Evaluation of Power Generation System Architectures for Manned Mars Missions

by

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B.S. Nuclear Engineering Technology, Excelsior College, 2013

Submitted to the System Design and Management Program in partial fulfillment of the requirements for the degree of

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Abstract

This work applies a systems approach to architectural definition, development and selection of power generating concepts capable of supporting a 20 crewmember Mars mission by the year 2040. The thesis confirms that current thin film solar technology is sufficient to sustain this mission, given the base of operations is located in the northern hemisphere (20°N-30°N) and is using regenerative fuel cells as an energy storage medium. Beyond those latitudes, calculations for a combination of thin film solar and a nuclear Brayton cycle architecture is needed to maintain sufficient power. The problem definition process is achieved through domain exploration, functional decompositions, and mapping the process functions to their objects of form. The thesis then identifies the constraints developed by the MIT Mars 2040 Project team and develops a sizing algorithm for the combined nuclear-solar systems dependent upon Martian latitudes. The highest scoring site location was Mawrth Vallis (22.6°N) for thin film solar system with regenerative fuels cells that can produce 239 kWe of power. The sizing model developed here is integrated into the Mars project’s comprehensive system model, which uses the calculated mass and volume values as inputs for their tradespace designs.

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I gratefully accept all of my future possibilities and accomplishments, which are a direct result of the support you have all shown me while at MIT.
Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B4C</td>
<td>Boron Carbide</td>
</tr>
<tr>
<td>DSM</td>
<td>Design Structure Matrix</td>
</tr>
<tr>
<td>ECLSS</td>
<td>Environmental Control and Life Support System</td>
</tr>
<tr>
<td>EDL</td>
<td>Entry, Descent and Landing</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ISRU</td>
<td>In-Situ Resource Utilization</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>JAXA</td>
<td>Japan Aerospace Exploration Agency</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>Li-Ion</td>
<td>Lithium Ion</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>OPD</td>
<td>Object Process Diagram</td>
</tr>
<tr>
<td>OPM</td>
<td>Object Process Methodology</td>
</tr>
<tr>
<td>RFC</td>
<td>Regenerative Fuel Cells</td>
</tr>
<tr>
<td>RTG</td>
<td>Radioisotope Thermoelectric Generator</td>
</tr>
<tr>
<td>SLS</td>
<td>Space Launch System</td>
</tr>
<tr>
<td>SP-100</td>
<td>100 kWe Space Reactor Prototype</td>
</tr>
</tbody>
</table>

Nomenclature

Areo-       Prefix used instead of “Geo” to denoted relationship with Mars as opposed to Earth (Areo-centric, Areo-graphy, Areo-thermal)

Definitions

Architecture is the selection and arrangement of concept elements that address the goals, requirements, and needs of the system’s stakeholders.

Brayton Cycle is where atmospheric air is compressed to an elevated pressure, heat is added at constant pressure, and then the compressed, heated air expands through a turbine. Expander work exceeds compressor work and provides net power as shaft rotation torque.[1]

Payload Fairing is the nose cone region of the launch vehicle used to protect the payload.

Power Density is the ratio of power produced to system volume, measured in W/m³.

Specific Power is the ratio of power produced to system mass, measured in kW/kg.
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1 Introduction

1.1 Science and Mission Basis

Energy is a key element to sustaining human existence. Humanity has learned to create various systems to harness Earth's energy for meeting our power needs. As we explore remote regions, the constraints placed upon our ability to harness energy, require more advanced system architectures. Exploration beyond Earth’s atmosphere helped develop advanced power systems that, meet the mission objectives of operating on the Moon and Low Earth Orbit (LEO). The next feasible step requires the development of a power generating architecture that will aid in a successful manned mission to Mars.

During the Planetary Society workshop, Society CEO Bill Nye called for the halting of further technology development and start "getting on the road" as soon as 2033, with hopes of landing a crew on Mars by 2040.[2] The MIT Mars 2040 Study project has taken on the challenge of developing a reference mission for establishing a “permanent sustainable human presence” of 20 crewmembers on the surface of Mars.[3]

Robert Zubrin, Founder of the Mars Society had proposed mission architectures where Mars mission crews could "live off the land".[4] Mars contains elements that are useful for sustained human existence. With an atmosphere predominately composed of carbon dioxide and a surface containing iron and aluminum, Mars provides additional resources useful to the development of a sustained presence beyond Earth.

Within recent years, private organizations beyond the traditional government space organizations (NASA, ESA, JAXA, etc.) have expressed an interest in sending humans to Mars.
Mars One has proposed to fund a group of four colonist through the revenue received from crowd funding and a televised broadcast of such a mission. Regardless of who takes the lead in human exploration and settlement of Mars, the means to sustain power generation across the mission profiles needs to be developed.

1.2 Definition and Purpose

This thesis sets forth to establish a feasible trade space of power generating architectures for a manned Mars mission or campaign, using technology which is currently available for delivering uninterrupted power in extremely isolated environments. Development of a model which can size and determine cost of the system will be based on inputs provided by the MIT Mars 2040 project. A viable set of architectures will enable the team in the process of narrowing their site selection.

This work builds on previous studies that have independently looked at individual components of providing power for Mars. Similar to here on Earth, the most viable power system architecture changes based on geographic location. Available areographic (Mars’ geographic) information indicates that different areological regions hold the potential for additional energy needed for power generation. Such information will influence the system design process.

The primary goal is to compile existing research in this area for enumerating system architectures and down select based on the constraints (needed power levels and selected site location) presented. Secondary to that would be the development of a viable tool which can be tailored to meet changes in the project’s mission requirements.
### 1.3 Approach and Thesis Structure

This thesis is designed to identify, filter and model power generating architectures that would sustain 20 crewmembers on a mission to Mars with currently available technology. The thesis structure is explained below in Figure 1.1.

| Chapter 2 | Describe the Scope of Mars Exploration, Present the Challenges for Power Generation on Mars |
| Chapter 3 | Present a Framework of Terrestrial Power Generating Architectures in Isolated Environments, Discuss Recent Technology Developments |
| Chapter 4 | Present Domains, Decompositions, Concept Form, Relationships, System Design Optimization, Operation Logistics |
| Chapter 5 | Identify the Criteria for Sizing Power Generating Architectures, Present MATLAB® used to Reduce the Architectural Tradespace |
| Chapter 6 | Summarize and Discuss Results |
| Chapter 7 | State Research Conclusions, Provide Recommendations for Further Study |

**Figure 1.1 - Thesis Structure**

Chapter 2 explores the problem space, where power generating architectures are difficult to design in the context of Mars exploration. Chapter 3 gives us the context of technology solutions that are successful at providing electrical power in isolated environments on Earth. Chapter 4 uses a systems engineering approach to explore power generating system architectures to develop a solution neutral design and allows the analysis of feasible architectures. Chapter 5 develops a model that will output sizing information which can be used as calculation inputs for the larger system. Chapter 6 analyzes information outputted from the model. Chapter 7 provides recommendations for the future development of a more inclusive model.
2 Problem Description

2.1 Mars Exploration Challenges

Stephen Hawking has said, “I don’t think the human race will survive the next thousand years, unless we spread into space. There are too many accidents that can befall life on a single planet”. Martian exploration leads to a greater scientific understanding of our ability to inhabit another planet. When looking at the factors needed to determine a species survivability, the larger an area of land that they inhabit, the more it decreases their risk to extinction level events, such as disease and a loss of resources. Mars is the next stage in the expansion of human habitation, although not insurmountable, the journey to establish a human presence on Mars will be challenging.

Timing is key factor when planning a trip to Mars, since the window of opportunity available to make the transit feasible opens every 26 months. Once in transit, the time required to reach Mars will take between 6-9 months using current chemical propulsion systems. Once on the surface, the choice to return to Earth is available in 40 days or 614 days, and the return flight duration is longer if we opt for the shorter duration on Mars. Appendix A lists the Earth to Mars opportunities leading up to a mission arriving at Mars by the year 2040.

The Mars mission success rate to date has been 18 out of 43 programs, with an additional two successes if we are to include combinations where orbiters have reached the planet, yet their associated landers did not [Appendix B]. The 2011 Mars Science Laboratory mission delivered the largest payload thus far when it deployed the 1 tonne Curiosity rover. The Mars 2040 team is looking to send payloads that would be 40t in size. Bringing that much mass to Mars at once
will require an advanced capability for entry, descent and landing (EDL). Methods are required to protect the payload from the frictional heat generated upon its entry into the atmosphere, then the object will need to be slowed down enough such that its contents are not damaged upon landing, and the ability to maneuver while descending will impact how close the payload is to its final destination.

Despite having enough atmosphere to facilitate EDL, it is far less than that which is found on Earth. The lack of atmospheric pressure would still require astronauts to don protective equipment when conducting an extravehicular activity (EVA), very similar to the spacesuits already utilized by them. The composition of the atmosphere is also inhospitable to human life, since it predominately consist of Carbon Dioxide (CO2).[7] Unlike Earth, Mars does not have a protective magnetic field and this allows solar winds to barrage the planet unimpeded. This thin atmosphere, increase the amount of space radiation that would reach individuals on the planet’s surface.

Average surface temperature ranges from -125 °C to 20 °C.[7] With respect to other locations in our solar system, these values are manageable to overcome. With coldest temperatures occurring just before dawn, adequate thermal control systems are needed for generating a suitable environment overnight, otherwise humans will not survive the cold. A surface gravity that is 37% of what it is here on Earth could have a positive benefit on structural engineering principles for natively built structures.[7] On the other hand, the prolonged effects of reduced gravity have caused muscle loss and bone demineralization, which could be dangerous for the astronauts that return.
2.2 Architectural Challenges for Power Generating Systems

Power generating architectures for space missions have traditionally been limited to systems expected to be operating predominately in the vacuum of space. Table 1 summarizes the Human Spaceflight: Mission Analysis and Design manual’s ranges for which power systems options apply with respect to mission duration.[7]

<table>
<thead>
<tr>
<th>Duration</th>
<th>&lt; 1 kW</th>
<th>1 kW – 100 kW</th>
<th>&gt; 100 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hr – 1 day</td>
<td>Batteries</td>
<td>Chemically fuelled turbines</td>
<td></td>
</tr>
<tr>
<td>1 day – 1 week</td>
<td>Fuel Cells</td>
<td>Cryogenic hydrogen/oxygen expansion engines</td>
<td></td>
</tr>
<tr>
<td>&gt; 1 week</td>
<td>Radioisotope Thermoelectric (RTG)</td>
<td>Photovoltaic (Solar)</td>
<td>Nuclear</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>Wind</td>
<td>Areothermal</td>
</tr>
</tbody>
</table>

Missions to Mars have the opportunity of utilizing power generating architectures not intended for space travel. Wind and Areothermal (Martian geothermal) energy are concepts which respectively provide energy on the same scale and duration as Solar and Nuclear. This thesis will explore them in the context of developing the solution space of generating power in remote locations.

2.2.1 Nuclear Power

Nuclear power systems can be classified as either being static or dynamic. Static nuclear power systems such as a radioisotope thermoelectric generator (RTG), produce heat through an array of thermocouples which absorb the decay heat that’s being generated from radioactive
material. While dynamic nuclear systems, use a thermal energy cycle, where heat generated from fission in a reactor is transferred to a medium that produced an expanded gas which can be used to drive a prime mover to transform mechanical into electric energy. The rotational movement of a current carrying conductor in an electromagnetic field provides the current flow which then becomes the electrical output of this generator.

RTGs function well on Mars. The low efficiencies of thermocouples to generated electricity gives this technology a low power to mass ratio averaging 5-20 W/kg.[7] This low specific power results in a system whose mass increases greater than nuclear dynamic reactors or solar arrays for the similar output of power. Resulting in an architecture that is limited to a power range less than 10 kW, which is insufficient as the primary power source for a manned mission.

Nuclear dynamic systems require equipment and piping capable of transferring heated gas to produce mechanical work. Steam is predominately used on Earth due to the heat transfer capability and abundance of water. Mars does not have a readily accessible source of water and the energy required to extract it from soil, makes water more valuable.

Being nuclear, both the static and dynamic systems become sources for ionizing radiation exposure, which leads to a higher risk of crew members developing cancer. Radiation protection measures to protect crew health can be summarized with minimizing the time, maximizing the distance and adding shielding between people and the radiation source. For a large dynamic nuclear system, these principles result in an exclusion zone around the reactor, where exploration is restricted.[9]
2.2.2 Solar Power

Solar power systems can also be classified as either being static or dynamic. Static technology being that of photovoltaic arrays which convert solar energy directly into electrical power through the use of the photoelectric effect. While dynamic solar refers to a solar thermal system where sunlight is focused to generate heat that can be utilized in a thermal energy cycle.

Table 2 - Solar Intensity at Planetary Distances

<table>
<thead>
<tr>
<th>Planet</th>
<th>Semimajor Axis of Orbit (AU)</th>
<th>(10^6 km)</th>
<th>Solar Intensity at Semimajor Axis</th>
<th>Solar Constant (mW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>0.387</td>
<td>57.91</td>
<td>6.673</td>
<td>902.9</td>
</tr>
<tr>
<td>Venus</td>
<td>0.723</td>
<td>108.21</td>
<td>1.911</td>
<td>258.6</td>
</tr>
<tr>
<td>Earth</td>
<td>1.000</td>
<td>149.60</td>
<td>1.000</td>
<td>135.3</td>
</tr>
<tr>
<td>Mars</td>
<td>1.523</td>
<td>227.94</td>
<td>0.431</td>
<td>58.3</td>
</tr>
<tr>
<td>Jupiter</td>
<td>5.203</td>
<td>778.30</td>
<td>0.037</td>
<td>5.0</td>
</tr>
<tr>
<td>Saturn</td>
<td>9.540</td>
<td>1427.00</td>
<td>0.011</td>
<td>1.5</td>
</tr>
<tr>
<td>Uranus</td>
<td>19.180</td>
<td>2869.00</td>
<td>0.003</td>
<td>0.4</td>
</tr>
<tr>
<td>Neptune</td>
<td>30.070</td>
<td>4498.00</td>
<td>0.001</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 2 above, exhibits how the solar energy that reaches Mars is less than what can be utilized here on Earth, due to the added distance from the Sun.[10] Levels are reduced even more, depending on the location of a Mars base, such as one built in the Polar Regions. The atmosphere can also impede solar production with the addition of suspended dust in the air, which reduces efficiency when the dust settles onto the solar arrays. Seasonal winds create dust storms that reduce visible sunlight up to 90%.[11]

2.2.3 Wind Power

Wind power systems are a power generating architecture which utilizes the natural availability of moving atmospheric gases. These gases apply a pressure when interacting with a solid object and the resultant force can be utilized on a prime mover to convert mechanical energy
to electrical. Winds are not strong enough directly on the surface of Mars to produce sufficient energy and the materials required to build modern windfarms off the ground, would require too much material from Earth.[9] The ability to build such systems using materials excavated from Mars, would initially require a large initial energy source and equipment needed for processing raw ore.

2.2.4 Geothermal Power

Similar to a dynamic nuclear system, the geothermal process use a thermal energy cycle, where some medium, typically water, absorbs heat that is coming from beneath the ground and becomes steam which can be directed towards a prime mover on the surface. The transformation of mechanical to electric energy is identical to the earlier nuclear example. Geothermal requires deep drilling equipment from Earth and access to large amounts of underground water.[9]

2.3 Problem Overview

This chapter explores the problem space, where power generating architectures are difficult to design in the context of Mars exploration. Then discusses the issues that specifically impede the different power generating architectures that will be explored in this thesis.
3 Review of Power Generating Architectures for Remote Locations

3.1 Terrestrial Power Generation in Isolated Environments

3.1.1 Nuclear Power in Antarctica

The 1.8 MW nuclear energy plant (PM-3A) provided electricity and steam to the scientific research outpost in Antarctica from 1962 to 1973.\[12\] A 1955 study, led by the U.S. Navy, concluded that nuclear could replace the fuel oil that was needed for power and heating. In August of 1960, the Atomic Energy Commission awarded the contract for construction to the Martin Marietta Corporation (now Lockheed-Martin), after receiving congressional approval.\[12\] Over the following two years the nuclear plant was built, tested, shipped and assembled on the edge of the McMurdo Antarctic research station.

Over the reactor’s 10 year life, it produced “78 million kilowatt hours” of electricity and distilled 13 million gallons of water.\[14\] Diesel generators had to provide backup power due to the nuclear plant experiencing shutdown periods for 20% of the time.

Initially intended to operate for 20 years, ongoing complications resulted in the early retirement of this facility. Hydrogen buildup due to the radiolytic decomposition of water resulted in the occurrence of fires within the reactor containment area. This resulted in the installation of a ventilation system needed to bring down the concentration of hydrogen in the air. Chloride contamination resulted in the cracking of protective seals which led to radioactive coolant leaks.\[12\] These leaks resulted in the shutdown and early decommissioning of PM-3A. To reduce the risk of contaminating the land surrounding the reactor plant site, all components and 2 meters of ground dirt were transported out of Antarctica.\[14\]
3.1.2 Wind Power off the Shores of Northern Europe

The largest number of offshore windfarms on Earth are located in waters between England and Denmark. The largest being the 630 MW London Array windfarm which consists of 175 turbines, over an area of 100 km².[15] Construction was impeded by offshore winds and frequent changes to the weather at sea. Planning of where to lay cables which are intersected by shipping lanes and special vehicle construction to install and bury those cables were unavoidable technical challenges. Transportation of materials is crucial when 110,000 tonnes of steel foundation was installed and 150,000 m³ of rocks from the seabed were excavated.[15]

Planning for an offshore windfarm requires the coordination with public policy that regulates marine activity, yet this still does not account for its spatial relationship to the environment typically found with land based windfarms.[16] As the number and size of offshore windfarms increases, attention needs to be given to their environmental impact. Originally intended to be expanded to 1,000 MW, the London Array construction was halted due to possible impact on endangered marine wildlife.[15]

3.2 Advancements in Power Generating Technology

3.2.1 Nuclear Power

The Brayton cycle for nuclear space power applications, has been studied since the 1960’s. The largest advantage being that it does not require a liquid moderator such as water. Atmospheric air is compressed, heated, and then expand through a turbine. Figure 3.1 below shows the simplified schematic diagram of a 1 MW Brayton cycle reactor system.[17]

Following the arrows through the system, shows how the compressed air is heated by the reactor, passes through the
recuperator (regenerative heat exchanger) where it expels residual heat to the incoming air that is headed for the reactor. Finally the heat exchange medium passes through a radiator, where as much thermal heat as possible is released, before returning to the compressor and starting the process over again.[18]

The design efficiency of a Brayton system to convert thermal power to generate the demanded electrical power output is in the range of 25 to 30 % efficiency, with supercritical Brayton cycles being developed, that are expected to reach 48% efficiency.[19] The supercritical Brayton cycle is designed to work with CO2 as its heat transfer medium, allowing for the Mars power generating system to remove the radiator from the system and replace the inlet to collect its CO2 from the atmosphere and outlet the exhaust as waste heat that can be repurposed by other systems, e.g., In-Situ Resource Utilization (ISRU).

Previous nuclear space power systems such as the SP-100 and Topaz I, were specifically designed to meet the requirements of space operation (absence of atmosphere and gravity). Studies have applied these systems as the power source for Lunar and Martian surface operations, yet an SP-100 system on Mars requires the addition of a “vacuum vessel for protection against the
environment".[20] These reactors are better suited for providing the energy needed for interplanetary space propulsion.

3.2.2 Geothermal Power

Electro-magnetic methods have improved enough to replace the traditional means of geothermal prospecting through the active drilling of holes.[21] Imaging the ground for anomalies based on deflections in density, can determine the presence of regions where higher temperature fluid exists, that can be used for geothermal energy.

3.3 Power Generating Overview

This chapter explores the background for isolated terrestrial power generating systems which experience conditions that can be analogous to aspects of operating on Mars. While also providing advancements that will be utilized in the selection process of the next chapter, when we explore solution neutral architectures.
4 Definition of Architectural Space and Influences

4.1 Domain of Study

The power generating system is part of the overall surface architecture sub-team for the MIT Mars 2040 Study project as seen in Figure 4.1. The Power generation system is connected to the other systems within the group as well as the larger domain. The surface team reports to the larger project team which is developing a mission plan for sending a crew of 20 people to Mars by the year 2040. The published results from this study, will add to the domain of design reference architectures that have been developed for going to Mars.

![Figure 4.1 - Mars Power Generating System and Associated Domains](image-url)
Government organizations such as NASA will develop, review and utilize these mission plans. Private organizations have also developed studies within this domain level, and will continue to do so as private industry expands further into the aerospace industry. Zooming out to the top level brings us to the public domain, where everyone who is not directly involved, is still part of the greater enterprise that has developed around this system.

4.2 Functional Decomposition

Next we decompose the power generating system into a 1st level decomposition of five primary functions in Figure 4.2. This generic architecture allows for the inclusion five categories of power generation for Mars. Then we dive into the 2nd level decomposition of each power architecture system, listed below, with Figure 4.3 through Figure 4.7.

- Dynamic Nuclear System
- Static Nuclear System
- Photovoltaic w/ Energy Storage System
- Wind Power System
- Areothermal Power System

![Surface Architecture](image)

Figure 4.2 - First Level Functional Decomposition of Mars Power Generating System
### Power Generating System Functional Domain (Dynamic Nuclear Systems)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Produce thermal energy</td>
<td>Maximize thermal energy utilization</td>
<td>Convert electricity to usable power level</td>
<td>Protect Mars from release of nuclear material</td>
<td>Indicate current system state</td>
</tr>
<tr>
<td>Transfer thermal energy from the heat source</td>
<td>Transfer excess thermal energy to atmosphere</td>
<td>Provide power to electrical/electronic components</td>
<td>Protect nuclear fuel from external influence</td>
<td>Provide system control</td>
</tr>
<tr>
<td>Produce electricity from thermal energy</td>
<td>Remove heat from power electronics</td>
<td>Store excess electricity</td>
<td>Protect crew from radiation exposure</td>
<td>Minimize transients to electrical distribution</td>
</tr>
</tbody>
</table>

### Figure 4.3 - Second Level Decomposition for Dynamic Nuclear System

---

### Power Generating System (Static Nuclear Systems)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Produce thermal energy</td>
<td>Maximize thermal energy utilization</td>
<td>Convert electricity to usable power level</td>
<td>Protect Mars from release of nuclear material</td>
<td>Indicate current system state</td>
</tr>
<tr>
<td>Transfer thermal energy from the heat source</td>
<td>Transfer excess thermal energy to atmosphere</td>
<td>Provide power to electrical/electronic components</td>
<td>Protect nuclear fuel from external influence</td>
<td>Provide system control</td>
</tr>
<tr>
<td>Produce electricity from thermal energy</td>
<td>Remove heat from power electronics</td>
<td>Store excess electricity</td>
<td>Protect crew from radiation exposure</td>
<td>Minimize transients to electrical distribution</td>
</tr>
</tbody>
</table>

### Figure 4.4 - Second Level Decomposition for Static Nuclear System

---

25
### Power Generating System (Photovoltaic w/ Energy Storage)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capture photonic energy</td>
<td>Maximize thermal energy utilization</td>
<td>Convert electricity to usable power level</td>
<td>Maximize energy utilization</td>
<td>Indicate current system state</td>
</tr>
<tr>
<td>Produce electricity from photonic energy</td>
<td>Remove heat from power electronics</td>
<td>Provide power to electrical/electronic components</td>
<td>Remove dust from panels</td>
<td>Provide system control</td>
</tr>
<tr>
<td></td>
<td>Cool energy storage system</td>
<td>Store excess electricity</td>
<td>Protect from wind damage</td>
<td>Minimize transients to electrical distribution</td>
</tr>
</tbody>
</table>

* Minimize Environmental Impact
  * Maximize energy utilization
  * Remove dust from panels
  * Protect from wind damage

* Monitor and Control System Operations
  * Indicate current system state
  * Provide system control
  * Minimize transients to electrical distribution

#### Figure 4.5 - Second Level Decomposition for Photovoltaic w/ Energy Storage System

### Power Generating System (Wind)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Convert pressure to mechanical energy</td>
<td>Maximize thermal energy utilization</td>
<td>Convert electricity to usable power level</td>
<td>Maximize energy utilization</td>
<td>Indicate current system state</td>
</tr>
<tr>
<td>Produce electricity from mechanical energy</td>
<td>Transfer excess thermal energy to atmosphere</td>
<td>Provide power to electrical/electronic components</td>
<td>Remove dust from panels</td>
<td>Provide system control</td>
</tr>
<tr>
<td></td>
<td>Remove heat from power electronics</td>
<td>Store excess electricity</td>
<td>Protect from dust damage</td>
<td>Minimize transients to electrical distribution</td>
</tr>
</tbody>
</table>

* Minimize Environmental Impact
  * Maximize energy utilization
  * Remove dust from panels
  * Protect from dust damage

* Monitor and Control System Operations
  * Indicate current system state
  * Provide system control
  * Minimize transients to electrical distribution

#### Figure 4.6 - Second Level Decomposition for Wind Power System
4.3 Assigning Elements of Form

The next step in the design process is to take the functional statements derived from the decomposition and assign objects of form to them. Table 3 has the objects of form listed for our nuclear dynamic and photovoltaic power generating systems next to their functions.

<table>
<thead>
<tr>
<th>Functional Decomposition Level</th>
<th>Function</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Convert energy to electrical power</td>
<td>Energy conversion units</td>
</tr>
<tr>
<td>2</td>
<td>• Produce thermal energy</td>
<td>Nuclear reactor</td>
</tr>
<tr>
<td>2</td>
<td>• Transfer thermal energy from the heat source</td>
<td>Coolant medium (gas, liquid moderator, or heat pipe)</td>
</tr>
<tr>
<td>2</td>
<td>• Produce electricity from thermal energy</td>
<td>Rotary dynamic power generating mechanism (Bryton / Sterling engine)</td>
</tr>
<tr>
<td>2</td>
<td>• Capture photonic energy</td>
<td>Solar panel array</td>
</tr>
<tr>
<td>2</td>
<td>• Produce electricity from photonic energy</td>
<td>Photovoltaic cells</td>
</tr>
<tr>
<td>Functional Decomposition Level</td>
<td>Function</td>
<td>Form</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------------------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td><strong>Manage waste heat</strong></td>
<td>Thermal transport equipment</td>
</tr>
<tr>
<td>2</td>
<td>• Maximize thermal energy utilization</td>
<td>Regenerative heat exchanger (recuperator)</td>
</tr>
<tr>
<td>2</td>
<td>• Transfer excess thermal energy to atmosphere</td>
<td>Thermal heat sink (radiator panels, heat fins)</td>
</tr>
<tr>
<td>2</td>
<td>• Remove heat from power electronics</td>
<td>Pumped fluid loop</td>
</tr>
<tr>
<td>2</td>
<td>• Cool energy storage system</td>
<td>Pumped fluid loop</td>
</tr>
<tr>
<td>1</td>
<td><strong>Distribute Electrical Power</strong></td>
<td>Electrical components</td>
</tr>
<tr>
<td>2</td>
<td>• Convert electricity to usable power level</td>
<td>Transformers, inverters, filters, rectifiers, converters</td>
</tr>
<tr>
<td>2</td>
<td>• Provide power to electrical/electronic components</td>
<td>Cabling, switchboards, load centers, power panels, breakers, fuses</td>
</tr>
<tr>
<td>2</td>
<td>• Store excess electricity</td>
<td>Batteries, fuel cells</td>
</tr>
<tr>
<td>1</td>
<td><strong>Minimize Environmental Impact</strong></td>
<td>Mechanical components</td>
</tr>
<tr>
<td>2</td>
<td>• Protect Mars from release of nuclear material</td>
<td>Reactor vessel, secondary containment</td>
</tr>
<tr>
<td>2</td>
<td>• Protect nuclear fuel from external influence</td>
<td>Radiation shielding from space radiation</td>
</tr>
<tr>
<td>2</td>
<td>• Protect crew from radiation exposure</td>
<td>Radiation shielding from reactor radiation</td>
</tr>
<tr>
<td>2</td>
<td>• Maximize energy utilization</td>
<td>Array placement correction equipment (solar tracker)</td>
</tr>
<tr>
<td>2</td>
<td>• Remove dust from panels</td>
<td>Dust cleaning devices (agitator, compressed air, mechanical sweep)</td>
</tr>
<tr>
<td>2</td>
<td>• Protect from wind damage</td>
<td>Ground anchors, distributed weights</td>
</tr>
<tr>
<td>1</td>
<td><strong>Monitor and control system operations</strong></td>
<td>Electronic components</td>
</tr>
<tr>
<td>2</td>
<td>• Indicate current system state</td>
<td>Sensors, reference temperature detectors, displays</td>
</tr>
<tr>
<td>2</td>
<td>• Provide system control</td>
<td>Controllers, actuators</td>
</tr>
<tr>
<td>2</td>
<td>• Minimize transients to electrical distribution</td>
<td>Under voltage trip, controllers</td>
</tr>
<tr>
<td>2</td>
<td>• Isolate energy source during system accidents</td>
<td>Overpressure relief valves, automated reactor shutdown</td>
</tr>
</tbody>
</table>

The system has been limited to only include solar power with energy storage and dynamic nuclear power, because those are the current power generating architectures that are fully developed for a 2040 mission.
4.4 Relationship between Functional Processes and Objects of Form

This section shows two methods for visually representing the relationship between the objects of a system. These connections can greatly impact design decisions, which is why it’s important to understand how they affect each other. The first method is Object Process Methodology (OPM) [22] by Dov Dori, which shows how form and function are connected and allows for a controlled zooming process. The second method is the Design Structure Matrix (DSM), as developed by Eppinger and Browning, [23] which gives a visual representation of system relationships overlaid onto an N-squared diagram.

4.4.1 Object Process Methodology

OPM is a systems engineering methodology which allows the relationship between structure and behavior to be displayed in a way that enables clearer communication and standardized documentation of the system elements. OPM is currently under development for acceptance as ISO standard (ISO/DPAS 19450) for automated system and integration processes.[24]

Transmitting ideas is crucial during the design process, and methods which allow for the conceptual modeling of systems greatly increase the user’s level of understanding. This methodology is flexible enough for both “designing new systems and for studying and improving existing ones.”[22] The objects, processes, and states which occupy the diagram, can be representative of either physical or informational systems. Of which, the processes at the highest level are the functions that add the most value to the stakeholders.

The highest level function of a power generating system, is its intended purpose of generating power. In the Object Process Diagram below, Figure 4.8 illustrates how the Mars 2040
power system process is connected to the objects of form from the level 1 decomposition. This model communicates that the power generating process requires the objects in the solid boxes, yet it affects the environmental elements that are represented with dashed boxes.

Figure 4.8 - First Level Object Process Diagram for Martian Power Generating System

Zooming into the second level for the power generating process, results in a new OPD shown with Figure 4.9 below. The level 2 functions are the same as those shown in Figure 4.3 through Figure 4.7. Here the relationships between processes and objects have greater detail.

Figure 4.9 - Second Level Object Process Diagram for Martian Power Generating System
OPCAT is the model-based software for OPM, which allows the OPDs to be simulated and automatically generates contextual code which describes the relationships within a system.

(Appendix C: Object Process Language (OPL) Model (OPCAT 3.0) For the Mars power generating system, converting energy to electrical power requires a nuclear reactor and a solar panel array, which in turn yields thermal energy and electrical energy. Next the process of distributing electrical power affects the electrical energy, while the thermal energy is affected by the waste heat management process. Finally the loop ends where the electrical power is transferred to the Mars surface base power, while the managed waste heat is transferred to the Martian atmosphere or reused in other systems such as ISRU.

4.4.2 Design Structure Matrix

The Design Structure Matrix (DSM) is a tool which visually displays the relationships of a system within an N-squared matrix. The elements of the system that are labeled down the left column of the matrix correspond to the elements that label the top row. The corresponding intersection in the grid, indicates the existence of a relationship between the two elements. The interactions between these can take the form of “energy, spatial, material or informational”. [23] DSMs can be reorganized to show the optimal configuration of a system, elements that map out the physical relationship between objects in a system can be “clustered” into new groupings, while DSMs with information flows are “partitioned” to illustrate a more contiguous work flow. [23]

The DSM for the power generating system is demonstrated in Figure 4.10. The objects of form have been grouped down the left column in terms of their first level decomposition. The structural relationships are symmetrically displayed across the diagonal line that passes through the DSM, this is typical of physical systems where the relationship between objects is bidirectional.
Figure 4.10 - Mars Power Generation Design Structure Matrix (DSM) Ordered by Functional Group

Figure 4.11 below, displays the clustering results for the Mars power generation, using the process described in Ronnie Thebeau’s thesis “Knowledge Management of System Interfaces and Interactions from Product Development Processes”.[25]

Figure 4.11 - MATLAB® Clustering Output for Mars Power Generation DSM
The algorithm has optimally organized the relationships of this system, as shown by the clustered DSM shown in Figure 4.12 below. The first cluster is a combination of the components needed to maintain the solar generation system, whereas the second cluster displays the same for the nuclear system. The largest cluster contains the majority of the electrical components, including the Brayton engine which is the turbine that initially generates the energy.

Figure 4.12 - Clustered Mars Power Generation Design Structure Matrix (DSM)

These tools allow a user the ability to visually represent their conceptual model and employ a structured means to convey the relationships between function and form before moving forward within the development of a project. Resulting in communication clarity, once all team members have the understanding of a system's intended purpose and how it functions internally.
4.5 Operational Logistics

Chapter 3 has shown us that planning for large scale energy generation requires an understanding of what is required of the system, what is available in the environment and what restrictions the system must face in order to be functional.

4.5.1 Power Demand

Robustness is the design property that manifests when a system is “immune to uncontrollable environmental factors and internal variables that are difficult to control”. On a manned mission, the ability for a power generating system to provide power in spite of disruption is imperative. Managing the power demand and assigning priority to which systems must maintain undisrupted service, supports the crew’s ability to regain full operational status. The systems resilience to disruption and its ability to regain mission ready status is fundamental to its robustness.

Power budget calculations for the Mars 2040 Study were calculated using values from the Human Spaceflight: Mission Analysis and Design handbook. Powered surface base systems consist of: ISRU, Greenhouse, Crew Habitat Amenities, Thermal Controls, ECLSS, Lighting, Freezers, Instrumentation/Control and Communications.

The surface architecture analyzed by the Mars 2040 project, requires large amounts of power to be utilized to meet mission objectives. Table 5 below illustrates the power budget breakdown needed to supply 20 crewmembers. The majority of these estimates are based on the architectural decisions to grow 60% percent of the mission’s food and extract resources from the environment.
Table 5 - Power Budget for Mars 2040

<table>
<thead>
<tr>
<th>System Name</th>
<th>Power Demand (kWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECLSS</td>
<td>8.80</td>
</tr>
<tr>
<td>Thermal</td>
<td>14.49</td>
</tr>
<tr>
<td>Emergency Loads</td>
<td>23.60</td>
</tr>
<tr>
<td>Crew Accommodation</td>
<td>82.93</td>
</tr>
<tr>
<td>Greenhouse</td>
<td>168.68</td>
</tr>
<tr>
<td>ISRU</td>
<td>470.30</td>
</tr>
<tr>
<td><strong>TOTAL PEAK DRAW</strong></td>
<td><strong>736.40</strong></td>
</tr>
<tr>
<td>+ 10% Margin</td>
<td>810.04</td>
</tr>
</tbody>
</table>

At 470 kWe, the ISRU plant requires a large portion of the estimated power consumption. This feature in the base architecture will allow the mission to extract water from the soil and use the electrolytic decomposition of water to build up chemical reserves of hydrogen and oxygen, which can be used as the fuel to power the ascent vehicle to return the mission crew members back to Earth. A portion of the energy needed to power the ISRU process can be reclaimed from the waste heat generated off the nuclear system. This synergy between the nuclear system and the ISRU system is one of the novel aspects explored in this thesis.

4.5.2 Potential Landing Sites

The location of the Mars base has implications on the power that will be able to be produced at that site. Solar energy being diminished with respect to its strength here on Earth, yet is strongest in the range between 20°N-30°N latitude.[27] Use of wind energy would become feasible at higher elevations or regions where areological formations have formed mountain ranges that funnel wind currents towards a central location.[28] While areas which show signs of previous volcanic activity can be explored as sites for potential thermal energy sources.
The presence of water and overall scientific value led the Mars 2040 study to select the following destinations (Table 6) during the preliminary site selection process.

Table 6 - Site Locations for Mars 2040 Project

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utopia Planetia</td>
<td>46.7°N</td>
<td>117.5°E</td>
</tr>
<tr>
<td>Mawrth Vallis</td>
<td>22.6°N</td>
<td>16.5°W</td>
</tr>
<tr>
<td>Gale Crater</td>
<td>5.4°S</td>
<td>137.8°E</td>
</tr>
<tr>
<td>Gusev Crater</td>
<td>14.5°S</td>
<td>175.4°E</td>
</tr>
<tr>
<td>Holden Crater</td>
<td>26.4°S</td>
<td>34.0°W</td>
</tr>
<tr>
<td>Hellas Planetia</td>
<td>42.4°S</td>
<td>70.5°E</td>
</tr>
</tbody>
</table>

Of these locations Mawrth Vallis falls within the desired region in the northern hemisphere expected to receive the most solar energy. Utopia Planitia and Hellas Planetia are not only the furthest from the equator, but also sit within areological indentations that are at elevations of deeper than -4000m of the mean Martian surface.[29] While Holden Crater is east of the Tharsis bulge, which is the largest area of historically volcanic activity on the surface of Mars, along with Valles Marineris, which forms a geological canyon that directs air flow.

4.5.3 Payload Fairing Size

NASA is currently developing a new Space Launch System (SLS) which will support future missions beyond Earth’s orbit.[30] The largest size within this platform of cargo vehicles, would be the 130-tonne design. The payload of the SLS fairing determines the size of vehicle payload which can fit within the nose cone of the launch system. According to the SLS Mission Planners Guide, the SLS 130-t is limited to a mass of 45,000 kg for a mission to Mars.[31] Volume assumptions and calculations will be discussed in section 5.4 “Combined MATLAB® Algorithm”.

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4.6 Architectural Overview

This chapter used a systems engineering approach to explore power generating system architectures to develop a solution neutral design that allowed the analysis of feasible architectures. The filtering and screening of those architectures was based on the initial requirement of minimizing further technology development, to initiate the necessary progress required to achieve a manned Mars mission by 2040.
5 Model for Martian Power Generating Architectures

5.1 Power Demand Calculations

For the purpose of these calculations, the Emergency power systems are intended to be the systems that are critical to regaining full system operability. Loss of power to these loads will result in the immediate impairment of mission capability. Freezer systems used to maintain cryogenic fuel storage would cause hazardous conditions if no longer powered. Environmental controls regulate the crew habitat’s atmosphere and waste byproducts. Instrumentation and control systems allow for the remote operation of system components that are not physically accessible. While communications are necessary for the crew to coordinate the recovery effort of the electrical distribution system. These systems are vital when restoring power to the remaining powered systems.

Backup power refers to the power needed to maintain the Emergency systems, in addition to loads which result in intermediate mission impairment if service is not returned to these systems. The greenhouse being the key driver in energy consumption with respect to food production, specifically the energy needed to power the proposed LED bulbs utilized in food growth. The remaining power consumption, in addition to backup, is a result of the ISRU production needed to produce CH4 and O2 for the ascent vehicle’s fuel. Loss of power to ISRU results in the long term impairment of mission capability.

- Emergency Power = ECLSS + Lighting + Freezers + Controls + Communications
- Backup Power = Greenhouse + Crew Habitat Amenities + Thermal + Emergency Power
- Total Power = ISRU Total + Backup Total
5.2 Nuclear Brayton System Sizing Criteria

As covered in Chapter 3, the Brayton cycle has been studied for nuclear space power applications since the late 1960’s. The engine is advantageous since it does not require a liquid moderator such as water. Atmospheric air is compressed, heated, and then expand through a turbine. Compressed air is heated by the reactor, and passes through the recuperator (regenerative heat exchanger) where it expels residual heat to the incoming air that is headed for the reactor. Finally the heat exchange medium passes through a radiator, where as much thermal heat as possible is released, before returning to the compressor and starting the process over again.

The dimensional calculations chosen for the Brayton system reactor sizing was based on the work developed by Courtney Rogge and Mike Kowalkowski for Perdue University’s Aquarius project.[32], [33] The design efficiency of a Brayton system to convert thermal power to generate the demanded power output in the range of 25 to 30 % efficiency, with supercritical Brayton cycles being developed, that are expected to reach 48% efficiency.[19] The calculations for this model were done with a conservative estimate of 25%.

\[ \text{Thermal Power} = \frac{\text{Total Power}}{\text{Brayton Efficiency}} \]

Dimensions of the reactor core are dependent on the required power that the system needs to produce. Using the heat cycle efficiency, we can calculate the thermal power needed to produce the desired electrical output. Thermal energy requirements also allow us to calculate the amount of energy which could be repurposed for other system requirements.
Figure 5.1 shows the geometric relationship of the reactor’s key elements that are sized in this model.

The reactor is calculated to be fueled with a 10 year life expectancy of enriched (12%) uranium nitride (UN) and undergoes fission regulated with eight boron carbide (B₄C) control rods similar to other space reactor designs.[34] Uranium Nitride has a specific energy of $5.57 \times 10^6$ MJ/kg, which can be converted to a working value of 178 kW-years/kg. This gives us the ability to calculate the required mass of fuel for a given thermal power requirement over an intended duration of 10 years.[35]

$$\text{Mass of the Fuel} = \text{Thermal Power} \times \frac{\text{Operational Duration}}{\text{Energy Density}}$$

With a density of 11,300 kg/m³ for Uranium Nitride, the Volume of the fuel can be retrieved from the previously calculated mass, and further used to calculate Fuel Height.[35]

$$\text{Fuel Height} = 2 \times \left(\frac{\text{Mass of the Fuel}}{2 \pi} \div \text{Fuel Density}\right)^{\frac{1}{2}}$$
Calculating the B₄C control rods volume and mass, requires their associated radius (0.59 cm) and density (2,520 kg/m³).[33]

\[ \text{Rod Volume} = \text{Rod Number} \times (\pi \times \text{Rod Radius}^2 \times \text{Fuel Height}) \]

The total volume of the core sums the volumes of the fuel mass and control rods. The total radius accounts for the added mass of the control rods. Reactor mass is the sum of the fuel, control rods and neutron reflector (thickness equal to 0.1 m), volume is based on the overall core height and radius.

\[ \text{Core Radius} = \sqrt{\frac{\text{Fuel Volume} + \text{Rod Volume}}{\pi \times \text{Fuel Height}}} + \text{Neutron reflector thickness} \]

The materials composition of the reactor vessel is a 0.05m inner layer of beryllium oxide (BeO) and a 0.05m outer layer of B₄C, helping to reflect neutrons back into the core. The radiator is based on a 100 kWe design where the radiator panels are aluminum and the shielding is lithium hydride and tungsten, and results in a 720 kg mass and 1.728 m³ volume.[36]

Estimating the heat exchange system size requires dimension calculations for the Brayton cycle engines and recouperators. This was done with the help of Rogge’s mass and volume sizing.[33]

\[ \text{Brayton Mass} = 10.155 \times (\text{Total Power}^{0.3719}) \times \text{Total Power} \]

\[ \text{Recouperator Mass} = 17.236 \times \left(\frac{\text{Total Power}}{0.24}\right)^{-0.3719} \times \left(\frac{\text{Total Power}}{0.24}\right) \]
Total System mass and volume results from the summation of the individual system elements required to build the nuclear Brayton cycle reactor system. Numerical results are shown later in this thesis, in Section 6.1 (System Comparative Analysis).

5.3 Martian Solar Latitude Calculations

During the 2008 International Astronautical Congress, Chase Cooper and Professor Ed Crawley presented an assessment of architectural options for surface power generation and energy storage on human Mars missions. Their values for specific power and power density for thin filmed solar power generation systems and their associated energy storage mediums (Li-Ion Battery or Regenerative Fuel Cell) are summarized in Appendix D: Specific Power and Power Density Values for Solar.[37]

Latitude data was calculated in increments of 5°, which requires the interpolation of values for a given latitude that fall within those intervals. Specific power is given in units of W/kg, which allows mass to be retrieved to a demanded power value, and power density (W/m^3) allows for the same extrapolation of volume.

5.4 Combined MATLAB® Algorithm for Sizing and Latitude

The original MATLAB code [Appendix E: Robustness and Sizing Code for Power Generating System] developed in this thesis combines the mass and volume calculations for a nuclear reactor and a thin film solar with energy storage system.

Initially, the code determines the dimensions of the reactor core by calculating the fuel mass and volume based on the total system output power needed. Next the code refers to the solar
latitude lookup table to interpolate the approximate solar system mass and volumes for a given latitudinal input.

| Table 7 - Calculated Fairing Payload Volume of Space Launch System vs Delta IV |
|---------------------------------|--------|--------------|----------------|
| Height (m) | Diameter (m) | Calculated Volume (m³) | Rated Volume (m³) |
| SLS 130-t  | 10     | 8.4          | 554.18         | 443 (estimate)  |
| Delta IV   | 19.1   | 5            | 375.03         | 300             |

Dimensions of the SLS 130-t payload fairing are of cylindrical shape that is 10m high and 8.4m across in diameter. This would give us an initial volume of 554.18m³, although not feasible to account for the entire space being available. The Delta IV launch system is only rated for utilizing 80% of its measured space as seen in Table 7. Estimated for the purpose of setting a feasible volume limit on the graphs, sets 443.34m³ (80% of SLS 130-t measured volume) as the volume limit for this system.

System mass and volume are then outputted for the Nuclear Brayton reactor, Thin Film Solar w/ Li-Ion Battery Storage and Thin Film Solar w/ Regenerative Fuel Cell Battery Storage systems.

5.5 Model Overview

This chapter develops a model that outputs sizing information which in turn will be used as inputs for the larger Mars 2040 project analysis. These calculations are transposed into MATLAB code, where it can be used to further visualize system relationships and help obtain an integrated system understanding.
6 Results Summary

6.1 System Comparative Analysis

The power budget calculations provide the basis for determining the minimum size of a backup power generating system. Figure 6.1 below, illustrates how the percentage of food grown for a crew size of 20, impacts the fraction of backup and emergency power required. In agreement with the 2040 Study’s planned surface layout, the MATLAB code in Appendix E: Robustness and Sizing Code for Power Generating System, calculates the conversion of thermal waste heat from the reactor for a portion of the energy utilized in the ISRU process. Allowing for demanded total power to increase at slower rate than backup power as the percentage of food grown increases.

![Power Output vs. Food Growth Percentage for Crew Size of 20](image)

Figure 6.1 - Impact of Food Growth Percentage on Power Demand

Table 8 below, shows the values of required power for each power demand classification with respect to food production. Backup power demand helps to size the design of the primary power
generating system. Nuclear with a Brayton engine, will be built in modular sizes, such that a single reactor is capable of powering all backup systems, thus minimizing disruption to all but long term mission systems. Primary power sizing will also exceed the value of weight to mass ratio for cases where a solar power generating system exceeds nuclear power output for a given base latitude. For power demand configurations where, minimum backup exceeds the tradeoff value, the minimum backup plus a 10% safety margin will be used instead.

Table 8 - Power Demand Classification with Respect to Food Production

<table>
<thead>
<tr>
<th>Food Production (%)</th>
<th>Required Power</th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Total (kWe)</td>
<td>Backup (kWe)</td>
<td>Emergency (kWe)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>509.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
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<tr>
<td>20</td>
<td>551.3</td>
<td>50.1</td>
<td>6.5</td>
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<tr>
<td>30</td>
<td>595.2</td>
<td>101.7</td>
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<td></td>
</tr>
<tr>
<td>40</td>
<td>640.7</td>
<td>154.9</td>
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<td>50</td>
<td>687.8</td>
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<td>60</td>
<td>736.4</td>
<td>266.1</td>
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<td>70</td>
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<td>324.1</td>
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<td>80</td>
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<td>90</td>
<td>897.8</td>
<td>444.8</td>
<td>51.8</td>
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<td>100</td>
<td>946.8</td>
<td>507.5</td>
<td>58.3</td>
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</tbody>
</table>

Maintaining power to emergency systems is crucial, in the event of an energy system disruption, a source of standby energy is needed that can satisfy emergency loads. A secondary power generating system, such as thin film solar with energy storage is sufficient to power emergency systems at a weight to mass ratio that is competitive with nuclear. Regenerative Fuel Cells (RFCs) as the energy storage medium have a lower specific power, yet Li-Ion batteries have a faster switching speed for continuous uninterrupted power and can be held at a floating charge.
until needed for emergency situations. The solar component provides the means to generate an independent recharge power in the event that nuclear in compromised.

The sizing algorithm produces a tangible representation of how the power generating architectures tradeoff between each other on the Martian surface in terms of total deployed system mass. Figure 6.2 graphs the system mass versus power output across Martian latitudes ranging from 60°S (indicated as the negative values on that scale) to 60°N. This range was chosen because solar power generated beyond these latitudes would be insufficient for a manned Mars mission with a crew size of 20. The Li-Ion energy storage option from Section 5.3, is represented here by the solid graph with the color gradient.

![System Mass vs. Power Output across Martian Latitudes (Nuclear Brayton & Solar w/ Li-Ion Energy Storage)](image)

**Figure 6.2 - Specific Power (kWe/kg) Comparison of Nuclear & Solar w/ Li-Ion Storage across Martian Latitudes 60°S to 60°N**
The graph for the solar powered system exponentially increases upwards at the outer longitudinal bounds. Achieving a minimal solar power architecture of 250 kWe, would require it's mass to be four times greater than its nuclear equivalent. The blue and white grid on this three dimensional chart represents the nuclear Brayton system. Reactors, being impartial to Martian latitude, are flat across the latitude axis. This indicates a flat line on the mass vs power output axis, which is a representation of mass specific power.

![Graph showing system mass vs. power output across Martian latitudes.](image)

**Figure 6.3 - Specific Power (kWe/kg) Comparison of Nuclear & Solar w/ RFC Storage across Martian Latitudes 60°S to 60°N**

The areas of the graph where the nuclear system obscures the view of the solar Li-Ion chart, is indicative of a region where the nuclear specific power exceeds the solar specific power. In other words, this region represents, where on the Martian surface and below what required power levels, a solar Li-Ion architecture is more mass efficient than its nuclear equivalent.
When compared with the solar RFC (regenerative fuel cell) architecture, seen in Figure 6.3, the “obscured region” has increased in size by 64.8%. This corresponds with the specific mass of the solar RFC system exceeding that of solar Li-Ion system. Achieving a minimal solar power architecture of 250 kWe, with this architecture would require it's mass to be three times greater than its nuclear equivalent at 60°N latitude.

6.2 Summary of Site Location Data

<table>
<thead>
<tr>
<th>Table 9 - Site Location Latitudes</th>
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<tbody>
<tr>
<td>Utopia Planitia</td>
</tr>
<tr>
<td>Mawrth Vallis</td>
</tr>
<tr>
<td>Gale Crater</td>
</tr>
<tr>
<td>Gusev Crater</td>
</tr>
<tr>
<td>Holden Crater</td>
</tr>
<tr>
<td>Hellas Planetia</td>
</tr>
</tbody>
</table>

Given the Mars 2040 project’s potential landing sites, individual information can be retrieved from the model for these particular locations. The values from Table 9 are inputted into the algorithm to provide a comparative visual analysis of how the technologies correspond with each other. As shown in Figure 6.4, the higher specific power of the Li-Ion battery storage system, results in a higher power to mass ratio overall when compared to the RFC system. The tradeoff region in the lower left corner of this figure shows the power output levels where a nuclear system is not viable based on their power to mass ratio. This is indicative of a solar power generating system’s ability to outperform nuclear systems under specific conditions (demanded power output, location) and still require less mass with respect to each other.
Solar power generating systems with demanded output power sizes less than 250 kW, fall within a mass range of four to thirteen metric tons, as seen in Table 10. These smaller weighted configurations are well below the payload fairing limit of 45,000 kg for the SLS 130T, but this does not account for any EDL mass. When these values are standardized with respect to each other, we are able to compare the specific power and power density across all locations for both solar power generating architectures. Table 11 confirms that locations in the Martian Northern hemisphere such as Mawrth Vallis are twice as capable to utilize solar power as Hellas Planetia, which is expected from site locations in the Southern regions.
Table 10 - Power, Mass, and Volume for the Tradeoff Points for Solar

<table>
<thead>
<tr>
<th>Location</th>
<th>Solar + Li-Ion</th>
<th>Solar + RFC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power (kWe)</td>
<td>Mass (kg)</td>
</tr>
<tr>
<td>Hellas Planetia</td>
<td>41</td>
<td>4319.33</td>
</tr>
<tr>
<td>Utopia Planetia</td>
<td>49</td>
<td>4772.70</td>
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<td>Holden Crater</td>
<td>60</td>
<td>5341.26</td>
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<td>Gusev Crater</td>
<td>71</td>
<td>5884.08</td>
</tr>
<tr>
<td>Gale Crater</td>
<td>79</td>
<td>6283.04</td>
</tr>
<tr>
<td>Mawrth Vallis</td>
<td>95</td>
<td>7019.05</td>
</tr>
</tbody>
</table>

Table 11 - Specific Power and Power Density for the Tradeoff Points for Solar

<table>
<thead>
<tr>
<th>Location</th>
<th>Solar + Li-Ion</th>
<th>Solar + RFC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specific Power (W/kg)</td>
<td>Power Density (W/m^3)</td>
</tr>
<tr>
<td>Hellas Planetia</td>
<td>9.49</td>
<td>955.93</td>
</tr>
<tr>
<td>Utopia Planetia</td>
<td>10.27</td>
<td>1136.63</td>
</tr>
<tr>
<td>Holden Crater</td>
<td>11.23</td>
<td>1328.61</td>
</tr>
<tr>
<td>Gusev Crater</td>
<td>12.07</td>
<td>1548.87</td>
</tr>
<tr>
<td>Gale Crater</td>
<td>12.57</td>
<td>1699.29</td>
</tr>
</tbody>
</table>
As discussed in Chapter 6, the volume difference between the two solar architectures is less than 1%, meaning that for a given power demand, almost the same sized system will be necessary. When these plot lines are graphed in Figure 6.5 with respect to the nuclear system and the payload fairing volume, we see an upper range to the volume benefits of the nuclear Brayton architecture. At a demanded output power of 2450 kWe, all of the project selected locations fall beneath the power density of nuclear.

![Power Output vs Volume](image)

Figure 6.5 - Payload Limit with Respect to Power Density (kWe/m³) for all Project Site Locations
This chart also demonstrates that all but one of the tradeoffs with respect to payload fairing, occur above the volume limits of SLS 130T. Mawrth Vallis is the only project site location remaining below the volume tradeoff limit and it appears that a nuclear Brayton plant scales better with respect to mass than volume, when compared to solar. A closer look at Figure 6.6 shows that a demanded output power of 700 kWe results in the three power generating architectures to have a volume between 340-350 m^3, falling under the payload limit of 443.34 m^3.

In the above Figure 6.6, the volume to power graph for Mawrth Vallis shows the specific power relationship between the nuclear and solar power generating architectures. Using the power
output tradeoff between nuclear Brayton and solar+RFC, we are given a system size value rated to output 242 kWe, and an additional safety margin of 10% increases the system to 266.2 kWe. This allows for the construction a backup power generating system of either architecture which is capable of satisfying food production up to 60%. Thus allowing for a redundant backup system to be built, minimizing mission risk in the event of failure or periodic shutdown.

<table>
<thead>
<tr>
<th>Mawrth Vallis Required Power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food Production (%)</strong></td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>Nuclear Brayton</td>
</tr>
<tr>
<td>Solar + RFC</td>
</tr>
<tr>
<td>Solar + Li-ion</td>
</tr>
</tbody>
</table>

The above Table 12, illustrates the configuration of power generating architectures at a Martian latitude of 22.6°N and 60% food production. Three 266.2 kWe nuclear Brayton systems provide the power necessary to maintain all systems, while a fourth 266.2 kWe system is maintained in standby as the backup power supply source. At this latitude, nuclear Brayton and solar+RFC have the same power to mass ratio, allowing for the flexibility of utilizing power generating systems that are independently impacted by different environmental factors on Mars. While the emergency systems can be maintained by a 36 kWe Solar-Li-Ion system which can be maintained on a floating charge to provide immediate power to mission critical systems.
Returning for a closer look at the Mass to Power graph (Figure 6.7) for Mawrth Vallis shows the specific power relationship between these architectures at lower power levels. The tradeoff between Nuclear Brayton and Solar+RFC shows that small scale nuclear plant is not beneficial when trying to preserve mass. As discussed in Section 4.5.1, the Mars 2040 team's calculations for a power budget, sits at 736.4 kWe. Breaking that down into Mawrth Vallis's tradeoff point between Nuclear Brayton and Solar+RFC, would bring us within the range of building a completed power generating system with 3 systems that each produce 250 kWe. Table 13 shows the mass and volume results for building 3 systems that produce 250 kWe. The Mass for both systems are

Figure 6.7 - Design Power Output (kWe) vs Mass (kg) for Mawrth Vallis Site
relatively close due to the specific power for both systems being close at this power level for the Mawrth Vallis site. Although the difference in volume between these systems, requires a solar system 46.2% larger, to produce the same power, at the same mass. However this system still falls within the SLS 130’s volume limit for payload.

Table 13 - Mass and Volume Comparison for Mawrth Vallis at 250 kWe

<table>
<thead>
<tr>
<th>Mawrth Vallis</th>
<th>1 System @ 250 kWe</th>
<th>3 Systems @ 250 kWe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (kg)</td>
<td>Volume (m^3)</td>
</tr>
<tr>
<td>Nuclear Brayton</td>
<td>13263.93</td>
<td>67.53</td>
</tr>
<tr>
<td>Solar+RFC</td>
<td>13446.04</td>
<td>125.48</td>
</tr>
<tr>
<td></td>
<td>39791.79</td>
<td>202.59</td>
</tr>
<tr>
<td></td>
<td>40338.12</td>
<td>376.44</td>
</tr>
</tbody>
</table>

When building these power generating architectures, the secondary effects that result from shared resources can be instrumental in choosing one architecture over another. As stated earlier, the waste heat from a nuclear power system can be utilized for ISRU, while the material resources needed to operate the RFCs are also utilized within the ECLSS system. Table 14 below illustrates what happens when we develop a hybrid architecture where the systems are evenly matched for power output. Scaling these systems up to 800 kWe provides sufficient energy to meet power demand responsibilities. We notice that for greater power levels, this combination occupies 45 m³ more space, while the smaller power systems require 4082 kg more.

Table 14 - Mass and Volume Comparison for Evenly Power Matched Architectures

<table>
<thead>
<tr>
<th>Mawrth Vallis</th>
<th>1 System @ 200 kWe</th>
<th>1 Systems @ 400 kWe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (kg)</td>
<td>Volume (m^3)</td>
</tr>
<tr>
<td>Nuclear Brayton</td>
<td>11359.03</td>
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<tr>
<td>Solar+RFC</td>
<td>10756.84</td>
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<tr>
<td></td>
<td>18636.19</td>
<td>141.16</td>
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<tr>
<td></td>
<td>21513.67</td>
<td>200.76</td>
</tr>
<tr>
<td>TOTAL</td>
<td>22115.87</td>
<td>148.28</td>
</tr>
<tr>
<td>X 2</td>
<td>44231.74</td>
<td>296.56</td>
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</table>

55
6.3 Results Overview

This chapter analyzes the information outputted from the model. Initially we see how much power is required to sustain 20 crewmembers on Mars, then we compare that with the selected architectures of Nuclear Brayton and Solar+RFC across a wide range of parameters. Next we narrow down our selection by looking at the weight to mass ratios tradeoffs for specific landing sites on Mars. Finally choosing the site that presents the most opportunity from a power generating perspective and analyzing that site through different scenarios.
7 Conclusions

7.1 Research Conclusions

The observations made in this thesis support the evidence that thin film solar technology is sufficient to sustain capable energy requirements, given the base of operations is located in the northern hemisphere (20°N-30°N) and the system is using regenerative fuel cells as its energy storage medium. Beyond those latitudes, the value of using solar drops off and eventually becomes a detriment as the mass of that system would far exceed that of a nuclear system to provide the same energy output. Among the set of site locations specified by the Mars 2040 Study project, Mawrth Vallis is the main reference input to the model, where the system architecture of solar power generation with RFC storage is the most beneficial in supplementing mission power needs.

The algorithm developed in this thesis, does not intend that Mawrth Vallis is the final solution, but a strong consideration when exploring system designs that do not need further product development. The model helps to illustrate where the tradeoff that exists between these two technologies and the Mawrth Vallis site is the perfect use case for a larger scale deployment of solar architectures.

7.2 Future Work

Developing systems that are capable of supporting life on Mars, has the added benefit of improving technologies that can be utilized on Earth. As improvements in power generating technologies bring down the specific mass and power density costs, the model will need to be updated to account for added capability of these technologies.
Additional factors can be introduced into the model as areological discoveries are made. Regions on the Martian surface that provide additional energy potential would determine the scale to which a colony will expand in the future. Site locations which are closer to land formations that focus wind currents, could be targeted as starting points for Martian built wind farms. While the discovery of water and underground heat energy would open the opportunity for areothermal energy. Adding regions that show signs of historically recent volcanic activity (i.e. Tharsis Bulge, Elysium Mons), as a directive guidelines for establishing the mission purpose for bases that are located nearby.

Beyond the model, a detailed packaging analysis of the power systems inside the payload fairing, will be helpful in determining the logistical sequence of power system shipments to Mars. Further development of nuclear power system waste heat utilization for ISRU production and similar resource sharing analysis for the ECLSS and RFC usage of oxygen and hydrogen. Finally an in-depth safety analysis to determine the failure modes that would initiate backup and emergency power conditions.
References


Appendices

Appendix A: Earth to Mars Mission Opportunities 2026 to 2045

Earth to Mars Mission Opportunities 2026 to 2045


<table>
<thead>
<tr>
<th>Launch Year</th>
<th>Earth departure date (m/d/yr)</th>
<th>Mars arrival date (m/d/yr)</th>
<th>C3 (km^2/s^2)</th>
<th>Right ascension (deg)</th>
<th>Declination (deg)</th>
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Appendix B: Historical Log of Mars Programs & Missions


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<td>Mars 6 Orbiter/Lander</td>
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<td>Success/Failure</td>
<td>Occultation experiment produced data and Lander failure on descent</td>
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<td>Located landing site for Lander and first successful landing on Mars</td>
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<td>Success</td>
<td>Returned 16,000 images and extensive atmospheric data and soil experiments</td>
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<td>More images than all Mars Missions</td>
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<td>Launch vehicle failure</td>
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<td>Lost on arrival</td>
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<td>Failure</td>
<td>Lost on arrival (carried on Mars Polar Lander)</td>
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<td>Operating lifetime of more than 15 times original warranty</td>
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<td>Returned more than 25 gigabits of data</td>
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<td>Exploring Mars' habitability</td>
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<td>Success</td>
<td>Develop interplanetary technologies and explore Mars' surface features, mineralogy and atmosphere.</td>
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Appendix C: Object Process Language (OPL) Model (OPCAT 3.0)

LEVEL 1 (System Diagram)

- Mars Surface Base Power is environmental and physical.
  - Energy Conversion Unit is physical.
  - Thermal Transport Equipment is physical.
  - Electrical Components is physical.
  - Mechanical Components is physical.
  - Electronic Components is physical.
  - Martian Atmosphere is environmental and physical.
  - Mars Mission Crew is environmental and physical.
  - Power Generating is physical.
  - Power Generating requires Thermal Transport Equipment, Electronic Components, Mechanical Components, Electrical Components, and Energy Conversion Unit.

LEVEL 2 (System Diagram – Power Generating)

- Mars Surface Base Power is environmental and physical.
  - Energy Conversion Unit is physical.
  - Energy Conversion Unit consists of Nuclear Reactor and Solar Panel Array.
  - Thermal Transport Equipment is physical.
  - Thermal Transport Equipment consists of Regenerative Heat Exchanger and Thermal Heat Sink.
  - Electrical Components is physical.
  - Electrical Components consists of Transformers, Cabling, and Batteries.
  - Mechanical Components is physical.
  - Mechanical Components consists of Radiation Shielding and Solar Tracker.
  - Electronic Components is physical.
  - Electronic Components consists of Displays and Controllers.
  - Martian Atmosphere is environmental and physical.
  - Mars Mission Crew is environmental and physical.
  - Distribute Electrical Power is physical.
  - Power Generating is physical.
  - Power Generating requires Thermal Transport Equipment, Electronic Components, Mechanical Components, Electrical Components, and Energy Conversion Unit.
  - Power Generating affects Martian Atmosphere and Mars Surface Base Power.

- Batteries is physical.
- Transformers is physical.
- Displays is physical.
- Thermal Heat Sink is physical.
- Regenerative Heat Exchanger is physical.
- Thermal Energy is physical.
- Electrical Energy is physical.
- Solar Panel Array is physical.
- Nuclear Reactor is physical.

Convert Energy to Electrical Power is physical.
Convert Energy to Electrical Power requires Nuclear Reactor and Solar Panel Array.

Distribute Electrical Power is physical.
Distribute Electrical Power requires Cabling, Batteries, and Transformers.
Distribute Electrical Power affects Electrical Energy.
Distribute Electrical Power yields Mars Surface Base Power.

Manage Waste Heat is physical.
Manage Waste Heat requires Thermal Heat Sink and Regenerative Heat Exchanger.
Manage Waste Heat affects Thermal Energy.
Manage Waste Heat yields Martian Atmosphere.

Minimize Environmental Impact is physical.
Minimize Environmental Impact requires Solar Tracker and Radiation Shielding.
Minimize Environmental Impact affects Martian Atmosphere.

Monitor and Control System Operations is physical.
Monitor and Control System Operations requires Controllers and Displays.
Appendix D: Specific Power and Power Density Values for Solar Arrays

Comparative Analysis of Power System Architectures:

The Case of Human Surface Mission [37], [38], [9]

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<th>Latitude (deg)</th>
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<th>Power Density (W/m^3)</th>
<th>Li-ion Batts (Li-ION) Specific Power (W/kg)</th>
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<td>10.62</td>
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<td>9.59</td>
<td>989.89</td>
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<td>721.09</td>
<td>8.07</td>
<td>726.74</td>
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<td>6.28</td>
<td>400.08</td>
<td>5.50</td>
<td>401.85</td>
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## Appendix E: Robustness and Sizing Code for Power Generating System

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function [TotalPowerReq,BackupTotal,EmergencyTotal] = MPRobust(CrewNum, GHReq)

% MPRobust.m
% Script for Food Production vs Power Robustness Configuration
% Wilfredo 'Alex' Sanchez
% Created: 17 MAY 2015

% INPUT:
% Number of Crew Members
% Percentage of Food Grown (%)
% OUTPUT:
% Total System Power (kWe)
% Backup Power Required (kWe)
% Emergency Power Required (kWe)

% This sizing code method was developed in cooperation with the
% MIT Mars2040 Study (2015) and uses information shared by Eric
% Ward, Nathan Bower & Chris McCormick.
% Sources:
% Larson WJ, Pranke LK, editors. Human Spaceflight: Mission Analysis and

% RobustMarsLat = input('Martian Latitude? (S* Represented as Negative
% Values) ');% CrewNum = input('Number of Crew Members? ');
% GHReq = input('Percentage of Food Grown? (0 - 100) ');

% Power Budget for Mars 2040 (Per Crewmember)
GreenHouse = GHReq * 0.68/20; %kWe
ECLSS = 0.44; %kWe
CrewHab = 4.14625; %kWe
Lighting = 0.125; %kWe
Freezers = 0.35; %kWe
Controls = 1; %kWe
Comms = 1; %kWe

PwrBudget = GreenHouse+ECLSS+CrewHab+Lighting+Freezers+Controls+Comms;
PwrBudgetTotal = PwrBudget * CrewNum;

% Waste Heat Calculation
Brayton_Eff = 0.25; %Percent
WasteHeat = 1-Brayton_Eff; %Percent

% Yearly Compound Requirements
CH4 = 3600; %kg/year (430W = .22kg CH4)
O2 = 4500; %kg/year
H2O = 225; %kg/year

% ISRU Requirements
ISRUatmos = (CH4*0.43)/0.22/365; %kWe
SoilH20Content = 8; %Percent
TotalH2O = H2O+0.25/0.111*CH4+(O2-2*CH4)/0.888; %kg
TotalH20pwr = TotalH2O*(3/SoilH20Content); %kWe
WasteHeatPwr = (PwrBudgetTotal+ISRUatmos)/WasteHeat; %kWth
NeedH20pwr = TotalH20pwr - WasteHeatPwr; %kW
ISRUsoil = NeedH20pwr*Brayton_Eff; %kWe
ISRUtotal = ISRUatmos + ISRUsoil; %kWe

%Thermal Requirements
Thermal = 0.023*(PwrBudgetTotal+ISRUtotal); %kWe

% Backup Power Required
BUperCrew =
GreenHouse+ECLSS+CrewHab+Lighting+Freezers+Controls+Comms+Thermal;
BackupTotal = BUperCrew * CrewNum;

% Emergency Power Required
EMERperCrew = ECLSS+Lighting+Freezers+Controls+Comms;
EmergencyTotal = EMERperCrew * CrewNum;

% Total System Power Required
Total_Power_Req = ISRUtotal + BackupTotal;

% % Backup Redundancy Calculation
% BUx2 = BackupTotal * 2;
% if (BUx2 < Total_Power_Req)
% RemPwr = Total_Power_Req - BUx2;
% else if (BUx2 > Total_Power_Req) % Redundant Backup Sufficient
% fprintf('\nTotal System Power Required is %4.2f kWe.\n',Total_Power_Req)
% fprintf('Backup Power Required is %4.2f kWe.\n',BackupTotal)
% fprintf('Emergency Power Required is %4.2f kWe.\n',EmergencyTotal)
% RemPwr = Total_Power_Req - BUx2;
% end
% Power_Req = RemPwr;
% [RxMass,RxVolume,RFCMass,RFCVol,BattMass,BattVol] =
MarsPower(Power_Req, MarsLat);
% if (RxMass < RFCMass) % Nuclear Dynamic
% fprintf('\nTotal System Power Required is %4.2f kWe.\n',Total_Power_Req)
% fprintf('Backup Power Required is %4.2f kWe.\n',BackupTotal)
% fprintf('Emergency Power Required is %4.2f kWe.\n',EmergencyTotal)
% fprintf('\nRemaining %4.2f kWe is Nuclear Brayton.\n',RemPwr)
% else if (RxMass > RFCMass) % Solar w/ RFC Storage
% RemPwr = Total_Power_Req - BUx2;
% end
% end

71
CrewVFoodPwr.m

% CrewVFoodPwr.m
% Script for Food Production vs Power Robustness Configuration
% Wilfredo.'Alex' Sanchez
% Created: 17 MAY 2015

clc
clear

rows = 10;
cols = 20;

CrewNum_values = linspace(0,20,rows);
GHReq_values = linspace(0,100,cols);

Total_Power_Req = zeros(rows, cols);
BackupTotal = zeros(rows, cols);
EmergencyTotal = zeros(rows, cols);

i = 1;
for crew = CrewNum_values
    j = 1;
    for grow = GHReq_values
        [Total_Power_Req(i,j),BackupTotal(i,j),EmergencyTotal(i,j)] = MPRobust(crew, grow);
        j = j + 1;
    end
    i = i + 1;
end

TPReq = Total_Power_Req(:,20);
BUTot = BackupTotal(:,20);
ETot = EmergencyTotal(:,20);

PowerGrid = [TPReq BUTot ETot];

% 3D Bar Graph of Power Output vs Food Production Percentage
figure (1)
plot(PowerGrid)
bar3(PowerGrid,'grouped')
title('Power Output vs. Food Growth Percentage for Crew Size of 20')
legend('Total Power','Backup Power','Emergency Power')
ylabel('Food Grown (%)')
new_yticks = (get(gca,'ytick')'*10);
set(gca,'yticklabel',new_yticks)
zlabel('Power Demand (kWe)')
function [RxMass,RxVolume,RFCMass,RFCVol,BattMass,BattVol] = MarsPower(Power_Req, MarsLat)

% MarsPower.m
% Brayton Reactor vs Solar Sizing
% Wilfredo 'Alex' Sanchez
% Created: 30 APR 2015
%
% INPUT:
% Power Required (kWe)
% Mars Latitude (°)
% OUTPUT:
% Reactor System Mass (kg)
% Reactor System Volume (m^3)
% Thin-Film Solar System w/ Regenerative Fuel Cell Storage Mass (kg)
% Thin-Film Solar System w/ Regenerative Fuel Cell Storage Volume (m^3)
% Thin-Film Solar System w/ Li-Ion Battery Storage Mass (kg)
% Thin-Film Solar System w/ Li-Ion Battery Storage Volume (m^3)
%
% Function to size Brayton nuclear reactor algorithm
% based on work developed by Courtney Rogge and Mike Kowalkowski
% Function to calculate solar power based on Martian latitude
% based on work developed by Chase Cooper and Wilfried Hofstetter
%
% Sources:
% Kerwin PT, Whitmarsh CL. A 1-Megawatt Reactor Design for
% Brayton-Cycle Space Power Application. Part 1 - Thermal
% Analysis and Core Design.; 1969. [17]
% Chang YI, LoPinto P, Konomura M, Cahalan J, Dunn F, Farmer M,
% Krajtl L, Moiseytysev A, Momozaki Y, Sienicki J, et al. Small
% Modular Fast Reactor design description. Argonne National Lab.,
% Argonne, IL (US); 2005. [36]
% Rogge C, Kowalkowski M. “Basic Reactor Fuel Mass and Volume Sizing,”
% Purdue University. Project Aquarius. Feb. 2007. [33],[32]
% Silver M, Hofstetter W, Cooper C, Hoffman J. Comparative Analysis
% of Power System Architectures: The Case of Human Mars Surface Missions.
% In: Mars: Prospective Energy and Material Resources. 2009. p. 351-368. [38]
% Cooper C, Hofstetter W, Hoffman JA, Crawley EF. Assessment of
% Architectural Options for Surface Power Generation and Energy

%Power_Req = input('Power Required (kWe)? ');
%MarsLat = input('Martian Latitude (°) Represented as Negative Values)? ');

% Rx CORE
Brayton_Eff = 0.25;
FuelDen = 0.96; % percent
UN_Energy = 65*(1000); % kW-days/kg
Rod_Number = 8;
Rod_Radius = 0.59*(1/100); % m
Neutron_Reflect_T = 0.1; % m
BeO_Thick = Neutron_Reflect_T/2; % m
B4C_Thick = Neutron_Reflect_T/2; % m

% MATERIAL DENSITIES
B4C_Den = 2.52*(1/1000)*(100)^3; % kg/m^3
BeO_Den = 3.0*(1/1000)*(100)^3; % kg/m^3
UN_Den = 11300*FuelDen; % kg/m^3
LiH_Den = 780; % kg/m^3
Tung_Den = 19.25*(1/1000)*(100)^3; % kg/m^3
Rod_Den = BeO_Den; % kg/m^3

% NUCLEAR Rx
Duration_Yrs = 10; % yrs
Duration = Duration_Yrs*365; % days
Rx_Eff = 0.98;
Power_Tot = Power_Req./Rx_Eff; % kW
Power_Thermal = Power_Tot./Brayton_Eff; % kW
FuelMass = Power_Thermal.*Duration./UN_Energy; % kg
FuelVolume = FuelMass./UN_Den; % m^3
FuelRadius = (FuelVolume./(2*pi))^(1/3); % m
FuelHeight = 2*FuelRadius; % m
FuelRadius_c = FuelRadius*100; % cm
FuelHeight_c = FuelHeight*100; % cm
Rod_Vol = Rod_Number*(pi*Rod_Radius^2*FuelHeight); % m^3
Rod_Mass = Rod_Vol*Rod_Den; % kg
Frame_Vol = FuelVolume + Rod_Vol; % m^3
Frame_Radius = sqrt(Frame_Vol./(pi*FuelHeight)); % m
Core_Radius = Frame_Radius + Neutron_Reflect_T; % m
Core_Height = FuelHeight + 2*Neutron_Reflect_T; % m
Core_Volume = pi.*Core_Radius.^2.*Core_Height; % m^3
B4C_Radius = Frame_Radius + B4C_T; % m
B4C_Volume = pi.*(B4C_Radius.^2 - Frame_Radius.^2).*FuelHeight... + 2.*(pi.*B4C_Radius.^2.*B4C_T); % m^3
B4C_Mass = B4C_Vol*B4C_Den; % kg
BeO_Volume = pi.*(Core_Radius.^2 - B4C_Radius.^2).*FuelHeight... + 2.*(pi.*Core_Radius.^2.*BeO_T); % m^3
BeO_Mass = BeO_Vol*BeO_Den; % kg
Neutron_Reflect_Mass = B4C_Mass + BeO_Mass; % kg
Core_Mass = FuelMass + Rod_Mass + Neutron_Reflect_Mass; % kg

% RADIATION SHIELDING
Li_Shield_T = 0.1; % m
Li_Shield_Vol = Li_Shield_T*1.1; % m
Li_Shield_Mass = Li_Shield_Vol*LiH_Den; % kg
ThermEff = Power_Tot./((0.24/100).*((Power_Tot-0)/Power_Tot)); % efficiency
Gamma_Radiation_Flux = (ThermEff/1000)*(2.3*10^3)/2.3/... (4*pi/(2*Li_Shield_T)^2)*3600*24*7; % rad / wk
Gamma_Reduction = Gamma_Radiation_Flux; % rad / wk
Tung_Shield_T = -8.12982207e-1*log(Gamma_Reduction); % cm
Tung_Shield_thick = Tung_Shield_T/100; % m
Tung_ShielVol = Tung_ShielThck.*(1/2.*(2.*CoreRadius).*1.25).^2*pi; %m^3
Tung_ShielMass = Tung_ShielVol.*Tung_Den; %kg
Shield_Mass = Tung_ShielMass + Li_ShielMass; %kg
Shield_Volume = Tung_ShielVol + Li_ShielVol; %m^3

% BRAYTON ENGINE
Mass_Brayton_1 = 41.973.*(PowerTot.^0.5832); %kg
Mass_Brayton_2 = 10.155.*(PowerTot.^-0.3719).*PowerTot; %kg
Mass_Brayton = (Mass_Brayton_1+Mass_Brayton_2)/2; %kg
Width_Brayton = 2/1000.*PowerTot.^0.88; %m
Height_Brayton = 2/1000.*PowerTot.^0.88; %m
Length_Brayton = 3/1000.*PowerTot.^0.88; %m
Volume_Brayton = Width_Brayton.*Height_Brayton.*Length_Brayton; %m^3

% RECOUPEPRATOR
Mass_Recoup_1 = 41.973*PowerTot.^0.5832; %kg/kWe
Mass_Recoup_2 = 17.236.*(PowerTot./0.24).^0.5566.*(PowerTot./0.24); %kg/kWth
Mass_Recoup = (2*Mass_Recoup_1 + Mass_Recoup_2)/3; %kg
Width_Recoup = Mass_Recoup/486.15; %m
Height_Recoup = Mass_Recoup/344.23; %m
Length_Recoup = Mass_Recoup/192.68; %m
Volume_Recoup = Width_Recoup.*Height_Recoup.*Length_Recoup; %m^3

% RADIATOR
% (100 kWe Design)
Rad_Mass100 = 720; %kg
Rad_Vol100 = 1.728; %m^3
Radiator_Mass = (PowerReq./100)*Rad_Mass100; %kg
Radiator_Volume = (PowerReq./100)*Rad_Vol100; %m^3

% REACTOR MASS & VOLUME
RxMass = (Radiator_Mass+Mass_Recoup+Mass_Brayton + Shield_Mass+Core_Mass)*3; %kg
RxVolume = (Radiator_Volume+Volume_Recoup+Volume_Brayton + Shield_Volume+Core_Volume)*3; %m^3

% SOLAR POWER VS MARS LATITUDE
MarsLatT = [-60 -55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40 45 50 55 60];
%Solar w/ Lithium-Ion Battery Storage - Mass Specific Power (W/kg)  
%Solar w/ Lithium-Ion Battery Storage - Volume Specific Power (W/m^3)  

% SPECIFIC POWER INTERPOLATION  
RxMassSP = (Power Req.*1000)/RxMass; %W/kg  
RxVolSP = (Power Req.*1000)/RxVolume; %W/m^3  
RFCMassSP = interpl(MarsLatT,RFCMassT,MarsLat); %W/kg  
RFCVolSP = interpl(MarsLatT,RFCVolT,MarsLat); %W/m^3  
BattMassSP = interpl(MarsLatT,BattMassT,MarsLat); %W/kg  
BattVolSP = interpl(MarsLatT,BattVolT,MarsLat); %W/m^3  

% SOLAR MASS & VOLUME  
RFCMass = (Power Req.*1000./RFCMassSP; %kg  
RFCVol = (Power Req.*1000./RFCVolSP; %m^3  
BattMass = (Power Req.*1000./BattMassSP; %kg  
BattVol = (Power Req.*1000./BattVolSP; %m^3  

% OUTPUT DISPLAY  
fprintf('TOTAL MASS & VOLUME')  
fprintf('------------------------------')  
fprintf('Reactor Mass is %4.2f kg.
',RxMass)  
fprintf('Reactor Volume is %4.2f m^3.
',RxVolume)  
fprintf('Solar-RFC Mass is %4.2f W/kg.
',RFCMass)  
fprintf('Solar-RFC Volume is %4.2f W/m^3.
',RFCVol)  
fprintf('Solar-Batt Mass is %4.2f kg.
',BattMass)  
fprintf('Solar-Batt Volume is %4.2f m^3.
',BattVol)  

fprintf('SPECIFIC POWER')  
fprintf('------------------------------')  
fprintf('Reactor Mass SP is %4.2f W/kg.
',RxMassSP)  
fprintf('Reactor Volume SP is %4.2f W/m^3.
',RxVolSP)  
fprintf('Solar-RFC Mass SP is %4.2f W/kg.
',RFCMassSP)  
fprintf('Solar-RFC Volume SP is %4.2f W/m^3.
',RFCVolSP)  
fprintf('Solar-Batt Mass SP is %4.2f W/kg.
',BattMassSP)  
fprintf('Solar-Batt Volume SP is %4.2f W/m^3.
',BattVolSP)  
end
AllLatitudes.m

% AllLatitudes.m
% Script for Brayton Reactor vs Solar Sizing Chart for All Latitudes
% Wilfredo 'Alex' Sanchez
% Created: 30 APR 2015

clc
clear

rows = 40;
cols = 40;

power_values = linspace(0,250,rows);
marslat_values = linspace(-60,60,cols);

RxMass = zeros(rows, cols);
RxVolume = zeros(rows, cols);
RFCMass = zeros(rows, cols);
RFCVol = zeros(rows, cols);
BattMass = zeros(rows, cols);
BattVol = zeros(rows, cols);

i = 1;
for power = power_values
    j = 1;
    for marslat = marslat_values
        [RxMass(i,j),RxVolume(i,j),RFCMass(i,j),RFCVol(i,j),BattMass(i,j),BattVol(i,j)] = MarsPower(power,marslat);
        j = j + 1;
    end
    i = i + 1;
end

% Superimposed 3D Graph of (RxMass/BattMass) v POWER
figure(1)
mesh(marslat_values, power_values, RxMass)
hold on
surf(marslat_values, power_values, BattMass)
hold off
title('System Mass vs. Power Output across Martian Latitudes (Nuclear Brayton & Solar w/ Li-Ion Energy Storage)')
legend('Nuclear Brayton','Solar+Li-Ion')
xlabel('Latitude (deg)')
ylabel('Power Output (kWe)')
zlabel('Mass (kg)')

% Superimposed 3D Graph of (RxMass/BattMass) v POWER
figure(2)
mesh(marslat_values, power_values, RxMass)
hold on
surf(marslat_values, power_values, RFCMass);
hold off


legend('Nuclear Brayton', 'Solar+RFC')

xlabel('Latitude (deg)')

ylabel('Power Output (kWe)')

zlabel('Mass (kg)')
ProjectSitesMass.m

% ProjectSitesMass.m
% Script for Mass Chart for All Project Sites
% Wilfredo 'Alex' Sanchez
% Created: 30 APR 2015

clc
clear

rows = 40;
cols = 40;

power_values = linspace(0,800,rows);
marslat_values = linspace(-60,60,cols);

PlotLat = (cols/120); %.33

RxMass = zeros(rows, cols);
RxVolume = zeros(rows, cols);
RFCMass = zeros(rows, cols);
RFCVol = zeros(rows, cols);
BattMass = zeros(rows, cols);
BattVol = zeros(rows, cols);

i = 1;
for power = power_values
    j = 1;
    for marslat = marslat_values
        [RxMass(i,j),RxVolume(i,j),RFCMass(i,j),RFCVol(i,j),BattMass(i,j),BattVol(i,j)] = MarsPower(power,marslat);
        j = j + 1;
    end
    i = i + 1;
end

% Utopia Planitia (46.7°N 117.5°E)
UP = (60+46.7)*PlotLat;
UPLat = round(UP);

% Mawrth Vallis (22.6°N 16.5°W)
MV = (60+22.6)*PlotLat;
MVLat = round(MV);

% Gale Crater (5.4°S 137.8°E)
GaC = (60-5.4)*PlotLat;
GaCLat = round(GaC);

% Gusev Crater (14.5°S 175.4°E)
GuC = (60-14.5)*PlotLat;
GuCLat = round(GuC);

% Holden Crater (26.4°S 34.0°W)
HC = (60-26.4)*PlotLat;
HCLat = round(HC);

% Hellas Planitia (42.4°S 70.5°E)
HP = (60-42.4)*PlotLat;
HPLat = round(HP);

% SLS 130T Payload Fairing Volume to Mars
% plot([0 2500],[443.34 443.34],'k*'); % 443.34 m^3

% Power Output vs Mass for All Locations
figure(1)
plot([0 2500],[45000 45000],',k-.','LineWidth',2);
hold on
title('Power Output vs Mass')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 800 0 50000])
plot(power_values, RxMass(:, UPLat),'r-','LineWidth',2)
plot(power_values, BattMass(:, UPLat),'g--','LineWidth',2)
plot(power_values, RFCMass(:, MVLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, MVLat),'g--','LineWidth',2)
plot(power_values, RFCMass(:, GaCLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, GaCLat),'g--','LineWidth',2)
plot(power_values, RFCMass(:, GuCLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, GuCLat),'g--','LineWidth',2)
plot(power_values, RFCMass(:, HCLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, HCLat),'g--','LineWidth',2)
plot(power_values, RFCMass(:, HPLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, HPLat),'g--','LineWidth',2)
hold off
legend('Payload Fairing','Nuclear Brayton','Solar+RFC','Solar+Li-Ion')
ProjectSitesVolume.m

% ProjectSitesVolume.m
% Script for Volume Chart for All Project Sites
% Wilfredo 'Alex' Sanchez
% Created: 30 APR 2015

clc
clear
rows = 40;
cols = 40;

power_values = linspace(0,2500,rows);
marslat_values = linspace(-60,60,cols);

PlotLat = (cols/120); % .33

RxMass = zeros(rows, cols);
RxVolume = zeros(rows, cols);
RFCMass = zeros(rows, cols);
RFCVol = zeros(rows, cols);
BattMass = zeros(rows, cols);
BattVol = zeros(rows, cols);
i = 1;
for power = power_values
    for marslat = marslat_values
        [RxMass(i,j),RxVolume(i,j),RFCMass(i,j),RFCVol(i,j),BattMass(i,j),BattVol(i,j)] = MarsPower(power,marslat);
        j = j + 1;
    end
    i = i + 1;
end

% Utopia Planetia (46.7°N 117.5°E)
UP = (60+46.7)*PlotLat;
UPLat = round(UP);
% Mawrth Vallis (22.6°N 16.5°W)
MV = (60+22.6)*PlotLat;
MVLat = round(MV);
% Gale Crater (5.4°S 137.8°E)
GaC = (60-5.4)*PlotLat;
GaCLat = round(GaC);
% Gusev Crater (14.5°S 175.4°E)
GuC = (60-14.5)*PlotLat;
GuCLat = round(GuC);
% Holden Crater (26.4°S 34.0°W)
HC = (60-26.4)*PlotLat;
HCLat = round(HC);
% Hellas Planitia (42.4°S 70.5°E)
\[
\text{HP} = (60-42.4) \times \text{PlotLat}; \\
\text{HPLat} = \text{round} (\text{HP}); \\
\]

% SLS 130T Payload Fairing Volume to Mars 
% plot([0 2500],[443.34 443.34],'k*'); % 443.34 m³

% Power Output vs Mass for All Locations 
figure(1) 
plot([0 2500],[443.34 443.34],'k-.','LineWidth',2); 
hold on 
title('Power Output vs Volume') 
xlabel('Power Output (kWe)') 
ylabel('Volume (m³)') 
axis([0 2500 0 3000]) 
plot([705.1,705.1],[346.8,346.8],'k.','MarkerSize',15); 
text(750,300,'Mawrth Vallis') 
hold off 

legend('Payload Fairing','Nuclear Brayton','Solar+RFC','Solar+Li-Ion')
MawrthVallisMass.m

% MawrthVallisMass.m
% Script for Mass Chart for Mawrth Vallis
% Wilfredo 'Alex' Sanchez
% Created: 30 APR 2015

clc
clear

rows = 40;
cols = 40;

power_values = linspace(0,250,rows);
marslat_values = linspace(-60,60,cols);

PlotLat = (cols/120); % .33

RxMass = zeros(rows, cols);
RxVolume = zeros(rows, cols);
RFCMass = zeros(rows, cols);
RFCVol = zeros(rows, cols);
BattMass = zeros(rows, cols);
BattVol = zeros(rows, cols);

i = 1;
for power = power_values
    j = 1;
    for marslat = marslat_values

        [RxMass(i,j),RxVolume(i,j),RFCMass(i,j),RFCVol(i,j),BattMass(i,j),BattVol(i,j)]] = MarsPower(power,marslat);
        j = j + 1;
    end
    i = i + 1;
end

% Utopia Planetia (46.7°N 117.5°E)
UP = (60+46.7)*PlotLat;
UPLat = round(UP);
figure(1)
plot(power_values, RxMass(:, UPLat),'r-', 'LineWidth', 2)
hold on
title('Utopia Planitia (46.7°N 117.5°E)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 250 0 20000])
plot(power_values, RFCMass(:, UPLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, UPLat),'g--','LineWidth',2)
hold off
legend('Nuclear Brayton','Solar+RFC','Solar+Li-Ion')

% Mawrth Vallis (22.6°N 16.5°W)
MV = (60+22.6)*PlotLat;
MVLat = round(MV);
figure(2)
plot(power_values, RxMass(:, MVLat),'r-','LineWidth',2)
hold on
title('Power Output vs Mass at Mawrth Vallis (22.6°N 16.5°W)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 250 0 20000])
plot(power_values, RFCMass(:, MVLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, MVLat),'g--','LineWidth',2)
hold off
legend('Nuclear Brayton','Solar+RFC','Solar+Li-Ion')

GaC = (60-5.4)*PlotLat;
GaCLat = round(GaC);
figure(3)
plot(power_values, RxMass(:, GaCLat),'r-','LineWidth',2)
hold on
title('Gale Crater (5.4°S 137.8°E)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 250 0 20000])
plot(power_values, RFCMass(:, GaCLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, GaCLat),'g--','LineWidth',2)
hold off
legend('Nuclear Brayton','Solar+RFC','Solar+Li-Ion')

GuC = (60-14.5)*PlotLat;
GuCLat = round(GuC);
figure(4)
plot(power_values, RxMass(:, GuCLat),'r-','LineWidth',2)
hold on
title('Gusev Crater (14.5°S 175.4°E)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 250 0 20000])
plot(power_values, RFCMass(:, GuCLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, GuCLat),'g--','LineWidth',2)
hold off
legend('Nuclear Brayton','Solar+RFC','Solar+Li-Ion')

HC = (60-26.4)*PlotLat;
HCLat = round(HC);
figure(5)
plot(power_values, RxMass(:, HCLat),'r-','LineWidth',2)
hold on
title('Holden Crater (26.4°S 34.0°W)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 250 0 20000])
plot(power_values, RFCMass(:, HCLat),'b:','LineWidth',2)
plot(power_values, BattMass(:, HCLat),'g--','LineWidth',2)
% hold off
% legend('Nuclear Brayton','Solar+RFC','Solar+Li-Ion')
%
% % Hellas Planitia (42.4°S 70.5°E)
% HP = (60-42.4)*PlotLat;
% HPLat = round(HP);
% figure(6)
% plot(power_values, RxMass(:, HPLat),'r-','LineWidth',2)
% hold on
% title('Hellas Planitia (42.4°S 70.5°E)')
% xlabel('Power Output (kWe)')
% ylabel('Mass (kg)')
% axis([0 250 0 20000])
% plot(power_values, RFCMass(:, HPLat),'b:','LineWidth',2)
% plot(power_values, BattMass(:, HPLat),'g--','LineWidth',2)
% hold off
% legend('Nuclear Brayton','Solar+RFC','Solar+Li-Ion')
% MawrthVallisVolume.m
% Script for Volume Chart for Mawrth Vallis
% Wilfredo 'Alex' Sanchez
% Created: 30 APR 2015

clc
clear

rows = 40;
cols = 40;

power_values = linspace(0,2500,rows);
marslat_values = linspace(-60,60,cols);

PlotLat = (cols/120); %.33

RxMass = zeros(rows, cols);
RxVolume = zeros(rows, cols);
RFCMass = zeros(rows, cols);
RFCVol = zeros(rows, cols);
BattMass = zeros(rows, cols);
BattVol = zeros(rows, cols);

i = 1;
for power = power_values
    j = 1;
    for marslat = marslat_values
        [RxMass(i,j),RxVolume(i,j),RFCMass(i,j),RFCVol(i,j),BattMass(i,j),BattVol(i,j)] = MarsPower(power,marslat);
    
        j = j + 1;
    end
        i = i + 1;
end

% % Utopia Planitia (46.7°N 117.5°E)
% UP = (60+46.7)*PlotLat;
% UPLat = round(UP);
% figure(1)
% plot(power_values, RxVolume(:,UPLat),'r-','LineWidth',2)
% hold on
% title('Power Output vs Mass')
% xlabel('Power Output (kWe)')
% ylabel('Volume (m^3)')
% axis([0 2500 0 3000])
% plot(power_values, RFCVol(:,UPLat),'b-','LineWidth',2)
% plot(power_values, BattVol(:,UPLat),'g-','LineWidth',2)
% hold off
% legend('Nuclear Brayton','Solar+RFC','Solar+Li-Ion')
% % Mawrth Vallis (22.6°N 16.5°W)
MV = (60+22.6)*PlotLat;
MVLat = round(MV);

figure(2)
plot([0 2500], [443.34 443.34], 'k--', 'LineWidth', 2);
hold on
title('Power Output vs Volume at Mawrth Vallis (22.6°N 16.5°W)')
xlabel('Power Output (kWe)')
ylabel('Volume (m^3)')
axis([600 800 300 460])
plot(power_values, RxVolume(:, MVLat), 'r-', 'LineWidth', 2)
plot(power_values, RFCVol(:, MVLat), 'b:', 'LineWidth', 2)
plot(power_values, BattVol(:, MVLat), 'g--', 'LineWidth', 2)
hold off

GaC = (60-5.4)*PlotLat;
GaCLat = round(GaC);
figure(3)
plot(power_values, RxMass(:, GaCLat), 'r-', 'LineWidth', 2)
hold on
title('Gale Crater (5.4°S 137.8°E)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 2500 0 3000])
plot(power_values, RFCMass(:, GaCLat), 'b:', 'LineWidth', 2)
plot(power_values, BattMass(:, GaCLat), 'g--', 'LineWidth', 2)
hold off
legend('Nuclear Brayton', 'Solar+RFC', 'Solar+Li-Ion')

GuC = (60-14.5)*PlotLat;
GuCLat = round(GuC);
figure(4)
plot(power_values, RxMass(:, GuCLat), 'r-', 'LineWidth', 2)
hold on
title('Gusev Crater (14.5°S 175.4°E)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 2500 0 3000])
plot(power_values, RFCMass(:, GuCLat), 'b:', 'LineWidth', 2)
plot(power_values, BattMass(:, GuCLat), 'g--', 'LineWidth', 2)
hold off
legend('Nuclear Brayton', 'Solar+RFC', 'Solar+Li-Ion')

HC = (60-26.4)*PlotLat;
HCLat = round(HC);
figure(5)
plot(power_values, RxMass(:, HCLat), 'r-', 'LineWidth', 2)
hold on
title('Holden Crater (26.4°S 34.0°W)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 2500 0 3000])
plot(power_values, RFCMass(:, HCLat), 'b:', 'LineWidth', 2)
plot(power_values, BattMass(:, HCLat), 'g--', 'LineWidth', 2)
hold off
legend('Nuclear Brayton', 'Solar+RFC', 'Solar+Li-Ion')
% axis([0 2500 0 3000])
% plot(power_values, RFCMass(:, HCLat), 'b:', 'LineWidth', 2)
% plot(power_values, BattMass(:, HCLat), 'g--', 'LineWidth', 2)
% hold off
% legend('Nuclear Brayton', 'Solar+RFC', 'Solar+Li-Ion')

% Hellas Planitia (42.4°S 70.5°E)
HP = (60-42.4)*PlotLat;
HPLat = round(HP);
figure(6)
plot(power_values, RxMass(:, HPLat), 'r-', 'LineWidth', 2)
hold on
title('Hellas Planitia (42.4°S 70.5°E)')
xlabel('Power Output (kWe)')
ylabel('Mass (kg)')
axis([0 2500 0 3000])
plot(power_values, RFCMass(:, HPLat), 'b:', 'LineWidth', 2)
plot(power_values, BattMass(:, HPLat), 'g--', 'LineWidth', 2)
hold off
legend('Nuclear Brayton', 'Solar+RFC', 'Solar+Li-Ion')