquatorMass1000kW} = 100 – [(300760 - 24200) \frac{100}{276560}] = 0 \quad (A4.52)$$

5. *Lunar Pole Location*

$$AV_{PolarMass25kW} = 100 – [(3400 - 1712) \frac{100}{2038}] = 100 \quad (A4.53)$$

$$AV_{PolarMass100kW} = 100 – [(13600 - 3500) \frac{100}{11500}] = 87 \quad (A4.54)$$

$$AV_{PolarMass250kW} = 100 – [(34000 - 6050) \frac{100}{31450}] = 84 \quad (A4.55)$$

$$AV_{PolarMass500kW} = 100 – [(68000 - 12100) \frac{100}{62900}] = 84 \quad (A4.56)$$

$$AV_{PolarMass1000kW} = 100 – [(136000 - 24200) \frac{100}{125800}] = 84 \quad (A4.57)$$

6. *Surface Contamination Avoidance*

$$AV_{SurfaceContamination} = 100 \quad (A4.58)$$

The end-of-life plans for the photovoltaic power system with regenerative fuel cells is removal from the lunar surface. This type of power can be completely removed. The location and power system level may increase the amount of material to be removed or recycled; however, the surface contamination level does not change.

7. *Non-nuclear Preference*

$$AV_{Non-NuclearPreference} = 100 \quad (A4.59)$$

Photovoltaic power with regenerative fuel cells is not a nuclear system.

8. *Low Developmental, Facility, and Operational Costs*

$$AV_{TRL} = (5 - 2) \frac{100}{3} = 100 \quad (A4.60)$$

E. KC12 AV Calculations

1. Ease of Maintenance

$$AV_{\text{Ease of Maintenance}} = (5 – 1)\ \frac{\mathbf{100}}{\mathbf{4}} = 100 \qquad \text{(A4.61)}$$

2. Long Operational Life

$$AV_{\text{Life Expectancy}} = (15 - 7)\ \frac{\mathbf{100}}{\mathbf{23}} = 35 \qquad \text{(A4.62)}$$

3. Low Mass

Location and power production are important for this attribute. Each location and system power are assigned individual attribute value.

4. Lunar Equator AV Calculations

$$AV_{\text{EquatorMass25kW}} = 100 – [(7519 - 2000)\ \frac{\mathbf{100}}{\mathbf{5519}}] = 81 \qquad \text{(A4.63)}$$

$$AV_{\text{EquatorMass100kW}} = 100 – [(30076 - 3500)\ \frac{\mathbf{100}}{\mathbf{26576}}] = 68 \qquad \text{(A4.64)}$$

$$AV_{\text{EquatorMass250kW}} = 100 – [(75190 - 6050)\ \frac{\mathbf{100}}{\mathbf{69140}}] = 65 \qquad \text{(A4.65)}$$

$$AV_{\text{EquatorMass500kW}} = 100 – [(150380 - 12100)\ \frac{\mathbf{100}}{\mathbf{138280}}] = 65 \qquad \text{(A4.66)}$$

$$AV_{\text{EquatorMass1000kW}} = 100 – [(300760 - 24200)\ \frac{\mathbf{100}}{\mathbf{276560}}] = 65 \qquad \text{(A4.67)}$$

5. Lunar Pole Location

$$AV_{\text{PolarMass25kW}} = 100 – [(3400 - 1712)\ \frac{\mathbf{100}}{\mathbf{2038}}] = 83 \qquad \text{(A4.68)}$$

$$AV_{\text{PolarMass100kW}} = 100 – [(13600 - 3500)\ \frac{\mathbf{100}}{\mathbf{11500}}] = 82 \qquad \text{(A4.69)}$$

$$AV_{PolarMass250kW} = 100 - [(34000 - 6050) \frac{100}{31450}] = 79 \quad (A4.70)$$

$$AV_{PolarMass500kW} = 100 - [(68000 - 12100) \frac{100}{62900}] = 79 \quad (A4.71)$$

$$AV_{PolarMass1000kW} = 100 - [(136000 - 24200) \frac{100}{125800}] = 79 \quad (A4.72)$$

6. Surface Contamination Avoidance

$$AV_{SurfaceContamination} = 50 \quad (A4.73)$$

The end-of-life plans for the thermal storage system does require abandoning material in place due to molten regolith solidifying around the heat exchanger. Abandoning a portion of the overall system in place permanently contaminates the lunar surface.

7. Non-nuclear Preference

$$AV_{Non\text{-}NuclearPreference} = 100 \quad (A4.74)$$

KC12 is not a nuclear system.

8. Low Developmental, Facility, and Operational Costs

$$AV_{TRL} = (2 - 2) \frac{100}{3} = 0 \quad (A4.75)$$

APPENDIX 3

Additional Charts and Graphs

Table 50: Equatorial Location Scoring Chart with Attribute Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational Life	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and	Agg. Utility
25	KRUSTY	0 (X)	22 (X)	68 (X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	71 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	0 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	81 (X)	50 (X)	100 (X)	0 (X)	X
100	KRUSTY	0 (X)	22 (X)	57 (X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	59 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	0 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	68 (X)	50 (X)	100 (X)	0 (X)	X
250	KRUSTY	0 (X)	22 (X)	55(X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	57 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	0 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	65 (X)	50 (X)	100 (X)	0 (X)	X
500	KRUSTY	0 (X)	22 (X)	55(X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	57 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	0 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	65 (X)	50 (X)	100 (X)	0 (X)	X
1000	KRUSTY	0 (X)	22 (X)	55(X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	57 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	0 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	65 (X)	50 (X)	100 (X)	0 (X)	X

Table 51: Polar Location Scoring Chart with Attribute Values

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational Life	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0 (X)	22 (X)	0 (X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	86 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	17 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	100 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	83 (X)	50 (X)	100 (X)	0 (X)	X
100	KRUSTY	0 (X)	22 (X)	0 (X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	62 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	87 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	82 (X)	50 (X)	100 (X)	0 (X)	X
250	KRUSTY	0 (X)	22 (X)	0 (X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	60 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	84 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	79 (X)	50 (X)	100 (X)	0 (X)	X
500	KRUSTY	0 (X)	22 (X)	0 (X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	60 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	84 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	79 (X)	50 (X)	100 (X)	0 (X)	X
1000	KRUSTY	0 (X)	22 (X)	0 (X)	0 (X)	0 (X)	100 (X)	X
	SP-100	0 (X)	0 (X)	100 (X)	0 (X)	0 (X)	33 (X)	X
	SDGTDP	100 (X)	35 (X)	60 (X)	50 (X)	100 (X)	33 (X)	X
	Photovoltaic	100 (X)	100 (X)	84 (X)	100 (X)	100 (X)	100 (X)	X
	KC12	100 (X)	35 (X)	79 (X)	50 (X)	100 (X)	0 (X)	X

Table 52: Weights added to Equatorial Location Score Chart

		Value Dimensions						
Lunar Power Demand (kW)	Power System Type	Ease of Maintenance	Long Operational Life	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and	Agg. Utility
25	KRUSTY	0 (0.1583)	22 (0.2417)	68 (0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	71 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	0 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	81 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
100	KRUSTY	0 (0.1583)	22 (0.2417)	57 (0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	59 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	0 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	68 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
250	KRUSTY	0 (0.1583)	22 (0.2417)	55(0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	57 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	0 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	65 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
500	KRUSTY	0 (0.1583)	22 (0.2417)	55(0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	57 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	0 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	65 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
1000	KRUSTY	0 (0.1583)	22 (0.2417)	55(0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	57 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	0 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	65 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X

Table 53: Weights added to Polar Location Score Chart

Lunar Power Demand (kW)	Power System Type	Value Dimensions: Ease of Maintenance	Long Operational Life	Low Mass	Surface Contamination Avoidance	Non-nuclear System Preference	Low Developmental, Facility, and Operational Costs	Agg. Utility
25	KRUSTY	0 (0.1583)	22 (0.2417)	0 (0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	86 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	17 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	100 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	83 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
100	KRUSTY	0 (0.1583)	22 (0.2417)	0 (0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	62 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	87 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	82 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
250	KRUSTY	0 (0.1583)	22 (0.2417)	0 (0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	60 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	84 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	79 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
500	KRUSTY	0 (0.1583)	22 (0.2417)	0 (0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	60 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	84 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	79 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X
1000	KRUSTY	0 (0.1583)	22 (0.2417)	0 (0.4083)	0 (0.0611)	0 (0.0278)	100 (0.1028)	X
	SP-100	0 (0.1583)	0 (0.2417)	100 (0.4083)	0 (0.0611)	0 (0.0278)	33 (0.1028)	X
	SDGTDP	100 (0.1583)	35 (0.2417)	60 (0.4083)	50 (0.0611)	100 (0.0278)	33 (0.1028)	X
	Photovoltaic	100 (0.1583)	100 (0.2417)	84 (0.4083)	100 (0.0611)	100 (0.0278)	100 (0.1028)	X
	KC12	100 (0.1583)	35 (0.2417)	79 (0.4083)	50 (0.0611)	100 (0.0278)	0 (0.1028)	X

APPENDIX 4

Acronym List

Acronym	Definition
SMART	Simple-attribute Rating Technique
EES	Engineering Equation Solver
PLS	Policy, Legal, and Safety
KRUSTY	Kilopower Reactor Using Stirling TechnologY
REC	Thermal Heat Concentrator and Receiver
TS	Thermal Storage
KC	Kalina Cycle (Ammonia-water Thermodynamic Engine)
TUR	Turbine
PU	Pump
RE	Reheater (Heat Exchanger)
RAD	Radiator
MX	Mixer
SEP	Separator
SPL	Splitter
THV	Throttling Valve
ESAS	Exploration Architecture Study
NASA	National Aeronautical and Space Administration
ROC	Rank Ordered Centroid
SMARTER	Simple-attribute Rating Technique Exploiting Ranks
TRL	Technology Readiness Level
SDGTDP	Solar Dynamic Ground Test Demonstration Project
TES	Thermal Energy Storage
DOE	Department of Energy
SRR	Systems Requirements Review
RAM	Reliability, Availability, and Maintainability
CBC	Closed Brayton Cycle
SD	Solar Dynamic
FPS	Fusion Power System
JIMO	Jupiter Icy Moons Orbiter
RPS	Radioisotope Power System
GPHS	General Purpose Heat Source
BOM	Beginning of Mission
SNAP	Systems for Nuclear, Auxiliary Power
US	United States
GPP	Giant Planets Panel
JPL	Jet Propulsion Laboratory

ISS	International Space Station
RGF	Regenerative Fuel Cell
PMAD	Power Management and Distribution system
ETEC	Energy Technology Engineering Center
AV	Value Function
DRM	Design Reference Mission
NEPA	National Environmental Policy Act
UN	United Nations
NPS	Nuclear Power Source
FOM	Figures of Merit
ISRU	In-situ Resource Utilization
LOX	Liquid Oxygen
kW	Kilowatt
MW	Megawatt
LEV	Lunar Expeditionary Vehicle
PR	Performance Requirement
NNSS	Nevada National Security Site
CPR	Compressor Pressure Ratio
AU	Astronomical Unit
SLS	Space Launch System
FLO	First Lunar Outpost
EIS	Environmental Impact Statement
EA	Environmental Assessment
RTG	Radio thermal Generator
OST	Outer space Treaty
ESA	European Space Agency
IADC	Inter-agency Space Debris Coordination Committee
JAXA	Japan Aerospace Exploration Agency

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