

# **Definition, Expansion and Screening of Architectures for Planetary Exploration Class Nuclear Electric Propulsion and Power Systems**

by

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Submitted to the System Design and Management Program  
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## **ABSTRACT**

This work applies a structured approach to architectural definition, expansion and screening of Nuclear Electric Propulsion and Power concepts capable of achieving planetary exploration class science missions. Problem definition is first achieved through the completion of domain identification, functional decompositions, determining interdependencies and mapping the functions to the general design form. The thesis then adapts an architectural framework that allows the introduction of a spectrum of architectural influences and further defines top-level goals and objectives. Concepts are described by functional elements and the associated concept combination matrices are generated by first level function. In order to resolve complexity, this analysis distinguishes between what are pivotal elements of the architecture and what are only design attributes. The most influential architectural concept elements form the basis for inclusion in the concept combination matrices. Reductions in concepts are first achieved through a filtering of the individual subsystem element combination matrices using the results of the architectural framework analysis and defined objectives and goals. Concept screening is then accomplished through the development of screening criteria and application of the criteria to a relative concept scoring matrix that rates the remaining system level concepts. The highest scoring concept combinations are identified for further quantitative study and potential technology investment. Applicability of the results is discussed for the formulation of a multidisciplinary design problem that can be further investigated when detailed subsystem models are developed.

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Finally, I would like to thank my parents Karl and Judy, children Melanie and Abigail, and wife Beth for sharing their lives and establishing the most valuable of life's architectural frameworks.

## Abbreviations and Acronyms

BRU	Brayton Rotating Unit
CBC	Closed Brayton Cycle
COPUOS	Committee on the Peaceful Uses of Outer Space
CTPC	Component Test Power Converter
DOD	Department of Defense
DOE	Department of Energy
DSM	Design Structure Matrix
EELV	Evolved Expendable Launch Vehicle
EP	Electric Propulsion
FPS	Free Piston Stirling
GEO	Geosynchronous Orbit
ISS	International Space Station
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
LFA	Lorentz Force Accelerator
MPD	Magnetoplasmadynamic Thruster
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NEPP	Nuclear Electric Propulsion and Power
NERVA	Nuclear Engine for Rocket Vehicle Applications
NTR	Nuclear Thermal Rocket
OMB	Office of Management and Budget
PPT	Pulsed Plasma Thruster
PPU	Power Processing Unit
REP	Radioisotope Electric Propulsion
RTG	Radioisotope Thermoelectric Generator
S/C	Spacecraft
SEI	Space Exploration Initiative
SEP	Solar Electric Propulsion
SNAP	Space Nuclear Auxiliary Power
SP-100	Space Power 100
SPAR	Space Power Advanced Reactor
SPDE	Space Power Development Engine
STAR-C	Space Thermionic Advanced Reactor-Compact
TE	Thermoelectric
TEM	Thermoelectric Electro Magnetic
TFE	Thermionic Fuel Elements
TPV	Thermophotovoltaic
TRL	Technology Readiness Level
USAF	United States Air Force
VVEJGA	Venus-Venus-Earth-Jupiter Gravity Assist

## Nomenclature

AU	Astronomical Unit equaling 149,597,870.691 km; the average distance from the Earth to the Sun
Delta V ( $\Delta V$ )	Change in velocity, or delta-V, in m/sec is a measure of energy required to change position in space.
$I_{sp}$	Specific impulse in seconds
Z value	Figure of merit for thermoelectric devices expressed in a ratio per degree Kelvin

## Definitions

**Architecture** is the selection and arrangement of the concept elements that address the goals, technical requirements, economic and policy influences and ultimately the needs of the customers and stakeholders.

**Dynamic Mission Planning** can be defined as the ability to change target science destinations throughout the mission execution phase as the result of new information or opportunities not previously accounted for during initial mission planning.

**Planetary Mission Class** is defined as a set of robotic exploration missions within the solar system that range from near solar to Kuiper Belt object observation.

**The Kuiper Belt** is a disk-shaped region past the orbit of Neptune approximately 30 to 100 AU from the Sun containing many small icy bodies. It is now considered to be the source of the short-period comets.

**Specific Mass** is the ratio of power system mass to power produced measured in kg/kW.

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# 1.0 Introduction

## 1.1 Science and Mission Basis

The vast nature of space and the fundamental human need to explore beyond the Earth's atmosphere provide the impetus to formulate advanced system architectures capable of returning a greater understanding of the solar system. To achieve this greater capability requires drawing upon the inimitable properties of nuclear power in order to travel to and learn what cannot be observed from the Earth or near Earth platforms. The Space Act of 1958, which established the National Aeronautics and Space Administration (NASA) as a Federal Agency, provides a broad spectrum of purpose and responsibility for the Agency. The current NASA vision is as follows:

- To improve life here, To extend life to there, To find life beyond

Correspondingly the current NASA mission is:

- To understand and protect our home planet
- To explore the Universe and search for life
- To inspire the next generation of explorers

...as only NASA can

Within NASA, the Office of Space Science is chartered with understanding the fundamental aspects of the evolution of the universe with a comprehensive understanding of its galaxies, stars, planets and life. The current mission of NASA's Office of Space Science is to seek the answers to three fundamental questions:<sup>1</sup>

- How did the Universe begin and evolve?

- How did we get here?
- Are we alone?

The Space Science Strategic Plan outlines the long-term goals, near term objectives and proposed strategies that address these challenges. NASA must consolidate the results and recommendations from many external organizations including the National Research Council, The Planetary Society, universities, Congress, the international science community and others in order to proceed with specific missions targeted at achieving the science goals.

As the missions become more challenging NASA must also develop the enabling technologies that make them possible. For planetary class exploration, Nuclear Electric Propulsion and Power (NEPP) systems offer capabilities that can make missions possible that are not possible today and can significantly enhance the scientific return of all other planetary missions. Increased power allows for new levels of science by providing higher levels of power for instruments and high bandwidth communications, allowing sufficient time to conduct experiments, providing access to areas previously not possible, enabling mobility at destinations and providing a resiliency for sustained operations. The use of nuclear electric propulsion can also decrease the time it takes for spacecraft to travel to the outer planets in addition to enabling multiple destinations, orbital change maneuvers and dynamic mission planning. Although the potential space applications for NEPP are vast, a pragmatic progressive approach that begins with planetary exploration, before moving to human missions, offers significant scientific returns for the investment and can potentially be leveraged for numerous future space applications.

## 1.2 Definition and Purpose

This document seeks to establish a promising set of NEPP candidate architectures for future detailed concept definition and technology investment efforts. Although the United States has only flown one nuclear reactor in space, a significant amount of work has been completed on nuclear technologies and space power systems since the 1950s although, as a matter of national policy<sup>i</sup>, very limited efforts have occurred over the last decade. Previous space nuclear efforts and planning activities have spanned a broad range of technologies and missions including Nuclear Thermal Rockets (NTR), multi-megawatt systems, multi-use platforms and interplanetary human missions. Over time an appreciable amount of concept designs, component testing and subsystem development for NEPP and other non-nuclear related space power and propulsion systems has been amassed. This activity will build upon previous efforts but will focus solely on planetary exploration class missions in the power range of 75 to 250 kW that can be achieved within ten to twelve years. This power range is based on previous and current NASA studies for planetary science missions. This requires a balanced approach to meeting mission requirements, assessing current capabilities and developing useful methods of concept selection. Additionally, the candidate architectural set must provide a viable pathway to a sustainable NEPP capability for NASA without either succumbing to near term flight gratification for political gains, which may compromise long-term objectives,

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<sup>i</sup> Although the Bush Administration's 1992 National Space Policy Directive (NSPD-6), Titled, Space Exploration Initiative, stated, "NASA, DOD, and DOE shall continue technology development for space nuclear power and propulsion..." Congress did not support the proposed initiative and insufficient funds were available in existing budgets for reactor development. Further, under the 1996 Clinton Administration, Presidential Decision Directive/ National Science and Technology Council (PDD/NSTC-8) doctrine, Titled, National Space Policy, stated, "The Department of Energy will maintain the necessary capability to support space missions which may require the use of space nuclear power systems..." however, the policy set by OMB and the Administration focused funding on RTG efforts.

or being so focused on future growth that the immensity of the challenge and diffused mission objectives cause the program to fail under its own design. Further, primary system goals and objectives must be focused on performance from a science and customer perspective rather than solely on a series of technical specifications constructed on the basis of creating a high performance NEPP system alone.

## **2.0 Problem Description and Background**

### **2.1 Planetary Exploration Challenges**

#### **2.1.1 Available Power**

Power availability challenges are inherent to space exploration. Table 1 illustrates planetary distances in Astronomical Units (AU) and the corresponding solar intensity in terms of the solar constant and incident energy in  $\text{mW}/\text{cm}^2$ . The fractional amount of total solar flux available makes solar power systems, such as photovoltaic or solar dynamic, impractical for outer planet missions. Additionally, performing missions in protracted shadowed environments or polar missions of planets nearer to the Earth also make such systems impractical due to energy generation and storage limitations. Planetary exploration scenarios also must consider environments that are clouded and contain high natural radiation environments that further preclude the use of solar power systems. Radiation damage in solar cell devices occur when neutrons or charged particles (electrons, protons, ions) collide with the atomic nuclei and electrons in the device material. The collisions cause ionization, where electrons are removed, and atomic displacement, where atoms are displaced from their lattice structure, which collectively degrade both the voltage and current characteristics of the cell.

**Table 1: Planetary Distances and Solar Intensities<sup>2</sup>**

<b>Planet</b>	<b>Astronomical Units</b>	<b>Solar Constant</b>	<b>Incident Energy (mW/cm<sup>2</sup>)</b>
Mercury	0.39	6.6735	902.900
Venus	0.72	1.9113	258.600
Earth	1.00	1.0000	135.300
Mars	1.52	0.4300	58.280
Jupiter	5.20	0.0369	4.999
Saturn	9.54	0.0109	1.487
Uranus	19.18	0.0027	0.368
Neptune	30.07	0.0011	0.149
Pluto	39.44	0.0006	0.087

Power is necessary for advanced scientific investigations and to date has been limited to tens to hundreds of Watts. Allowing scientific payloads to move from hundreds to thousands of Watts provides for active experimentation in addition to enhanced passive observation. This includes new suites of radar experiments, advanced spectrometry, multi-spectral imaging, increased temporal resolution and the ability to provide high data rate communications. NEPP systems offer significantly higher power levels for science, provide the ability to operate in a variety of hostile planetary environments and generate power independent of solar distance.

### **2.1.2 Propulsion Requirements**

Issues relating to propulsion include the ability of delivering increased payloads to greater distances, reducing the time required to deliver the payload, flexibility in launching independent of planetary alignments, performing orbital maneuvers at the destination and enabling multiple destinations. It should be noted that NEPP systems are still dependent on chemical stages to achieve Earth orbit from which they depart. Presently, total chemical systems only have enough propulsive energy to achieve a flyby

or “snapshot” on outer planetary missions rather than an orbital opportunity in which detailed studies could be undertaken over a longer period of time.

Reaching the outer planets and beyond takes tremendous amounts of propulsive energy and requires planetary launch assists to accomplish chemical only missions. For example, the Galileo mission used gravity assists from Venus and Earth to gain enough momentum to travel to Jupiter. As a result, Galileo spent the first three years of its journey making flybys of Venus and Earth before it was ready to swing outward toward Jupiter. Cassini is currently on a similar tour of the solar system, on its way to Saturn, and is using a VVEJGA (Venus-Venus-Earth-Jupiter Gravity Assist) trajectory. Planetary assists are essentially auxiliary propulsion. They take time, are directly coupled to the ability to perform the mission and consequently can become a significant launch constraint when planning outer planetary missions. Although the use of planetary gravity assists is not necessary with NEPP they could be used, if desired, to augment NEPP mission trajectory designs.

Increasing the efficiency of the propulsion system is directly related to increased payloads. Developing NEPP systems with low weight to power ratios, or specific mass, will result in increased payloads over that of current chemical systems for planetary missions. NEPP systems also provide acceleration over a large part of the mission trajectory that results in higher velocities. As mission distance increases, the trip time may decrease relative to chemical missions due to the increased velocities achieved.

One of the most demanding requirements is for orbital maneuvers at the destination or having capability to move from one destination to another. Orbital mission flexibility at the destination allows for plane, altitude and eccentricity changes that enable

a variety of scientific capabilities. Maneuvering at a planetary destination would make possible the study of both equatorial and polar regions and would allow a spacecraft to move about a ring system. Multiple destinations, for example, could be moving from one moon to another within the Jovian system or moving among objects within the Kuiper Belt. Having both sufficient power available from the reactor and employing efficient propellant usage, through electric propulsion systems with high specific impulse, will allow mission planners to begin addressing these challenging propulsion requirements.

### **2.1.3 Energy, Power, Mass and Time**

The following figure is a classic representation found in many nuclear space reference materials that broadly depicts the capability of different space power systems to address both power and mission duration requirements. The region of interest in the 75-250 kW ranges for planetary travel durations is highlighted in Figure 1. Although solar energy is depicted in several regions in Figure 1, its applicability is significantly diminished as a result of the incident energy available (Table 1). This will result in the downward movement of the overall solar curve as the figure is applied to increasing distances from the sun.

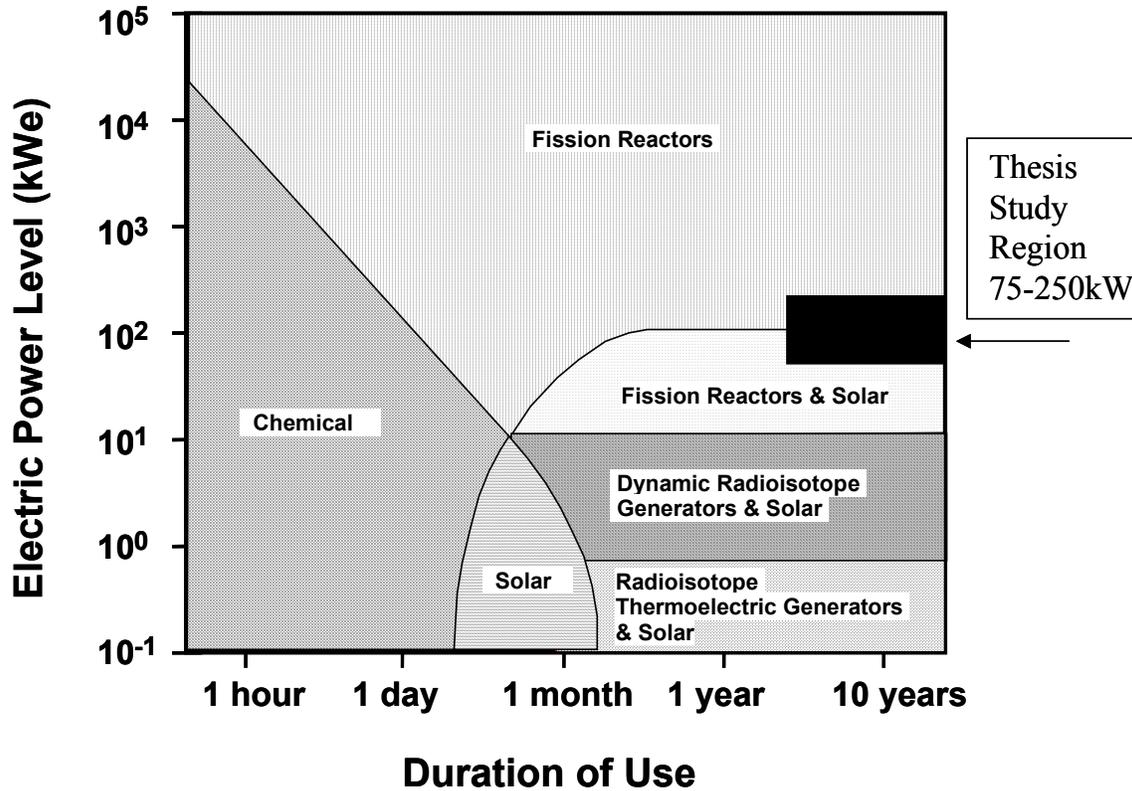


Figure 1: Power Level and Duration Mapping for Various Space Power Systems

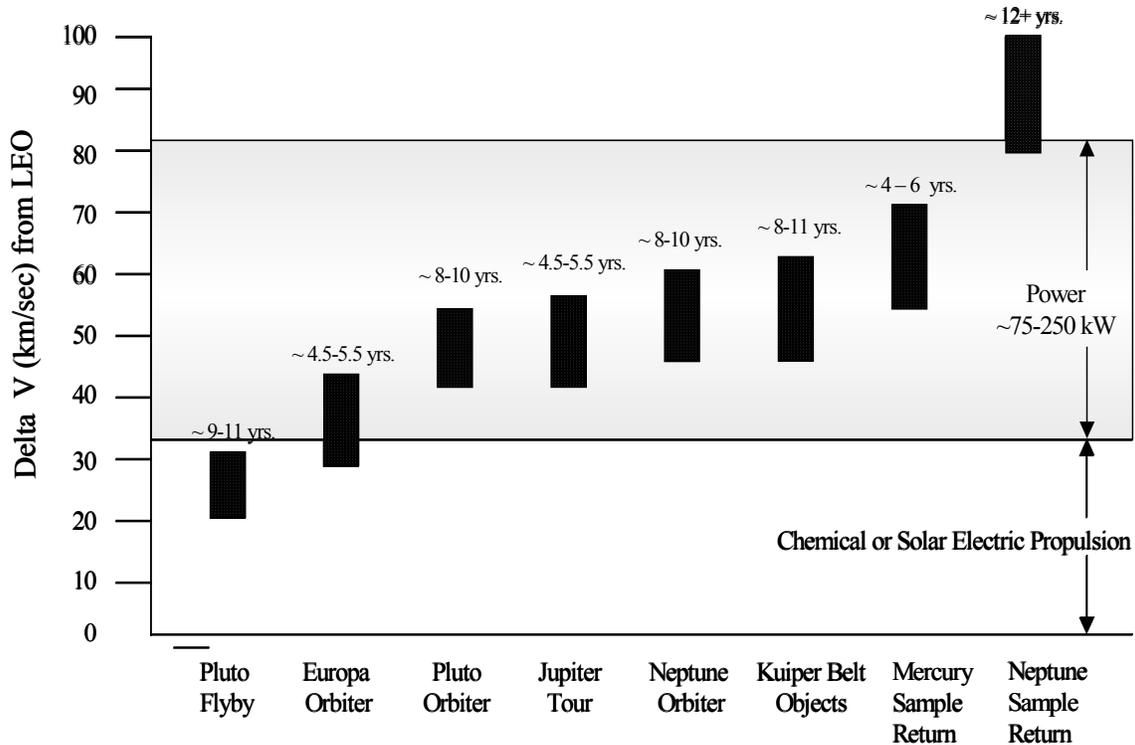
### 2.1.4 Potential Missions for Nuclear Electric Propulsion

Many different mission specific scenarios have been developed assuming the use of NEPP that illustrate the advantages of NEPP over alternative propulsion and power concepts. Outer planet exploration (orbiting vs. flyby snapshots), touring multiple planetary moons or planetary objects and sample return missions clearly benefit from this capability. Inner planet science missions could also be significantly enhanced with both the increased power available at the destination and the potential for sample return using the available propulsion. Example missions considered include:

- Europa Orbiter
- Neptune Triton Orbiter/Trans-Neptunian Explorer

- Titan Explorer
- Multiple Kuiper Belt Objects Rendezvous
- Uranus Orbiter/Probe
- Jupiter Grand Tour of Moons
- Pluto/Charon Orbiter/Probe
- Mercury Sample Return
- Europa Sample Return
- Titan Sample Return
- Multiple Asteroid Sample Return
- Comet Nucleus Sample Return
- Trojan asteroids and Centaur minor planets
- High power Mars Orbiter

Figure 2 provides approximate ranges of delta V, power level, and trip times associated with a few example NEPP missions. There are many factors such as planetary location, payload mass, launch vehicle capability and NEPP performance that will impact these ranges. For comparison two example missions are provided that fall both below and above the thesis study range.



**Figure 2: Example Missions, Delta V, Time and Power Approximations**

## 2.2 Architectural Challenges

NEPP systems are complex and can be considered highly multidisciplinary in nature. Disciplines range from the technical aspects of space nuclear reactors, power conversion, heat rejection, power electronics, electric propulsion and mission design to formidable safety, launch approval and political issues. It is essential that clear goals, functional domains, functions and architectural influences are identified before expanding and reducing the candidate sets. Identifying the most influential constituent components of the concept sets is a critical step to resolving the intricacies and interdependencies that drive the reduced sets and ultimately the final architecture. Concurrently, the process of simplifying the inherent complexity and ambiguity that exists in NEPP systems is paramount in satisfying technical, communicative, organizational and political objectives.

## 2.3 Fundamentals of Nuclear Electric Propulsion

A nuclear electric propulsion system uses nuclear fission to generate heat that is then converted into electricity to power an electric thruster. NEPP systems are characterized as low thrust, high specific impulse systems ( $I_{sp} > 1000$  sec) as compared to high thrust less efficient systems such as nuclear thermal or chemical propulsion. Electric propulsion systems accelerate a gas to very high exhaust velocities and can be used with solar or nuclear (e.g. isotope or reactor) based power systems. Combining the high power densities of nuclear reactors with the efficiencies of electric propulsion yields notable system advantages over chemical missions for interplanetary distances.

A nuclear reactor is used to contain, sustain and control a fission reaction. International space law requires that only uranium-based fuels be used in space nuclear reactors. Energy is released when  ${}_{92}\text{U}^{235}$  is split or fissioned upon absorbing neutrons. A fission reaction becomes self-sustaining when at least one neutron per fission event survives to create another fission reaction. The multiplication factor  $k$  is used to describe the fission chain reaction and is defined in Equation 1 as:<sup>3</sup>

$$k = \frac{\text{Number of nuclear fissions (or neutrons) in one generation}}{\text{Number of nuclear fissions (or neutrons) in the immediately preceding generation}} \quad (1)$$

In Equation 1, when  $k = 1$  the fission reaction is critical or self-sustaining. For  $k < 1$  then the reaction is subcritical and for  $k > 1$  the reaction is supercritical. For start up,  $k$  is maintained  $> 1$  until the desired thermal output is achieved at which time the reactor is then controlled with neutron absorbing rods and/or neutron reflectors to maintain a  $k = 1$  state. For shutdown the control rods are inserted into the reactor and/or neutron reflectors are opened to achieve  $k < 1$ . The resulting thermal energy is removed by

coolants that can then be used to drive a turbine cycle and generator to produce electricity, or for static systems, a thermoelectric or thermionic conversion to electricity.

Electric propulsion can be used over a wide range of missions including GEO station keeping and orbital plane changes, orbital transfer (LEO to GEO), and interplanetary travel. Different electric propulsion devices can be used depending on the mission requirements. Electric propulsion devices create significantly higher exhaust velocities in the range of 40-90 km/sec versus around 4-5 km/sec for chemical systems. Exhaust velocities directly relate to specific impulse, a measure of propulsion efficiency, by the equation:

$$c = g I_{sp} \quad (2)$$

Where  $c$  is exhaust velocity,  $g$  is the acceleration of gravity on the Earth's surface and  $I_{sp}$  is specific impulse. Specific impulse is defined as the amount of total impulse obtained for the weight (in 1g) of fuel expended. The high exhaust velocities allow for a reduction in required propellant mass as illustrated in Equation 3 or in an alternate expression that is commonly known as the Rocket Equation, Equation 4.

$$M_f/M_o = e^{-(\Delta V/c)} \quad (3)$$

$$\Delta V = I_{sp} * g * \ln (M_o / M_f) \quad (4)$$

Here  $M_f$  is the final spacecraft mass,  $M_o$  is the initial spacecraft mass (including propellant) and  $\Delta V$  is the achievable velocity increment.

Due to power limitations, electric propulsion systems produce low thrust, and in order to create enough velocity, operate through most of the mission profile. Mission profiles that utilize electric propulsion may also include a deceleration phase of the

mission that can enable orbital capture or, given sufficient energy and propellant, multiple orbits and exits of planetary, moon or asteroid systems.

For Earth escape or orbit raising missions (e.g. LEO to GEO orbit transfer), or high planetary gravity environments, a spiral trajectory is used to overcome the higher localized gravity and compensate for the low acceleration. Consequently for Earth orbital missions, while propellant requirements and system mass and launch vehicle requirements decrease, trip times will increase.

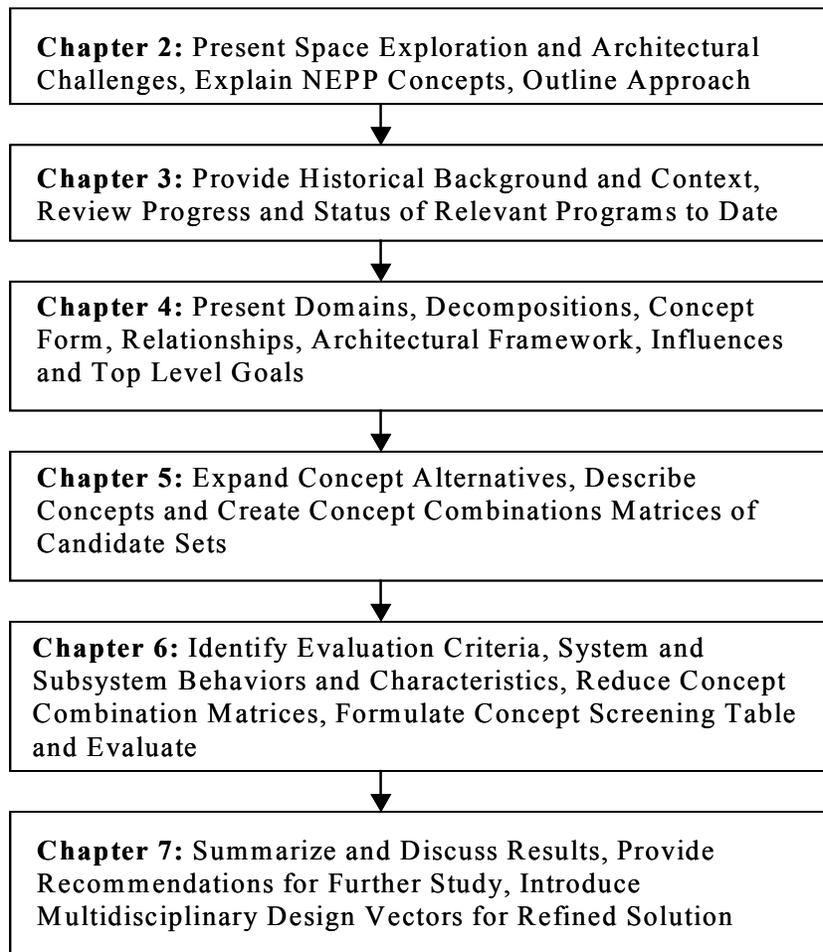
Differences in trip times, as compared to chemical missions, will eventually decrease as distances increase and NEPP vehicles can follow a more direct trajectory without the use of time consuming planetary gravity assists. Additionally, having the ability to use direct planetary trajectories allows for less restrictive launch windows that decouples the launch date from limited planetary alignments.

Electric propulsion systems require high power levels to generate acceleration or thrust. Theoretically, power levels can range from 10's of kilowatts to 10's of megawatts for an NEPP system. The benefits of electric propulsion increase as the mass of the propulsion system or specific mass, as expressed as the ratio of propulsion system mass to power delivered, decreases. Introducing nuclear power significantly increases power densities and lowers the specific mass of electric propulsion systems for planetary applications. In summary the benefits are: (1) The ability to reach interplanetary destinations in a propellant efficient manner which allows for more science payload over propellant loading for a given launch vehicle, (2) The ability to uncouple complex mission designs using planetary gravity assists due to the direct trajectories capability, (3) Potentially decreasing trip time to planetary destinations (4) Having high power levels at

the destination for enhanced science and communication applications and (5) Having power and propulsion available to perform orbital maneuvers at the destination.

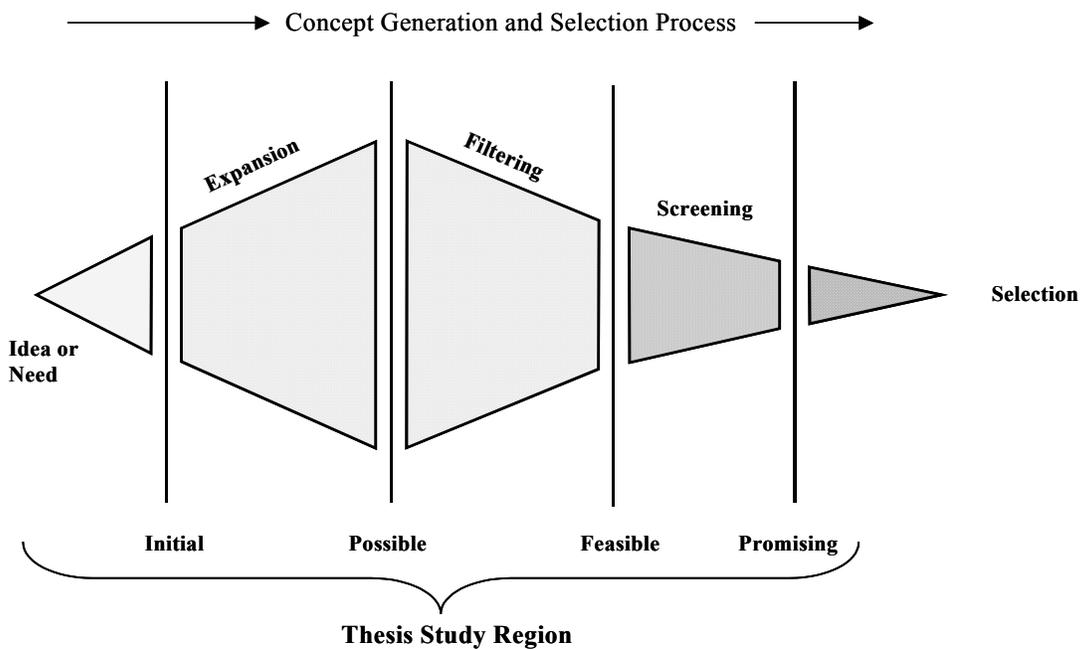
## 2.4 Approach and Thesis Structure

The thesis is designed to identify, filter and screen candidate architectures for a NEPP system through a structured process. The thesis road map is illustrated in Figure 3.



**Figure 3: Thesis Structure and Road Map**

The thesis process is also graphically presented in Figure 4 using an adaptation from de Weck and Crawley<sup>4</sup> that depicts the concept generation and selection process. Chapter 2 provides the need or idea that begins the process. Chapter 3 initiates the expansion process by reviewing what has been done in the past to address similar needs. Chapter 4 provides an analysis of the problem through establishing domains, functional decomposition, mapping function to concept, illustrating interrelationships, analyzing influences and providing top level goals. Chapter 5 establishes the possible concepts and presents the concept combinations. Chapter 6 uses the information from earlier chapters to establish feasible concepts by filtering the concept combinations, identifying screening criteria and applying the screening criteria to the remaining concepts to identify the most promising candidates. Chapter 7 introduces a methodology and provides recommendations to obtain a final selection.



**Figure 4: Thesis Process and Study Region**

## **3.0 Review of Progress in Nuclear Electric Propulsion**

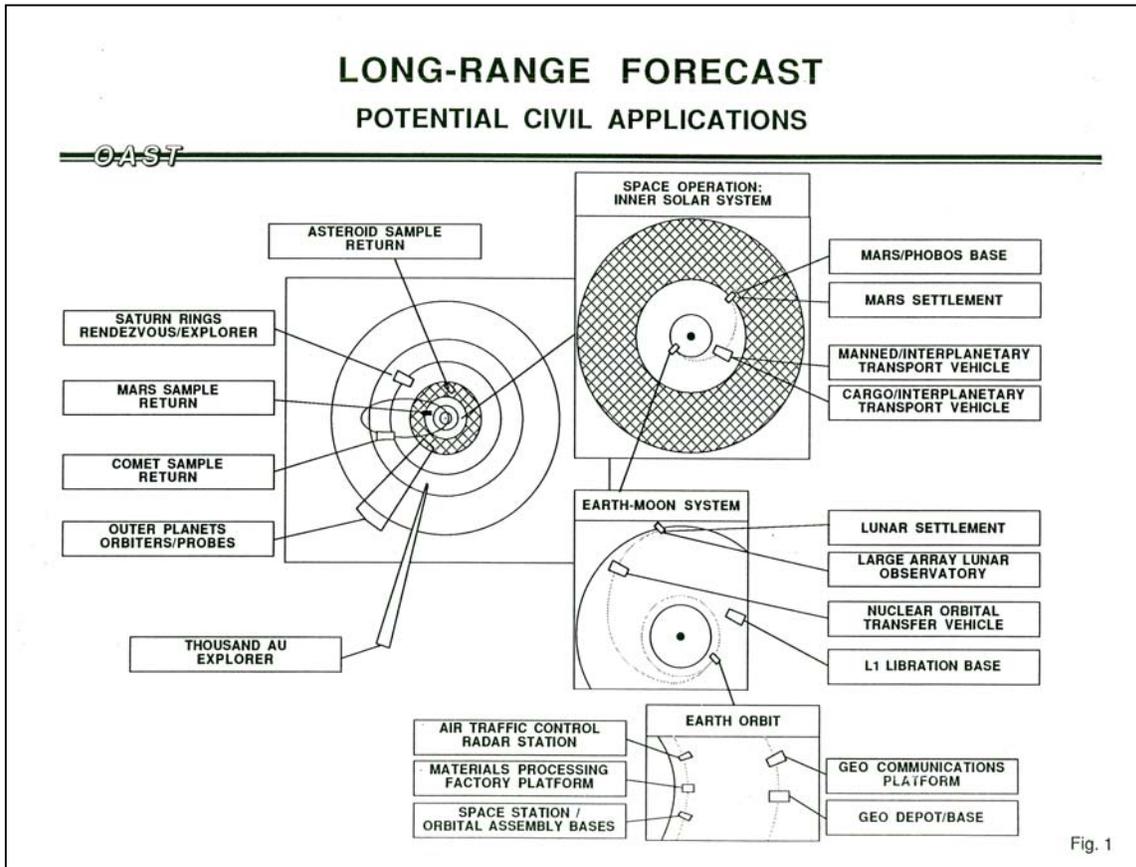
### **3.1 Historical Context of Nuclear Space Systems**

The history of nuclear propulsion can be traced to the writings of Dr. Robert Goddard and others prior to World War II where the concept of heating a working fluid to high temperature using fission for use as a rocket propellant was introduced.<sup>5</sup> After World War II interest increased in developing nuclear weapons that could be delivered via a ballistic trajectory over intercontinental distances. Because chemical rockets were limited in payload and range, nuclear rockets were pursued within the official nuclear rocket program, code-named Project Rover, beginning in 1955.<sup>6</sup> The Rover/ NERVA (Nuclear Engine for Rocket Vehicle Applications) program involved government laboratories, university and industry partners, and resulted in the development of several reactors and ground experimental engines. Project Rover ended in 1973 parallel with the ending of the Apollo program as future space missions were unclear and chemical rocketry had made significant advancements in both range and payload capability for military and civilian purposes.

Concurrently the study of small nuclear reactors for satellite use began, and in 1951 the Air Force had arranged for the Atomic Energy Commission to begin work on small reactors suitable for use as power sources in satellite vehicles.<sup>7</sup> By 1953 Air Force headquarters directed the research and development command to investigate the feasibility of starting development work on an auxiliary nuclear power plant for a satellite.<sup>8</sup> The various earlier efforts and projects eventually became the Space Nuclear Auxiliary Power (SNAP) Program which in 1961 successfully orbited the Transit 4A spacecraft with a SNAP-3B, 2.7 W Radioisotope Thermoelectric Generator (RTG).<sup>9</sup>

Greater power levels were pursued and in 1965, SNAP-10A, the only nuclear fission electrical power system launched by the U.S., was placed in Earth orbit. The system was designed to produce 30kW of thermal power and 500 W of electrical power.<sup>10</sup> The system was placed in a planned 4,000-year lifetime Earth orbit and, after successful startup and operation, was shut down due to a series of spurious electronic signals.<sup>11</sup> The SNAP-10A also flight tested electric propulsion cesium ion thrusters although the results were inconclusive.<sup>12</sup>

The U.S. program continued to pursue higher performing RTG power systems rather than reactor systems in contrast to the Soviet Union which focused their efforts primarily on reactor based systems. Interestingly the Soviet Union has orbited approximately 35 reactor based power systems.<sup>13</sup> After approximately a decade long gap the U.S. began once again to investigate reactor systems, and in 1979 the Space Power Advanced Reactor (SPAR) Program was initiated to address anticipated space power needs.<sup>14</sup> The SP-100 program that was initiated in 1983 as a joint program between NASA, the Department of Defense (DOD) and the Department of Energy (DOE) evolved from the SPAR program. The goal of SP-100 was to develop the nuclear and power technologies necessary to provide tens to hundreds of kilowatts of electrical power for seven years at full power over ten years of operation. Applications were targeted for both future military and civilian missions. NASA presented potential civil applications to the House of Representatives, Subcommittee on Energy Research and Development, in March 1988 with the following chart in Figure 5.



**Figure 5: SP-100 Chart used in 1988 Congressional Testimony**

The SP-100 program made significant progress in understanding the technologies required for development of space reactor power systems, but unfortunately was cancelled in 1992 before any of the planned reactor flights. It should be noted that in this same time period there was a DOE, NASA and DOD effort to formulate design concepts for the Multimegawatt Program that investigated high power systems for a variety of military and civilian applications. This aspect of the program separated from NASA and continued under the Reagan Administration's space defense initiatives. These programs, like similar programs that preceded them, had difficulty in retaining and articulating a true mission need. It can be theorized that having such a large power

range, tens to hundreds of kW, and a variety of mission requirements, ranging from survivable military reconnaissance platforms and directed energy weapons to civilian human piloted missions, actually diffused the mission purpose to the point that a single compelling need was lost to justify continuance. That is one reason why this thesis focuses on a narrower power and applications range.

Recent efforts in the early 90's, with the Space Exploration Initiative (SEI), announced by President Bush in 1989, once again introduced the possibility of including nuclear technologies in the suite of enabling space technologies. However after a few years of study this also failed to achieve Congressional support due to the perceived development costs of a human Moon, Mars and interplanetary exploration program. The SEI effort did provide a temporary resurgence and interest in nuclear space systems and, at a minimum, allowed NASA and others to provide an updated assessment of technology requirements and required investments to complete such a family of missions.

Accidents are also a very important part of nuclear space history, as nuclear incidents have a direct bearing on future policy, program structure and architectures. There have been four failures of U.S. nuclear space activities in either the launch or in-space operations phase of the mission. Three involved Radioisotope Thermoelectric Generators (RTGs) and the fourth involved the one and only U.S. flight reactor. In 1964 a Transit 5B navigation satellite failed to achieve orbit and burned up in the upper atmosphere as designed. The second involved the 1965 SNAP-10 reactor that shut down early and remains in a nuclear safe orbit. The third incident occurred in 1968 during the first minute into the launch of a Nimbus weather satellite. After the launch vehicle malfunctioned and was destroyed, the RTGs fell into the Santa Barbara Channel but were

subsequently recovered. The last failure was the reentry of the Apollo XIII lunar module in 1970 that carried RTGs. The RTGs reentered with the lunar module and survived reentry intact. The Apollo XIII RTGs remain at the bottom of the South Pacific Ocean where they are presumed to be intact. In each case the safety design features remedied any adverse consequences that may have resulted from the nuclear material.

The Soviet space program was not as fortunate, and in 1978 caused an international incident with the reentry of the Cosmos 954 nuclear reactor powered satellite over Canada's Northwest Territories. The reactor was designed to burn-up on reentry, however debris was found over a 600 km tract.<sup>15</sup> Although no large fuel particles were found, several large metallic fragments with high radioactivity levels were discovered.<sup>16</sup> This event was highly significant and focused world attention on safety and policy issues associated with the use of nuclear space power systems.

In summary, over the last 50 years, mission requirements behind the various space nuclear programs have changed dramatically as the driving forces have moved from intercontinental ballistic missiles through the different phases of the Cold War competition. These forces have caused investments in technologies to rise and fall and with them national infrastructure and capabilities. The challenge today is to provide a focused mission requirement that can be clearly communicated and maintained throughout the development program. This also must be accompanied by reinvigorating national capability to deliver on such systems in a safe manner.

### **3.2 Recent and Relevant Program Results**

As noted earlier the SP-100 program has made the most significant recent progress in the understanding and development of space based reactor power systems.

The program began with over 100 different concepts for the reactor system and competed liquid metal, gas cooled, thermionic and heat pipe reactors in combination with various thermoelectric, thermionic, Brayton, Rankine and Stirling energy conversion systems. The program selected twelve and then three concepts for further evaluation and development, which were: 1) High temperature, liquid metal cooled, pin-fuel element reactor with thermoelectric conversion 2) an in-core thermionic power system, and 3) a low-temperature, liquid metal cooled, pin-fuel element reactor with Stirling cycle conversion.<sup>17</sup> In 1985 the program selected the high temperature liquid metal (lithium) pin-fuel element reactor with thermoelectric conversion for development to flight readiness although some work continued on technologies that supported alternative architectures. This activity proceeded through design, analysis, development and component testing before cancellation. In the same time period of SP-100, the Soviet Union orbited a new generation of nuclear reactors, named Topaz I, that evolved from thermoelectric systems to multi-cell in-core thermionic systems in the range of 5 kW.<sup>18</sup>

The design, analysis, component development and alternative architectures investigated under SP-100 represent the most recent and comprehensive efforts to date to develop a space based nuclear power system with the required power ranges for NEPP systems. A significant amount of information existed in industry, academia and government on many aspects of this activity. However the momentum of industry investments and industry support of concepts is critical for success in government projects and this momentum has fundamentally been lost over the last 10 years. Exceptions to this are advancements in non-nuclear power components such as radiators, electronic propulsion devices and power electronics. One consequence of this is that at

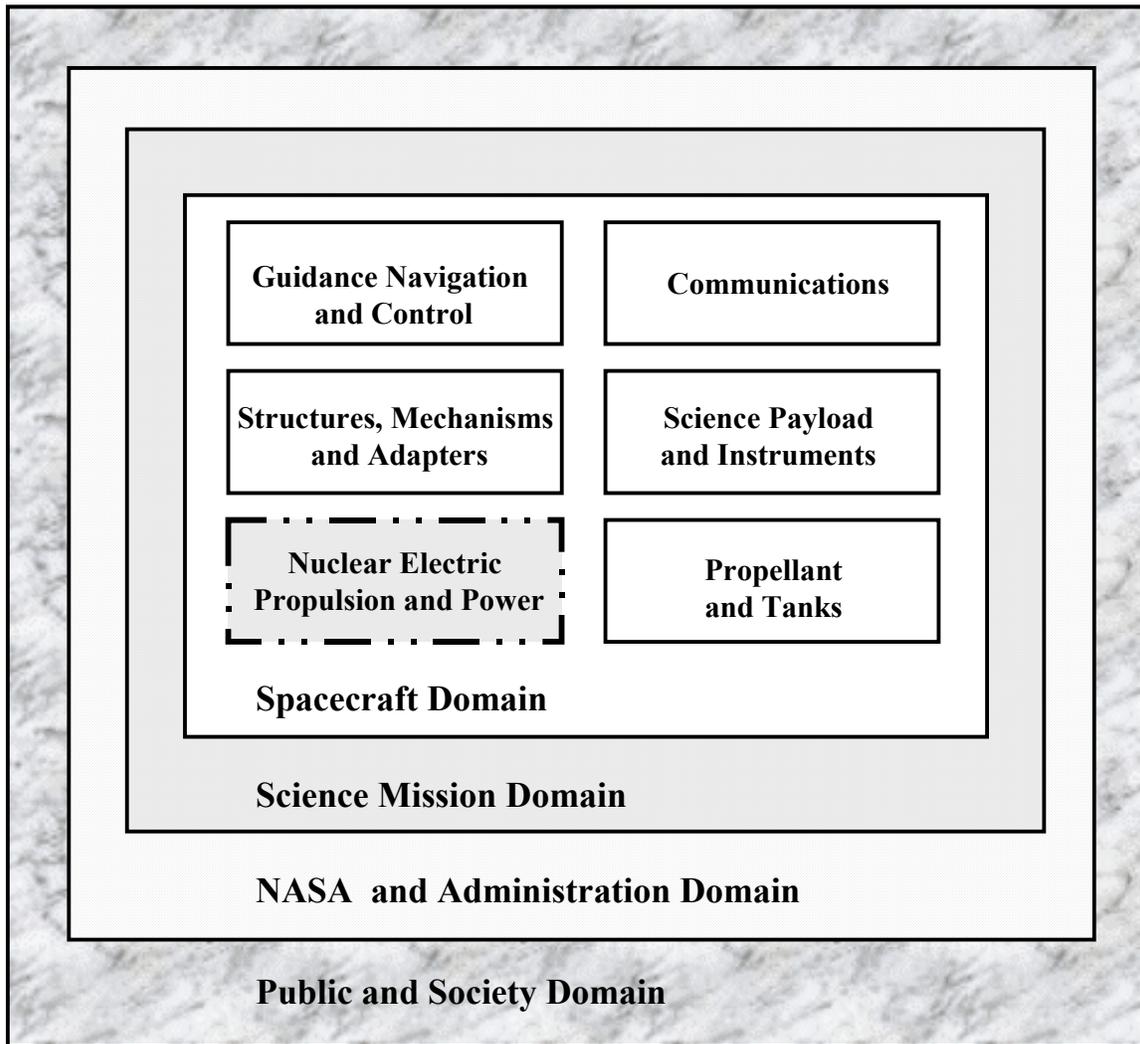
the present time no single concept bias presently exists for a planetary class system. Therefore this thesis will not accept the selected SP-100 concept as final, due to changing requirements and technological advancements, but reopen the trade space to include current information.

## **4.0 Definition of Architectural Space and Influences**

### **4.1 Domain of Study**

The NEPP system is part of the larger Spacecraft, Science Mission, NASA and Administration, and Public and Society domains depicted in Figure 6. The NEPP system possesses interrelationships within the NEPP subsystem domain itself and relationships with each of the progressive external domains. Both the external and internal domains of the NEPP system influence the NEPP system architecture and must be considered through evaluation frameworks. The Science Mission domain sets payload requirements and mission requirements such as power level, lifetime and physical environmental conditions. The NASA and Administration domain reflects the current Executive Branch policy as planned by the Office of Management and Budget (OMB) and implemented by NASA. This would include the mission selection, overall objectives and the type of technical program created to support the mission requirements. The Public and Society domain encompasses Congress, public groups, external organizations and international considerations that provide the constituency for missions and programs, the funding approval and ultimate customer base for the science products. This domain is also the most influential in setting and enacting safety requirements, policies, laws and international agreements for the use of nuclear power in space.

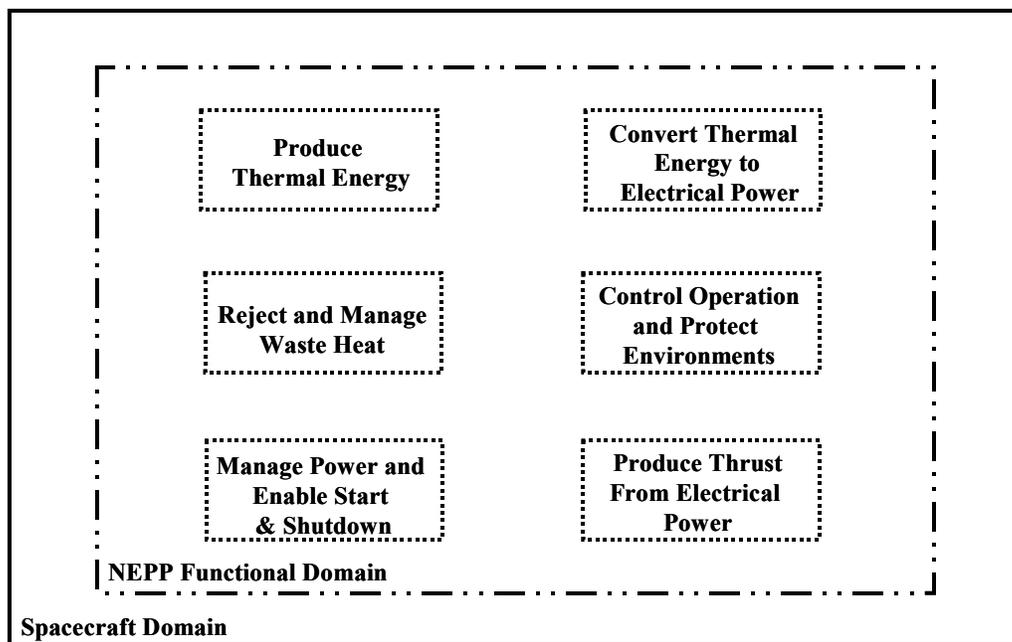
Figure 6 begins the decomposition or “zooming” process from the larger systems and environments and illustrates the sources of architectural influences that are addressed in the architectural framework study in Section 4.6. The following sections continue “zooming in” from the spacecraft level to the first and second level NEPP functional decompositions.



**Figure 6: NEPP System and Associated Domains**

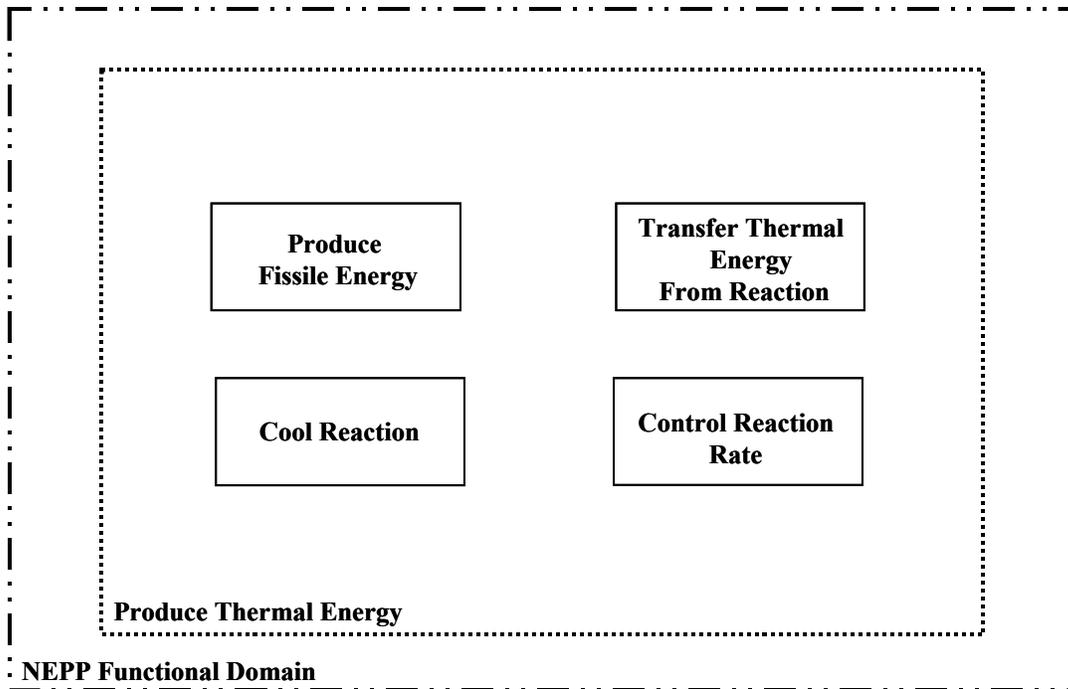
## 4.2 Functional Decomposition

The highest-level functional decomposition of the NEPP system is depicted in Figure 7. The decomposition resulted in six primary functions. Each of these functions is interrelated in different ways with the other NEPP functions in addition to the progressive external domains identified in Figure 6. “Control Operation and Protect Environments” could potentially be separated into two separate first level functions although for this thesis will remain aggregated. The remaining functions are unique.

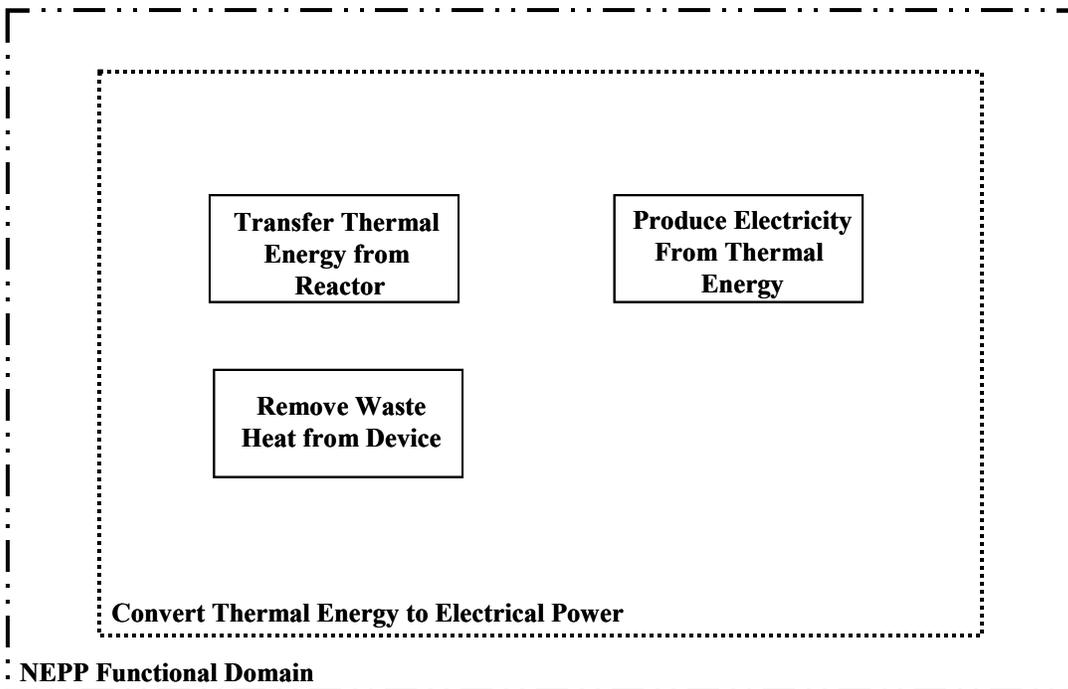


**Figure 7: First Level Functional Decomposition of the NEPP System**

From the first level, the second level functional decompositions are derived in the following figures by continuing to “zoom-in” on each of the first level NEPP functions. Second level decomposition becomes more challenging as function begins to merge with the design attributes. The following second level decompositions offer one approach to expressing function while maintaining concept neutrality for this problem.



**Figure 8: Second Level Decomposition: Produce Thermal Energy**



**Figure 9: Second Level Decomposition: Convert Thermal Energy to Electrical Power**

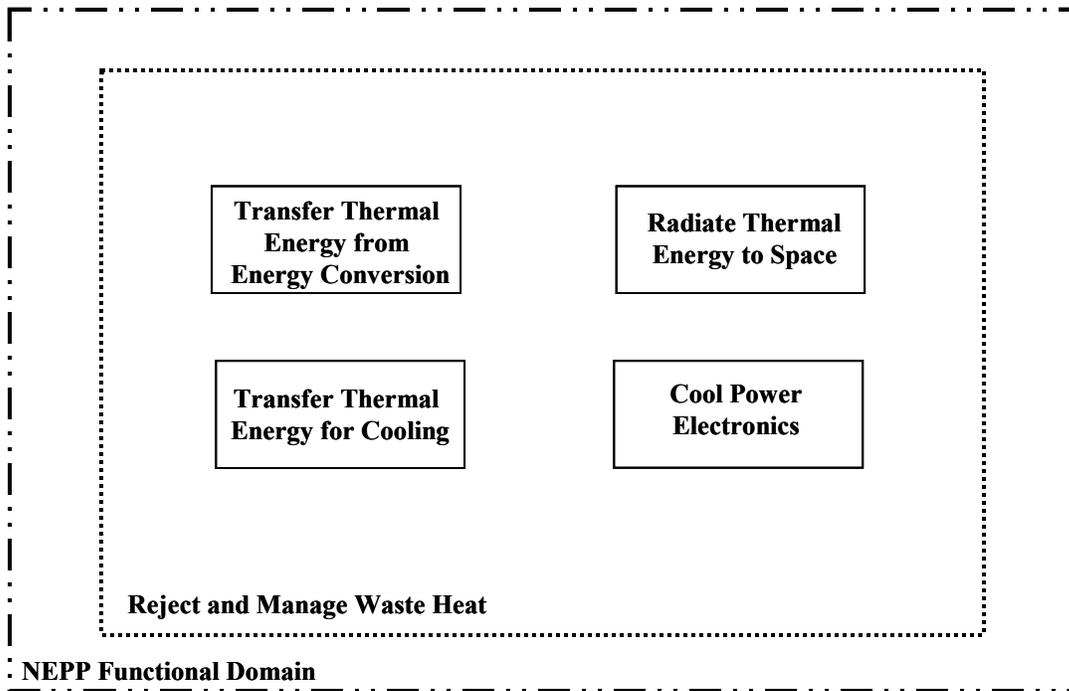


Figure 10: Second Level Decomposition: Reject and Manage Waste Heat

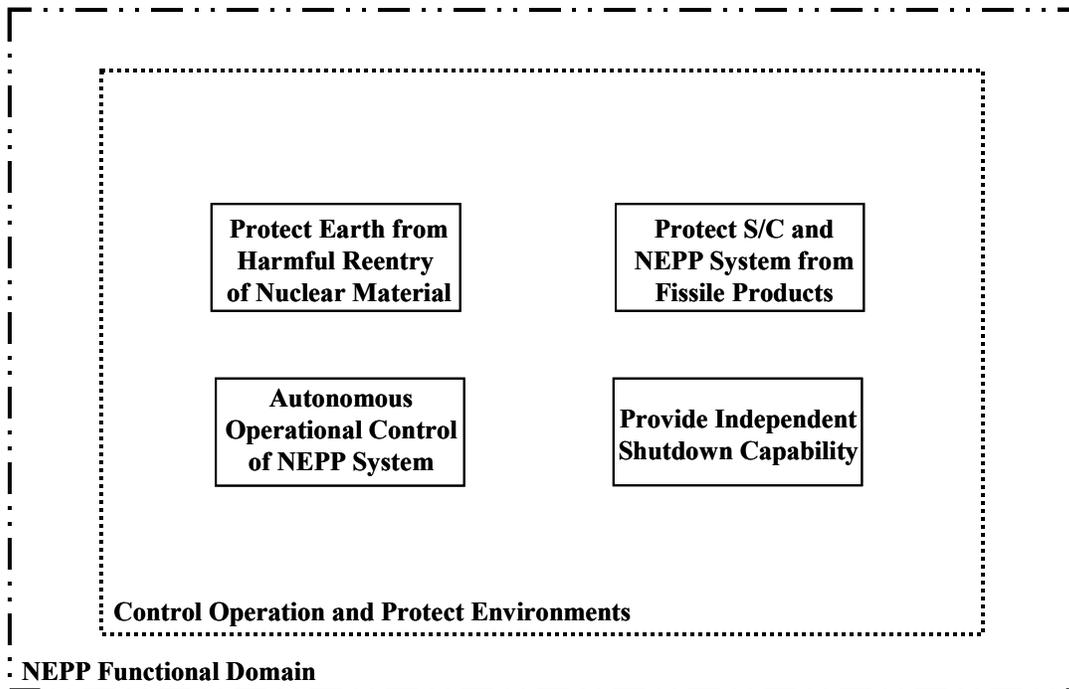
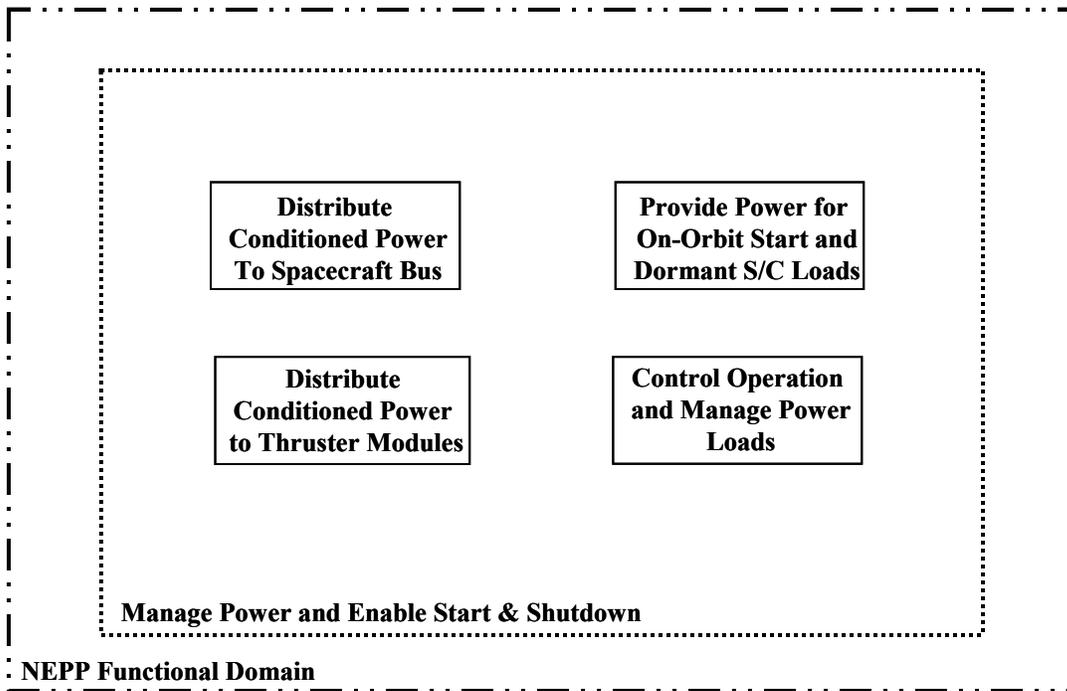
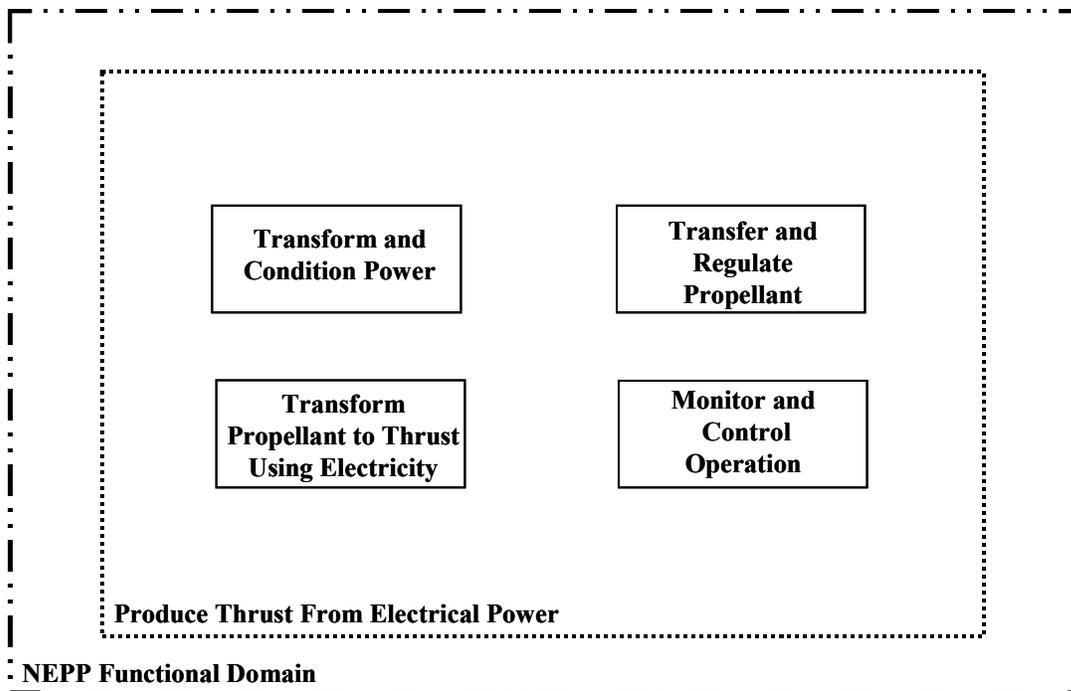


Figure 11: Second Level Decomposition: Control Operation and Protect Environments



**Figure 12: Second Level Decomposition: Manage Power & Enable Start & Shutdown**



**Figure 13: Second Level Decomposition: Produce Thrust from Electrical Power**

## 4.3 Emergence of Form

This section will introduce the general concept design or form that addresses the functional requirements. Descriptions of general candidate concepts are mapped to the first and second level functional decomposition levels in Tables 2 and 3. Chapter 5 will continue to move beyond the general design concept solution, or concept neutral solution, to design or concept specific solutions that take the form of the architecture. At this point candidate concepts will be presented that will subsequently be reduced by identified architectural influences and top-level goals and objectives.

**Table 2: Form or Concept from Function**

<b>Functional Decomposition Level</b>	<b>Function</b>	<b>General Design Concept or Form</b>
<b>1</b>	<b>Produce thermal energy</b>	<b>Nuclear reactor</b>
2	Produce fissile energy	Nuclear fuel
2	Transfer thermal energy from fissile reaction	Fuel cladding and core component geometry
2	Cool reaction	Coolant
2	Control reaction rate	Control rods or drums, actuation mechanisms, neutron reflector, instruments/sensors, moderator and controller
<b>1</b>	<b>Convert thermal energy to electrical power</b>	<b>Energy conversion devices (static or dynamic)</b>
2	Transfer thermal energy from reactor	Pumped gas, liquid loop or heat pipe to heat exchanger
2	Produce electricity from thermal energy	Static thermal to electric devices or dynamic (linear or rotary) devices
2	Remove waste heat from device	Pumped gas, liquid or heat pipe or conductive method
<b>1</b>	<b>Reject and manage waste heat</b>	<b>Radiator, transport and management devices (accumulators, condensers, recuperator)</b>
2	Transfer thermal energy from power conversion	Pumped fluid loop or heat pipes
2	Radiate thermal energy to space	Radiator panels
2	Cool power electronics	Cold plate/pumped fluid loop
2	Transfer thermal energy for cooling	Pumped fluid loop

**Table 3: Form or Concept from Function (Continued)**

<b>Functional Decomposition Level</b>	<b>Function</b>	<b>General Design Concept or Form</b>
<b>1</b>	<b>Control operation and protect environments</b>	<b>Distributed electronic components/ shielding</b>
2	Protect spacecraft and NEPP system from fissile products	Radiation shield(s) (gamma and neutron)
2	Protect Earth from harmful reentry of nuclear material	Structural vessel for containment of reactor and fuel and reactor reentry shield
2	Autonomous operational control of NEPP system	Microprocessors, controllers, instrumentation and software
2	Provide independent shutdown capability	Independent microprocessor, controller and software
<b>1</b>	<b>Manage power and enable start and shutdown</b>	<b>Distributed power and electronic components</b>
2	Distribute conditioned power to spacecraft bus	Cabling, transformers, rectifiers, filters, inverters, converters and electronics
2	Distribute conditioned power to thruster modules	Cabling, transformers, rectifiers, filters, inverters, converters and electronics
2	Control operation and manage power loads	Controller, electronics, software and power processing devices
2	Provide power for on-orbit start and dormant spacecraft loads	Solar arrays, batteries, cabling, controller
<b>1</b>	<b>Produce thrust from electrical power</b>	<b>Electric Propulsion devices</b>
2	Transform and condition power	Power processing unit
2	Transfer and regulate propellant	Propellant feed system
2	Transform propellant into thrust using electricity	Electric propulsion design specific thrusters
2	Monitor and control operation of thrusters	Controller, sensors, electronics

#### 4.4 NEPP Domain and Functional Interrelationships

Interrelationships between the NEPP functions and the spacecraft subsystems will impact architectural, design and requirements decisions. The following figures illustrate where primary interrelationships occur between NEPP functions and where interrelationships occur between the NEPP functions and the higher-level spacecraft domain. The functional interrelationships depicted maintain concept specific neutrality.

While there are several methods that can be used to expose interrelationships using design form, this functional portrayal helps to validate the first level decomposition and identify functional coupling that exists in some of the subsequent concepts. A separate figure is provided for mechanical, thermal, power, signal and environmental interrelationships using unidirectional or bi-directional links. The terms are used to generally describe the physics rather than the specific type of force, energy or level that would be required in a design exercise.

The last category varies from the first four in that it also describes the products of function rather than the essential elements of the function itself. These elements are principally deleterious and include the radioactive products from the reactor, the thruster effluence, thermal loads from the radiators and vibrations or torques from dynamic power conversion.

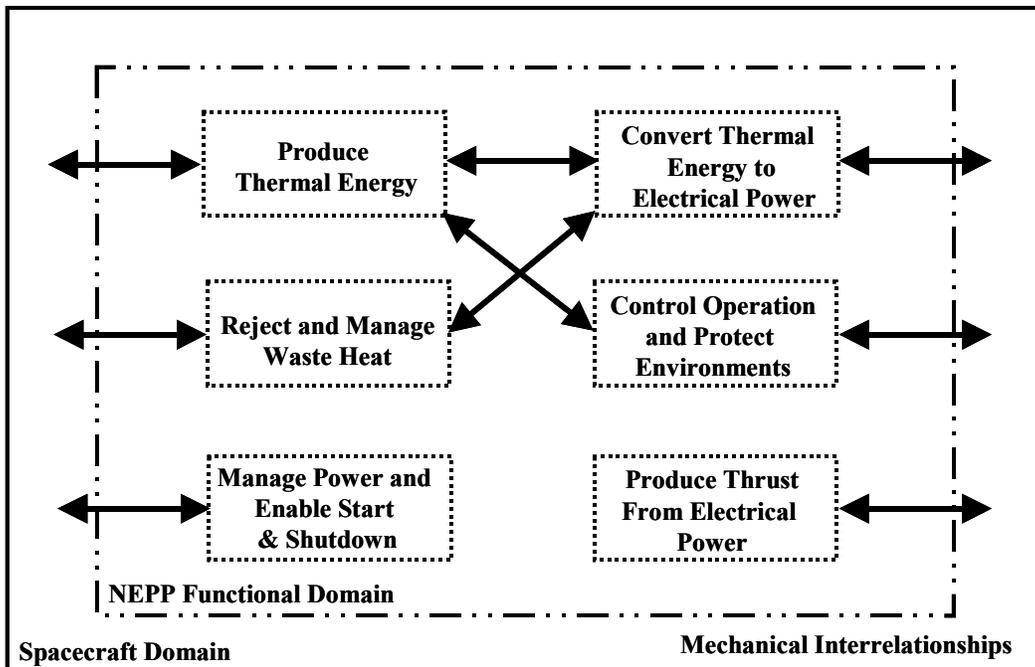


Figure 14: Mechanical Interrelationships



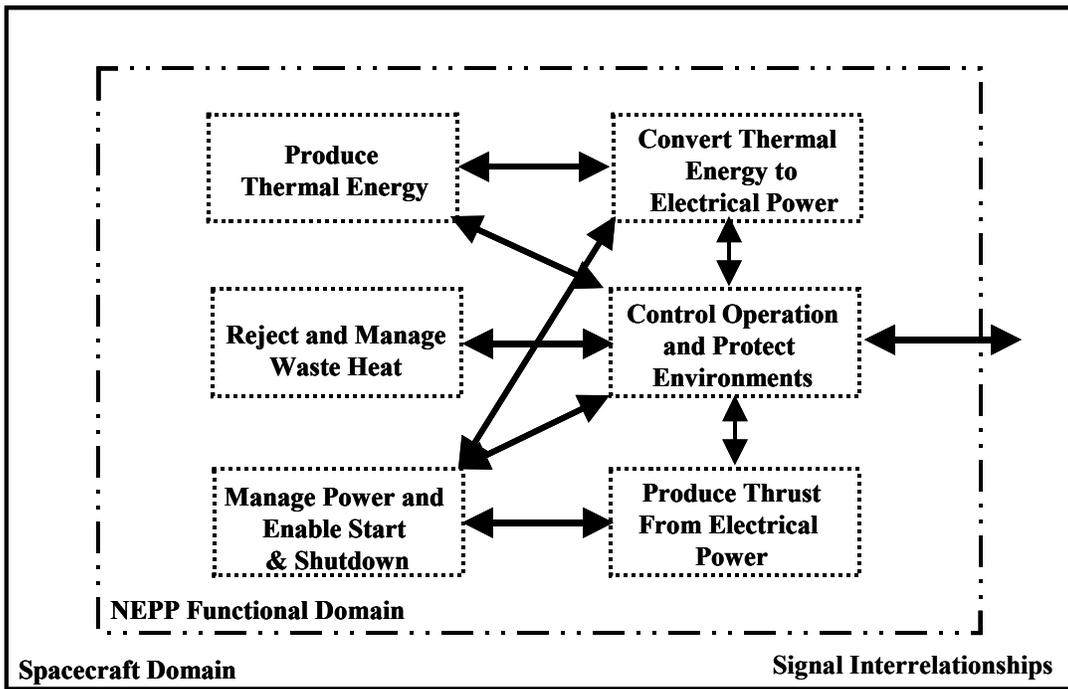


Figure 17: Signal Interrelationships

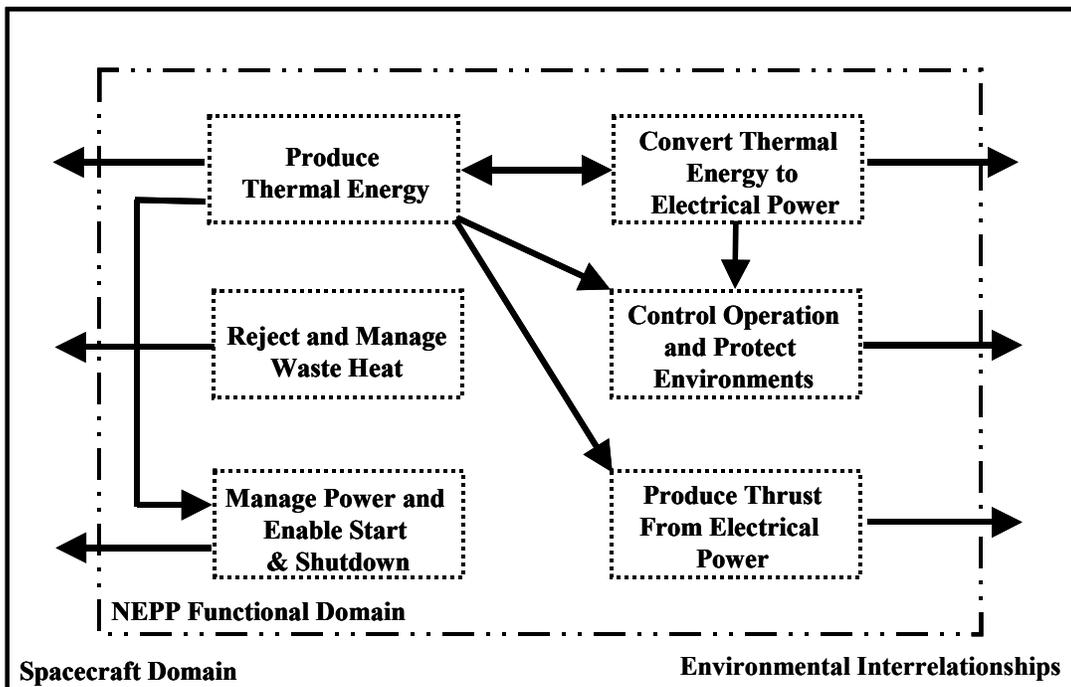


Figure 18: Environmental Interrelationships

Figure 19 provides a summary of the NEPP interrelationships. This helps reveal the internal complexities that are critical to selecting promising concepts. This summary mapping exposes the high coupling between the functions of “Produce Thermal Energy” and “Convert Thermal Energy to Electrical Power”. It also illustrates the high downstream or cross-functional influence of the reactor and power conversion system.

Relationship M - Mechanical T - Thermal P - Power S - Signal E - Environmental	NEPP Functions					
	Produce Thermal Energy	Convert Thermal Energy to Electrical Power	Reject and Manage Waste Heat	Control Operation and Protect Environments	Manage Power and Enable Start & Shutdown	Produce Thrust from Electrical Power
NEPP Functions						
Produce Thermal Energy		M,E,T,S	T	M,E,S	E,P	E
Convert Thermal Energy to Electrical Power			M,T	S,E	P,S	
Reject and Manage Waste Heat				S,T	T,P	
Control Operation & Protect Environments					P,S	S
Manage Power & Enable Start & Shutdown						P,S
Produce Thrust from Electrical Power						

**Figure 19: Summary of NEPP Interrelationships**

Figure 20 provides an example summary of the interrelationships that can exist between the NEPP systems and the spacecraft domain. Some of these relationships, such as the thermal relationships, are dependent on the spacecraft architecture. The high occurrence of Environmental and Power relationships will appreciably impact architectural and design decisions. Similar diagrams could be constructed for the subsequent hierarchical domains in Figure 6.

	Guidance Navigation and Control	Communications	Structures, Mechanisms and Adapters	Science Payload and Instruments	Propellant and Tanks
<b>NEPP Functions</b>					
<b>Produce Thermal Energy</b>	E	E	M,E	E	E
<b>Convert Thermal Energy to Electrical Power</b>	E	E	M	E	
<b>Reject and Manage Waste Heat</b>	T,M,E	T,M	T,M,E	T,M,E	
<b>Control Operation &amp; Protect Environments</b>	S	S	M,S	S,E	
<b>Manage Power &amp; Enable Start &amp; Shutdown</b>	P,S	P,S	P,M	P,S	P,S
<b>Produce Thrust from Electrical Power</b>			M	E	T,M,S

Relationship  
M - Mechanical  
T - Thermal  
P - Power  
S - Signal  
E - Environmental

**Figure 20: Summary of NEPP to Spacecraft Domain Interrelationships**

#### 4.5 Determination of Top Level System Goals and Objectives

Top-level system goals must reflect a balance of performance, schedule, cost and risk objectives. Over constraining these variables can cause failure from the start of a program or project. Additionally, allowing grandiose visions to envelope the decision making process for system goals and objectives is equally detrimental for a complex NEPP system. The very first statement addresses the ultimate goals and objectives of the architecture and takes the form of a mission statement for the thesis. Value is delivered to the science community through the NEPP system by delivering data that could not otherwise be obtained. This is followed by top-level goals and objectives that provide further specificity and drive the highest-level architectural decisions. System requirements will follow these goals and objectives.

Highest level Goal and Objective:

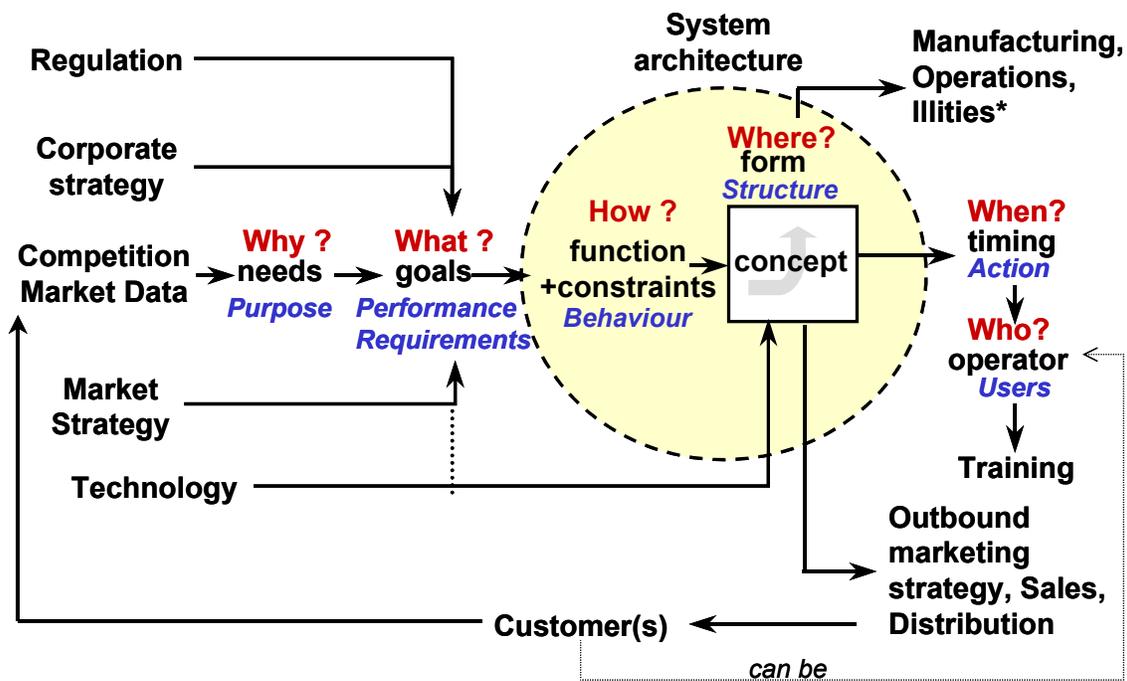
**To safely and appreciably advance the scientific return of planetary class missions using the enabling properties of NEPP systems while complying with national and international laws and regulations.**

Top-level Goals and Objectives:

- 1) To provide safe operations through all phases of development, delivery, launch, operation and disposal of the NEPP system including planetary protection
- 2) To provide a platform that can be adapted to encompass different planetary class missions in approximately the 75-250 kW power range
- 3) To complete the launch of the NEPP system and spacecraft within ten to twelve years from program start.
- 4) To launch the completed NEPP spacecrafts using a single expendable launch vehicle including propellant. This is approximately 18,000 kg.
- 5) To operate at full power for eight to ten years and reduced power for ten to twelve years in addition to proving on-orbit start capability.

## 4.6 Architectural Framework

This section examines significant influences on the NEPP architectural concepts that must be considered in the subsequent concept filtering and screening phase of the systems architecture process. The following figure from de Weck and Crawley<sup>19</sup> depicts a framework for such an analysis. The following sections step through an adaptation of this framework for an NEPP system that forms the basis for the concept combination matrix reductions and concept screening evaluation criteria.



*\*Reliability, Servicability, Environmental Impact, Upgradeability, Flexibility, etc...*

**Figure 21: Systems Architecture Framework<sup>20</sup>**

### 4.6.1 Safety and Regulation

Safety is the highest priority and will significantly influence the selection of architectures, designs and operations of an NEPP system. The main safety concern is the release of any significant amounts of radioactive fuel or radioactive products after the reactor has been operated. This concern spans from component development through safe disposal of the completed system. The nuclear safety launch approval process is formidable and is governed by both the National Environmental Policy Act (NEPA) and Presidential Directive/ National Security Council Memorandum number 25, “Scientific or Technological Experiments with Possible Large-scale Adverse Environmental Effects and Launch of Nuclear Systems into Space”. NASA ensures compliance with the NEPA process through NASA NPG 8580.1, “Implementing The National Environmental Policy

Act and Executive Order 12114”, and compliance with the Presidential Directive through NPG 8715.3, “NASA Safety Manual”. The USAF ensures compliance through Air Force Instruction 91-110, “Nuclear Safety Review and Launch Approval Process for Space or Missile Use of Radioactive Material and Nuclear Systems” which also serves as a guiding document for interagency approval process activities.

The safety phases include transportation to the launch site and on stand operations, launch, ascent, safe orbit and in-space operations including mission termination and safe disposal. A considerable amount of information is required to support these activities including the preparation of environmental impact statement data books, public information statements, safety analysis reports, safety evaluation reports, contingency planning, spacecraft reentry analysis and the adequate consideration of alternative technologies. These processes and procedures cause many interagency sub-processes to occur including the Interagency Nuclear Safety Review Panel (INSRP), which serves to coordinate the various supporting tasks among the responsible organizations. Ultimately, the President or the Director of the Office of Science and Technology Policy must sign for the launch of a nuclear reactor.

International space law must also be considered as a prevailing element in the development of an acceptable architecture. The Committee on the Peaceful Uses of Outer Space (COPUOS), set up by the United Nation’s General Assembly in 1959, is the international forum for the development of international space law. Since its inception, the Committee has concluded five international legal instruments (Treaties and Agreements) and five sets of declarations and legal principles governing space-related

activities.<sup>21</sup> One of the Principles is entitled “Principles Relevant to the Use of Nuclear Power Sources In Outer Space” which contains a section outlining reactors (Figure 22).<sup>22</sup>

## **2. Nuclear reactors**

(a) Nuclear reactors may be operated:

(i) On interplanetary missions;

(ii) In sufficiently high orbits as defined in paragraph 2 (b);

(iii) In low-Earth orbits if they are stored in sufficiently high orbits after the operational part of their mission.

(b) The sufficiently high orbit is one in which the orbital lifetime is long enough to allow for a sufficient decay of the fission products to approximately the activity of the actinides. The sufficiently high orbit must be such that the risks to existing and future outer space missions and of collision with other space objects are kept to a minimum. The necessity for the parts of a destroyed reactor also to attain the required decay time before re-entering the Earth's atmosphere shall be considered in determining the sufficiently high orbit altitude.

(c) Nuclear reactors shall use only highly enriched uranium 235 as fuel. The design shall take into account the radioactive decay of the fission and activation products.

(d) Nuclear reactors shall not be made critical before they have reached their operating orbit or interplanetary trajectory.

(e) The design and construction of the nuclear reactor shall ensure that it cannot become critical before reaching the operating orbit during all possible events, including rocket explosion, re-entry, impact on ground or water, submersion in water or water intruding into the core.

(f) In order to reduce significantly the possibility of failures in satellites with nuclear reactors on board during operations in an orbit with a lifetime less than in the sufficiently high orbit (including operations for transfer into the sufficiently high orbit), there shall be a highly reliable operational system to ensure an effective and controlled disposal of the reactor.

### **Figure 22: Excerpt on International Space Law for Nuclear Reactors<sup>23</sup>**

The regulatory and safety approval process will impact the NEPP architecture in several ways. The current U.S. space nuclear system design philosophy is for full fuel containment in the event of launch failure or inadvertent orbital reentry. This means if a reentry were to occur the reactor must reenter without dispersing radiation in the upper

atmosphere and must impact the Earth in an intact state. This is different from the earlier approach taken on the SNAP-10A reactor, which was designed to break-up and burn-up all radioactive material on atmospheric re-entry. The containment approach to safety directly affects reactor and reactor shield designs in addition to qualification approaches. This results in a mass penalty through the additional shielding and structural containment requirements.

The reactor must also be launched in a subcritical state and further must not be operated prior to launch in order to eliminate any fission product inventory within the system. This subcritical state must be maintained until a nuclear safe orbit or planetary trajectory has been achieved. This includes remaining subcritical in the event of credible accidents that may occur from transport to on-orbit operation. Launch into a nuclear safe orbit is one that precludes the reentry of nuclear fission products prior to a safe level of decay. Further, the orbit must be adequately removed from the Earth's orbital debris fields and the operational reactor must not have the potential to harm any current or future missions. Safe operation also extends to planetary protection or endangering the opportunity to make a discovery on a planet or planetary atmosphere. This impacts the approach taken to test, qualification and mission design. To a lesser extent, the way the reactor and fuel are packaged and shipped to the launch site (e.g. together or separate) may also affect combined subsystem configurations.

#### **4.6.2 Corporate Strategy**

The high public exposure in a civilian nuclear space program makes safety a fundamental tenet throughout the full product life cycle. Included in this philosophy is the ability to effectively communicate risk and safety issues to the public. Continuous

risk management and communications strategies must be employed that involve advocates as well as environmentally conscious groups with differing opinions. Perception plays an important role and to this end the architecture that is clearly communicated and comprehended attracts; the complicated architecture repels.

Because of the tremendous expense involved in flying an NEPP system the architecture should leverage past research and development results to the maximum extent practical. The relevant national experience exists primarily with the residual SP-100 knowledge base for space systems development and possibly the US Navy for operational experience with respect to deployed nuclear systems. High development costs will also mandate that the system platform be adaptable or evolvable to multiple missions within a range of power requirements for future planetary missions. This may also result in a stepped approach where the architecture may initially be heavier, produce less power and perform less efficiently than its future versions; provided it could accommodate technological improvements.

The architecture should be adaptable and evolvable in order to envelope several classes of planetary exploration missions. However, this goal should only be taken to a point that does not fundamentally change the initial configurations or major subsystems selected and qualified. For example, changes in materials alone may allow higher operating temperatures that result in higher systems efficiencies and increased payloads or distance/time relationships without changing the primary system configuration. A strategic incremental approach that considers evolvability and adaptability within the planetary mission class is critical. Additionally, to the extent practical, other mission classes may be considered (e.g. human) to further leverage the investment as long as

scaling considerations do not supersede sound adaptability decisions for planetary missions. For example, scaling a multi-megawatt system architecture down to meet planetary class requirements will yield different results than allowing applicable NEPP subsystems of planetary class missions to evolve to support higher power systems.

Space nuclear power systems and mission destinations are inherently political and must consider current Executive and Legislative policy when selecting architectural options. This includes the influence of the science community on current and pending legislation. For example, both the 2003 Senate version of the NASA spending bill, Senate Report 107-222, and House Report, 107-740, include \$105 million for a mission to Pluto that NASA did not request in the FY 2003 President's Budget to Congress. Pluto is an ideal mission for NEPP; however, it cannot be achieved by the desired 2006 launch date if NEPP were used. If the legislation becomes final, NASA must execute a chemically propelled "flyby mission" using RTGs that will yield less science than an orbital NEPP mission. This will take substantial resources and remove a desired mission from the potential NEPP near term mission set.

The 2003 House Report also included specific language stating: "An increase of \$40,000,000 for the Europa mission. In light of the high priority by the National Academy decadal study for a Europa Orbiter Mission and the public support for Europa exploration as indicated by the recent survey of the Planetary Society..." This follows a recent National Research Council activity called the Decadal Planning that advocated a Europa mission that also performs reconnaissance on Ganymede and Callisto.<sup>24</sup> This Jovian Tour mission is an ideal candidate for NEPP and can potentially become the first

mission in a series if the platform can deliver on the needs of the scientific and political communities.

This scenario becomes influential by driving a decision to select an architecture that can be delivered the earliest to avoid the same situation with other near term popular missions. Additionally, flying early provides tremendous leverage for a sustained investment in the nuclear space program. However, this almost single criterion approach can be detrimental to other long-term space exploration goals, as the use of only the most available components becomes the de facto system. The architecture must balance competing political pressure to deliver a system relatively quickly with the long-term goals of the space program.

Lastly, strategies that force the architecture to become everything to multiple organizations, such as SP-100 intended to perform with its multiple agency and multiple mission approach, must be avoided when top-level goals and requirements conflict. For example, in the SP-100 program the requirements for military programs were very different from those of planetary exploration programs. This also extends to human rated programs that require megawatts of power rather than kilowatts. Vision towards these programs should be tempered with the present planetary exploration challenges. Finally it is paramount that a set of compelling missions are defined and communicated that can justify the resources required to develop NEPP and instill a true mission “pull” rather than a technology “push”.

### **4.6.3 Competition**

Competition is addressed by discussing alternative space power technologies that may be able to support planetary exploration class missions. While many of these

technologies and architectures are suitable for a particular mission they may only address a portion of the overall desired mission spectrum capability of planetary class NEPP systems. Many of the competing technologies are maturity, volume, mass or energy limited by underlying physics or the environment at the target destinations. Examples include Solar Electric Propulsion (SEP) missions that use solar arrays to provide power to an electric propulsion system. SEP systems do offer advantages over chemical systems by providing a more efficient use of propellant, through the use of high efficiency electric propulsion, and a decoupling of planetary alignments with mission design trajectories. Flight heritage of this type of system was achieved through a 1998 NASA mission, Deep Space 1, which successfully demonstrated the use of solar electric propulsion for an extended science mission to the Comet Borrelly.<sup>25</sup> Although SEP systems offer benefits over chemical missions they are unable to supply the increased power at the planetary destinations for sophisticated science and communications payloads.

For planetary exploration missions, nuclear based systems provide tremendous capabilities and to date have taken the form of radioisotope systems. Flight heritage is very important to mission managers and radioisotope systems have a demonstrated safe and reliable flight record for lower power solar limited missions. Radioisotope power systems derive their energy from the decay of radionuclides rather than from a fission reaction within a reactor power system. These systems can use either static or dynamic energy conversion techniques to provide electrical power although only static systems have flown to date. Radioisotope Thermoelectric Generators (RTGs), which use static thermoelectric power conversion, have been used for numerous Department of Defense

and NASA space missions since 1961. The following table lists NASA’s flight history of using both power and heating radioisotope units.

**Table 4: NASA Radioisotope Missions<sup>26</sup>**

<b>NASA Missions</b>	<b>Launch Year</b>	<b>Approximate Power Level per Unit (We) (Total units)</b>	<b>Type of Thermoelectric Conversion</b>
Nimbus B-1	1968 (aborted)	-	-
Nimbus III	1969	28 (1)	PbTe
Apollo 11	1969	Heater Units	-
Apollo 12	1969	73 (1)	PbTe
Apollo 13	1970 (aborted)	-	-
Apollo 14	1971	73 (1)	PbTe
Apollo 15	1971	73 (1)	PbTe
Apollo 16	1972	73 (1)	PbTe
Apollo 17	1972	73 (1)	PbTe
Pioneer 10	1972	40 (4)	PbTe/TAGS*
Pioneer 11	1973	40 (4)	PbTe/TAGS
Viking 1	1975	35 (2)	PbTe/TAGS
Viking 2	1975	35 (2)	PbTe/TAGS
Voyager 1	1977	150 (3)	SiGe
Voyager 2	1977	150 (3)	SiGe
Galileo	1989	285 (2)	SiGe
Ulysses	1990	285 (2)	SiGe
Pathfinder	1996	Heater Units	SiGe
Cassini	1997	285 (3)	SiGe

\* Tellurides of Antimony, Germanium and Silver

Dynamic radioisotope power systems offer higher efficiencies (>20% thermal to electric) and higher power to weight ratios than static conversion systems and can also be used for planetary exploration when combined with electric propulsion. Radioisotope Electric Propulsion (REP) has been shown to be very effective at delivering small spacecraft (~100 to 300 kg, not including power and propulsion) to outer planetary destinations in reasonable trip times when using direct high velocity chemical escape trajectories with electric propulsion deceleration and capture.<sup>27</sup> While offering a more

rapid and efficient alternative to all chemical missions the REP systems are payload and power limited at the destination.

Hybrid propulsion systems that combine both low and high propulsion acceleration systems on the same platform offer attractive mission design benefits, growth capability and high power at target destinations. A bimodal nuclear electric propulsion system allows for the elimination of prolonged Earth escape spiral trajectories that low acceleration NEPP systems must use to escape planetary gravity wells. This reduces total mission time and reduces the total  $\Delta V$  requirement for the EP portion of the mission. These missions could depart directly from circular parking orbit altitudes of 500 to 800 km rather than spiraling out from the 1000-2500 km altitudes for NEPP missions. This could be achieved while maintaining decay lifetimes of greater than 400 years to satisfy safety concerns.<sup>28</sup> In addition to reducing departure altitudes, providing higher acceleration than NEPP and providing sufficient power at target destinations, bimodal systems also significantly enable future human exploration missions. While attractive, the combined nuclear thermal rocket and NEPP systems do add significant amounts of complexity to the already challenging problem of designing, qualifying, launching and operating a nuclear space power and propulsion system. A vision that is greater than planetary class exploration, such as human mission, would have to be embraced as a principle objective in order to justify the additional complexity and capital investment required for a bimodal architecture.

#### **4.6.4 Customer and Market Strategy**

The thrust for investment in NEPP systems must emanate from national policy within the Executive Branch followed by legislative support of Congress. The cost to

develop, qualify, launch and operate an NEPP system can only be taken on by the government rather than commercial entities. Stakeholders can be identified as the originating appointed federal executives responsible for policy and execution, congressional representatives and staff and the constituent supporters of an NEPP program initiative. The customers, in addition to the government agencies, are ultimately the many diverse groups within the scientific and educational communities. This includes many universities, Government appointed councils within the National Research Council and the National Academy of Sciences, the Planetary Society and other space organizations. The constituent base is driven by both scientific and political motives and therefore market and customer value must be delivered accordingly.

One additional intermediate customer group that can be considered is the mission managers. These individuals must also be convinced that NEPP systems would be the best choice for their missions. Although the mission managers themselves will not solely select the use of an NEPP system they can be influential in the decision process. Unfortunately, no single mission can afford the development of the NEPP system and hence it may be difficult for a single mission manager to justify. This would most likely lead to a less capable mission platform being selected rather than flying none at all due to prohibitive total mission costs. This dilemma helps to justify an administrative decision that seeks to develop a capability by amortizing the development cost across several missions rather than basing the developmental decision on a single mission destination.

An NEPP system investment will exceed two billion dollars and involve many people and organizations. This figure is based both on industry parametric cost models and current internal NASA estimates.<sup>29</sup> In many cases complex public system

architectures must satisfy local optima rather than global optima to achieve overall program success. Ironically, the success of selecting a complex architecture is dependent upon the cross-organizational structures put in place to transcend the functional hierarchies tasked to design and implement the architecture itself.

NEPP is part of a long-term investment in the development of technologies that will enable new levels of space exploration. NASA's budget will most likely sustain modest growth and should, at a minimum, increase commensurately with inflation.

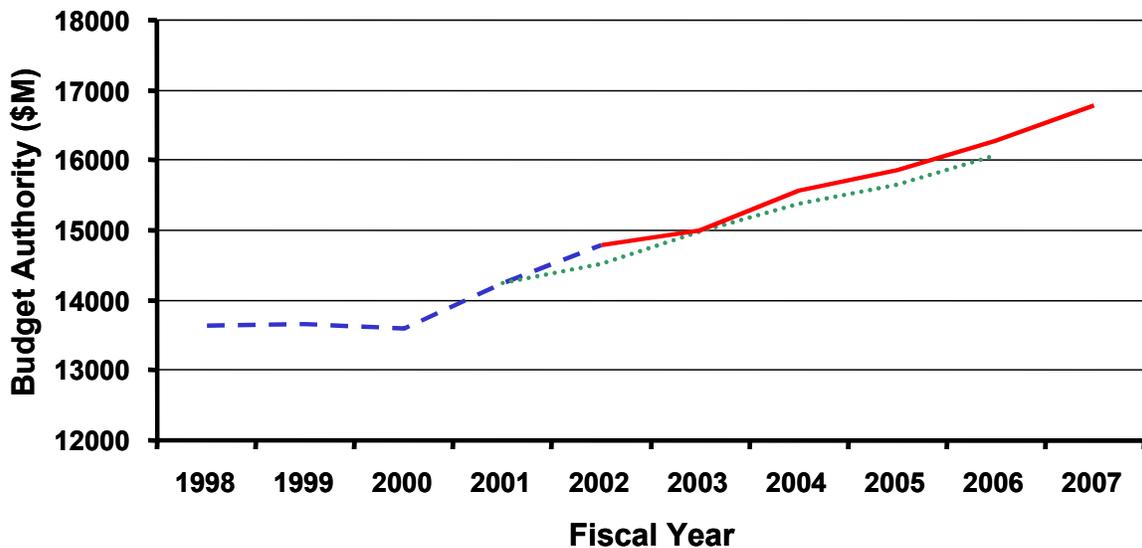


Figure 23: NASA Budget Trend<sup>30</sup>

In this environment any new initiative becomes a priority by inclusion as something else is displaced in what essentially becomes a zero sum budget. Because of the significant hiatus in space nuclear programs an investment in the national core competence will also be necessary. This is a significant commitment because of the multi-year funding required to reinvigorate such a capability.

### 4.6.5 Technology

Because of the significant costs associated with the development of an NEPP system, the technology investments must be clearly guided by the end application. Too many concurrent activities with different end goals will quickly diffuse limited resources and impede overall progress. It is imperative that investments remain focused on the top-level goals and objectives and make up for the disruption in nuclear space systems development. General key technology development drivers include:

- Lowering specific mass of the NEPP subsystem components (e.g. reactor, radiator, energy conversion) which results in lower dry mass and increased payload or propellant mass
- Increasing lifetime of components and subsystems
- Advancing autonomous operations for remote destinations
- Developing high temperature materials that allow for higher system operating temperatures, higher efficiencies and consequently lower NEPP system specific mass
- Designing subsystem components for high planetary radiation environments

While complementary power and satellite technologies have advanced over the last decade, direct nuclear technologies such as advanced fuel qualification, reactor design and materials development, have not made significant progress. Strategically it is important to assess what was accomplished in the past and determine the remaining contemporary technical issues. Although the following listings are architecture specific

to a liquid metal reactor with a thermoelectric power conversion unit, it is relevant to current concept selection and potential technology investment decisions. In 1987 the top ten technical challenges for SP-100 were listed as follows<sup>31</sup>:

1. Safety
  - a. Core cooling with loss of coolant
  - b. Reactor control and safety drives
  - c. End of mission disposal
2. Thermoelectric cell technology
  - a. Electrical insulator development and performance
  - b. Electrical contact resistance
3. Fuel pin design and performance validation
  - a. Fuel pellet development
  - b. Fuel clad liner development
  - c. Fuel pin clad creep strength
4. Thawing coolants
  - a. Startup from frozen lithium
5. Highly reliable heat transport loop
  - a. Hermetic
  - b. TEM pump development and performance
6. System lifetime
  - a. N<sub>2</sub> loss from fuel elements
7. System mass
  - a. Compliance with specification
8. Gas accumulator/separator
  - a. Li<sup>7</sup> versus natural lithium
9. Heat pipe design and manufacture
  - a. Transient performance/re-thaw
10. Radiation shield temperature control

Later in 1991 J. Mondt of JPL listed the Technical challenges as the following:<sup>32</sup>

#### System Level

- Verified power versus lifetime prediction codes
- Verified reliable 10 year system design margin codes
- Startup from frozen lithium in zero gravity
- Flight system acceptance tests

#### Subsystems

##### Reactor

- Verified prediction of fuel pin behavior
- Verified 10 year creep strength of PWC-11

- Verified transient behavior

#### Reactor Instrumentation and Controls

- Reflector control drive actuator insulators and electromagnetic coil lifetime
- Temperature sensors lifetime
- Radiation hardened multiplexer amplifiers lifetime

#### Shield

- Verified LiH swelling properties

#### Heat Transport Subsystem

- Gas separator performance and plugging lifetime
- TEM pump (TE/Busbar) bond performance and lifetime
- TEM pump (Cu/Graphite Bus Duct) bond performance and lifetime

#### Converter Subsystem

- Electrodes and bonds to TE legs lifetime
- TE cell assembly low cost fabrication
- High figure-of-merit TE material performance and lifetime ( $Z = 0.85 \times 10^{-3} \text{ K}^{-1}$ )
- Cell to heat exchanger bond performance and lifetime

#### Heat Rejection Subsystem

- Carbon-Carbon to titanium bond performance and lifetime
- Low cost and low mass heat pipe lifetime

Fortunately other non-nuclear parts of the NEPP system have made advancements through commercial, military and civilian space programs. Power management and distribution have advanced through projects like the International Space Station, although the radiation environment remains the most challenging aspect of nuclear power system electronics design and qualification. Large area/ low mass heat rejection technologies have also advanced through the International Space Station and numerous satellite programs. Lastly, electric propulsion technology has made significant advancements in civil, military and commercial applications. In addition to several development flights, electric propulsion is presently used for commercial geosynchronous satellite attitude

control and was used as the primary propulsion system on NASA's 1998 Deep Space 1 mission, which used solar concentrator arrays and 2.1 kW to power the electric thrusters. NEPP systems will require the development of higher power and more efficient thrusters than are currently flying today.

#### **4.6.6 Downstream Influences**

Test, integration and qualification are some of the first downstream considerations that may influence concept selection following manufacturability. In addition to MIL STD 1540D, Test Requirements for Space Vehicles, there are nuclear specific test requirements that must also be evaluated. Further, regulation stipulates that only DOE or their indemnified contractors are permitted to test and assemble space nuclear reactors or RTGs. Nuclear tests are expensive and time consuming so it is therefore advantageous for NASA to have a concept that allows for some level of non-nuclear testing prior to any actual systems level nuclear tests in order to partially or fully qualify subsystem concept designs. The interrelationship functional diagrams in Chapter 4 should be considered in testing and qualification in order to simulate as many critical interfaces as possible and determine what can be performed outside of an expensive ground based operational nuclear test. The power conversion, heat rejection, propulsion and some controls subsystems testing are candidates for non-nuclear testing using a simulated heat source and simulated space environment. Concepts that do not highly couple the first or second level functions identified in the decompositions offer advantages to this testing approach.

There are many operational requirements to consider although it is difficult to discern any that result in unique NEPP concepts. Autonomous operations beyond fault detection that include intelligent actions will also be part of all concepts due to the

communication distances. Operational considerations further include planetary protection measures that are part of NASA's NPG 8020.12B, Planetary Protection Provisions for Robotic Extraterrestrial Missions. Depending on the mission classification, different levels of microbial reduction for an entire planetary spacecraft will be required prior to launch.

The most difficult downstream influences to incorporate are the future NASA missions outside of the planetary class. This necessitates careful consideration as this can produce a plethora of extended requirements due to the open-ended nature of the potential missions. In fact different systems such as NTR or bimodal may be better architectural choices for high power human missions. However, desires for human exploration or planetary surface applications must be assuaged with the realities of future NASA budgets and the realization that human requirements invoke a significantly higher level of complexity and cost. Alternatively, not considering future human missions, given the projected (> \$2B) investment for developing space nuclear capabilities, may be viewed as equally myopic. Consideration should be given to the extent that investments in concepts can be leveraged for the advancement of future systems. It therefore becomes critical to differentiate between concepts that directly scale to the development of future systems and those that progressively and affordably adapt, evolve and advance technology and capability.

#### **4.6.7 Legacy and Current Capability**

The only U.S space reactor platform that flew did so in 1965 and produced only around 500 Watts of electrical power. Any capabilities to reproduce this same system have essentially been lost over time. The SP-100 program work, while not producing a

flight reactor, did significantly advance the technology readiness of higher power space nuclear power system components. As a result of this activity, the preferred SP-100 concepts will most likely have more than a moderate influence in the selection of a reactor concept.

While time has eroded some of the space nuclear technical, manufacturing, testing and infrastructure capabilities that were present during the SP-100 program, time has also advanced the state of the art for non-nuclear power and propulsion. Electrostatic ion propulsion has made distinct advancements through NASA's Deep Space 1 mission and NASA continues to seek higher performance levels through recently awarded in-space propulsion research and development contracts. The International Space Station is also a significant architectural and design reference for NEPP platforms through its use of high power 120 V DC power distribution and large area heat pipe radiators. While power conversion systems have not commensurately advanced, Brayton systems were studied and did accomplish limited development efforts for use with a 25 kW solar dynamic power generation module for the International Space Station. The Brayton system was also used in 1994 for a 2 kW solar dynamic ground demonstration test at the NASA Glenn Research Center. Static thermoelectric advancements have also modestly progressed due to various government investments.

Investments in nuclear fuel technology for space applications have languished since the SP-100 program. Terrestrial fuel programs seek different outcomes targeted at reduced waste and safe disposal rather than tailoring fuels for high temperature lightweight designs. Uranium oxide (UO<sub>2</sub>) is widely used domestically and is a well-understood fuel. While uranium nitride (UN) was pursued under SP-100, it did not

complete a full qualification program and would require additional resources to fully qualify. Selection of any fuel that is different from the either of these would result in a major investment to achieve full space qualification.

## **5.0 Expanded Sets of Candidate Architectures**

### **5.1 Description of Concepts and Components**

This section introduces more specific alternative concepts for the NEPP subsystems. This is achieved by further expanding the general architectural concepts or forms from the functional decompositions presented in Chapter 4. In order to resolve complexity, this section attempts to distinguish between what are pivotal elements of the architecture and what are only design attributes. The most influential architectural concept elements form the basis for inclusion in the concept combination matrices.

#### **5.1.1 Nuclear Reactors**

Space reactors that can potentially address the objectives of NEPP space science missions can be grouped into three major architectural or design categories: liquid metal cooled, heat pipe and gas cooled. Each of these reactors differs by how heat is extracted from the core. One additional design, called in-core thermionic, which is also discussed under the power conversion section, combines both the reactor and power conversion system together in a single reactor design. Reactors can operate in the thermal, epithermal or fast neutron spectrum of operation although space reactors under consideration are in the fast spectrum. This is primarily due to the increased mass associated with the additional moderator required for thermal or epithermal operation.

As long as the safety requirements are met, the mass advantages of the fast spectrum reactors will dominate the decision process.

Each of these reactor designs can be varied by the selection of fuels, fuel geometry, cladding, coolants and respective constituent materials and components. Selecting an operating temperature is very critical as it directly impacts overall system efficiency and determines the choice of fuels, coolant and materials and appreciably affects downstream NEPP subsystems. Changing the cladding and internal structural materials allows for increased operating temperatures. The broad materials selection categories include stainless steels, super-alloys and refractory alloys (e.g. tantalum and niobium alloys). The use of refractory alloys will allow for higher temperature operation and greater system efficiencies but may present development and qualification challenges. Other than material selection, reactor control design through drums, control rods and actuators and neutron reflectors are not considered driving architectural elements and will be dependent on system selection. Any physical local control scheme must be redundant and safe by design, independent of reactor selection.

The reactor fuel can be in solid, liquid or gaseous form although the potential candidates for NEPP planetary class will be limited to solid form due to technical maturity. Considerations for selecting fuels include both technical and practical considerations. Technical parameters include density, thermal conductivity, melting point, temperature stability, thermal/mechanical properties, chemical compatibility, irradiation behavior and swelling from fission gasses. Practical considerations include the ability to fabricate and qualify, current capability of domestic infrastructure and accumulated operational experience. Broad categories of fuels include uranium oxides,

nitrides, carbides and ceramic matrix (cermets). Candidate fuel types for NEPP include: uranium-zirconium-hydride (U-ZrH), uranium nitride (UN), uranium oxide (UO<sub>2</sub>), uranium carbide (UC) fuels and cermet fuels. The U-ZrH fuel was used for the SNAP-10 flight reactor.<sup>33</sup> Fuel selection impacts overall reactor density and mass and is significant to overall system performance.

Fuel cladding serves as the interface between the fuel and coolant and can be combined with different material layers to achieve optimal characteristics such as thermal, structural and chemical compatibility. Cladding and core components selection are highly fuel and temperature dependent and when assessing reactor designs the combination must be addressed concurrently. Designing the reactor to operate at higher temperatures can also move the structural materials from stainless steel designs to super alloys to refractory materials. The higher operational temperatures are also propagated through the downstream NEPP energy conversion and radiator and thermal management subsystems. The selection of fuel and cladding may not change the reactor architecture, other than materials, but will impact other subsystems due to different operating temperatures. Candidate refractory cladding and structural materials for higher temperature systems include rhenium, tungsten, molybdenum, tantalum and niobium based materials, or more advanced metal/ceramic matrix composites.

Coolant selection is reactor and temperature dependent and can be in liquid or gaseous form depending on the reactor. Liquid metal reactor coolants include Na, K, NaK and Li; Heat pipe reactors include Na and K; and gas cooled reactor candidates include He, Xe or a combination of He and Xe.

The reactor and fuel types are clearly two pivotal and influential elements of the architecture although other elements are less clear. One way to aggregate the cladding, internal materials and coolant selection is to first decide the operating temperature, as all of these elements directly follow from this decision. The break points follow along the material temperatures of stainless steels, super-alloys and refractory alloys or ceramic composites. The concept matrix will use a low, medium and high temperature range to capture these material options with low representing a stainless steel system (~950 K), high representing a refractory alloy system (>1200 K) and medium representing a combination of materials (e.g. refractory cladding, super alloy components) that fall somewhere in-between the low and high temperatures material break points.

**Table 5: Concept Combination: Produce Thermal Energy**

<b>Produce Thermal Energy</b>		
<b>Reactor</b>	<b>Fuel</b>	<b>Operating Temperature</b>
Liquid Metal	UN	Low
Gas Cooled	UO <sub>2</sub>	Medium
Heat Pipe	UC	High
	UC <sub>2</sub>	
	U-ZrH	
	Cermets	

### 5.1.2 Energy Conversion Devices

The first large architectural division in energy conversion is between static and dynamic systems. Static devices include thermoelectric, thermionic and thermophotovoltaic (TPV), while dynamic devices include Rankine, Brayton and Stirling cycles. Dynamic systems offer significantly higher efficiencies than static systems, although they introduce vibration and/or torque into the spacecraft system. Dynamic devices use an alternator to produce Alternating Current (AC) while the static devices

directly convert thermal energy to Direct Current (DC) power. Critical design properties and discriminators include: Reliability, mass ratios, lifetime, scaling to higher power levels, power output characteristics, vibration and torque and system efficiency. The following paragraphs provide a brief summary of the devices.

### **5.1.2.1 Static Devices**

Thermoelectric devices directly convert thermal energy into electrical energy using the Seebeck effect, which establishes a voltage potential by maintaining different junction temperatures across two dissimilar metals within a closed circuit. Thermoelectric devices are solid state and use a figure of merit property “Z” which relates thermal conductivities, electrical resistivities and the Seebeck coefficient for two dissimilar materials in order to ascertain device level operational characteristics. The higher the “Z” value the higher the overall efficiency of the converter. Higher operating temperature differences also allow for higher efficiencies but are limited by material selection. Efficiencies of current devices range from 4-8% although advanced future designs such as segmented thermoelectric devices that use a combination of materials, target efficiencies between 10-15%. These devices can be configured in series and parallel arrangements for increased system reliability. Historically, all U.S. space nuclear power systems and all but two Russian nuclear space reactors have used thermoelectric devices.<sup>34</sup> Thermoelectric devices began with PbTe device materials and evolved to higher performing SiGe devices.

Thermionic devices also directly convert thermal energy to electrical energy. Thermionic devices produce electricity by radiating electrons from a hot emitter surface across a small gap to a cooler collection surface. These passive devices have been

investigated for both in-core and out-of-core operation. The U.S. performed ground testing of these systems although never flew a nuclear thermionic conversion system. The Russian space program performed ground tests and flight-tested two thermionic reactor units named Topaz. Efficiencies range from 10-15% for these devices and like thermoelectric devices they can be wired in series and parallel combinations for redundancy. Thermionic devices can also be coupled radiatively, which allows a physical separation of the nuclear fuel from the converters and reduces some of the issues regarding fuel swelling and dimensional stability but also increases the fuel operating temperature to over 2000 K.

Thermophotovoltaic devices operate similar to photovoltaic devices but use the infrared spectrum for energy. These devices also allow for a direct thermal to electric conversion and system reliability through redundant configurations. Achieving higher efficiencies requires concentrators to increase incident energy and multi bandgap devices to convert a higher portion of the available energy. Depending on concentration level and devices, efficiencies can range from 10 to 35 or more percent of incident energy.

### **5.1.2.2 Dynamic Devices**

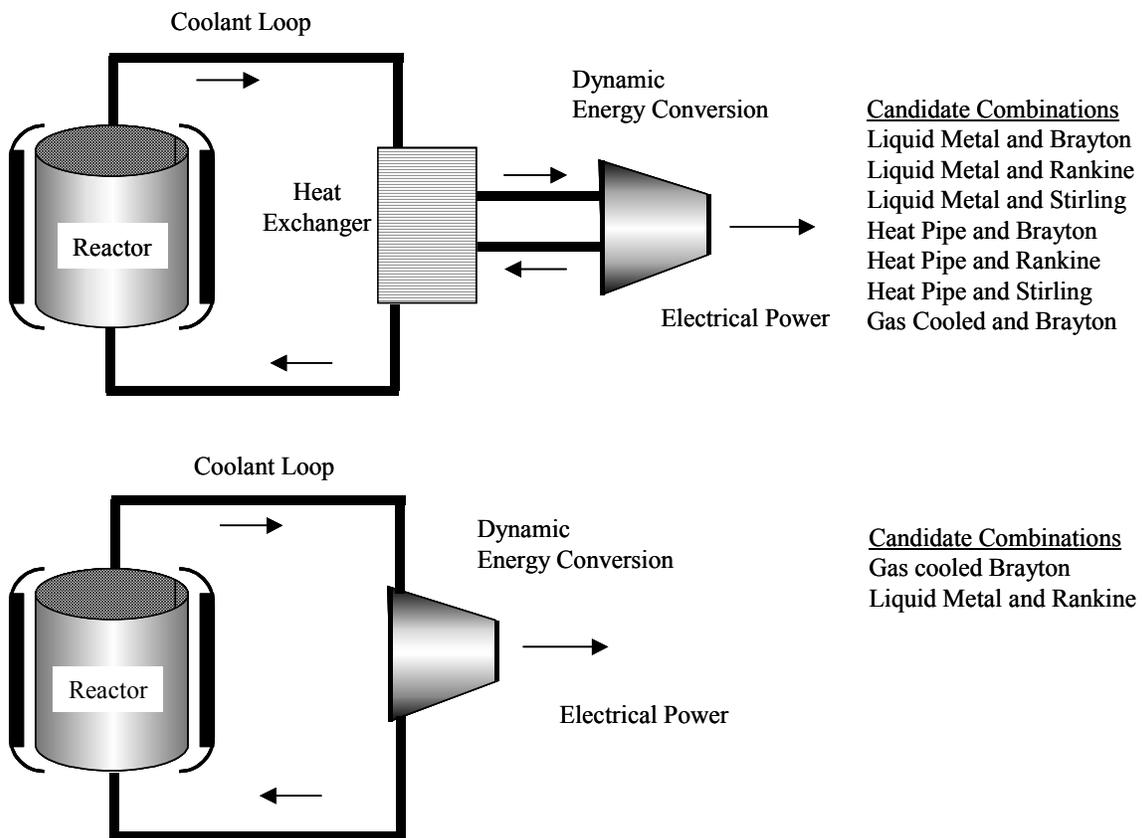
Rankine systems are used extensively in large terrestrial steam power generation applications although adapting the cycle to space applications presents a new set of challenges. Rankine cycles were studied under the SNAP program extending through the early 1970's, which represents the primary source of materials, component and subsystem ground test database.<sup>35</sup> Rankine systems use a two-phase system that boils a working fluid from the heat exchanger, uses the vapor to power a multi-stage turbine and rotary alternator and then condenses the vapor back to a liquid at the radiator. Working

fluids include NaK, Hg, K, H<sub>2</sub>O and organics. Efficiencies range from 15-20% for space systems. Advanced Rankine systems can be directly coupled to a liquid metal reactor eliminating the need for a heat exchanger.

The closed Brayton conversion cycle uses heat energy from the reactor to heat an inert working gas. The gas expands through a turbine driving a compressor and power producing rotary alternator. Cycle efficiency is improved by using a recuperator that uses the hot turbine exhaust to preheat the working fluid before it returns to the heat source. Efficiencies range from 20-25% and can be increased using higher temperature materials. Working fluids include He, Xe, Kr or a mixture. A Brayton system uses a heat exchanger to obtain heat from the reactor. However, the Brayton system can also directly couple to a gas-cooled reactor by using the same cooling and working gas eliminating the need for the separate heat exchanger.

The Stirling cycle is a closed thermally driven system that derives its power from heat flow between a source and a sink. The system moves a piston and displacer in between hot and cold cycles within a sealed volume. As the piston moves back and forth it creates AC power using a linear alternator. Systems are configured with the pistons oriented in an opposing fashion for dynamic stability. This type of engine operates at high efficiencies in the range of 20-30% and is used for a variety of terrestrial applications. The interface with the reactor is through a heat exchanger and, unlike the other dynamic cycles, offers no direct coupling options due to the inherent properties of the constant volume device. This cycle was pursued in several past automotive, energy and space power programs and is produced commercially for lower power applications.

There are different architectural options for joining the major functions of producing thermal energy and converting thermal to electric energy for dynamic systems. The primary option for dynamic systems is to use a heat exchanger to couple the reactor coolant to the energy conversion cycle working fluid loop. An alternate method for Brayton and Rankine is to directly couple the reactor coolant to the working fluid of the energy conversion cycle as illustrated in Figure 24. Although many potential combinations could be made to work, there are only certain combinations that allow for efficient heat transfer and the corresponding lower mass advantage. For example gas cooled reactors are only considered for use with Brayton systems.



**Figure 24: Indirect and Direct Dynamic Power Conversion Architectures**

Dynamic Brayton and Rankine power conversion devices also allow for a direct drive option that can produce a high voltage output from the power conversion alternator directly to the electric propulsion device’s Power Processing Unit (PPU). This allows the elimination of components required to step up voltages and/or frequencies required for the electric propulsion devices. Stirling devices use a linear alternator that produces a low frequency output so this option is not applicable. Pivotal architectural elements for power conversion are included in the following table. Both the direct or indirect heat exchange decision and high power electric propulsion output decision only apply to dynamic systems. Working fluids and structural materials are a function of temperature of operation that is set by the reactor operating temperature so they are not called out as individual discriminators. Operating temperature is captured in the “Produce Thermal Energy” table and will combine with this table in the full concept selection matrix. The number of devices used is a function of device type, mission power requirements and redundancy requirements and is therefore not individually specified.

**Table 6: Concept Combination for Convert Thermal Energy to Electrical Power**

<b>Convert Thermal Energy to Electrical Power</b>		
Device	Heat Exchange	High Power EP Drive
<i>Dynamic</i>	<i>Dynamic</i>	<i>Dynamic</i>
Rankine	Direct (Brayton & Rankine)	Direct (Brayton & Rankine)
Brayton	Indirect (All)	Indirect (All)
Stirling		
<i>Static</i>	<i>Static</i>	<i>Static</i>
Thermoelectric (SiGe)	Indirect	Indirect
Thermoelectric (PbTe)		
Segmented Thermoelectric		
Thermionic in-core		
Thermionic ex-core		
Thermophotovoltaic		

### 5.1.3 Radiators and Thermal Management

Space radiators must reject waste heat by radiation heat transfer. Radiators can be passive two-phase devices such as heat pipes or loop heat pipes or can be active single phase pumped fluid loops. Radiator design and fluid selection are dependent on the operating temperature and power conversion systems selected. Independent system attributes that impact system performance include efficient heat transfer, material compatibility, surface emissivity and mechanisms and joints if the radiators are deployable. Two of the most critical performance measurements for radiators include the mass per square meter of radiating surface and the ability to stow the radiator area in a fixed launch vehicle volume. Concepts can be fixed structures or deployable structures. For deployable systems the type of deployment mechanisms becomes another important design trade. The pivotal architectural concepts are the type of system used for heat transfer to and from the radiator, the heat transfer device within the actual radiator and the geometry. Attributes such as low mass per unit area, environmental protection (e.g. micrometeoroids, ultraviolet, atomic oxygen) and high emissivity are critical to all concepts.

Space radiator designs have continued to improve independently of nuclear systems through the advancement of commercial, DOD and NASA satellite power systems including the International Space Station. Reduction in the mass per area ratio is one of the most significant radiator system parameter considerations. SP-100 targeted around  $12 \text{ kg/m}^2$ , International Space Station flight radiators are around  $15 \text{ kg/m}^2$  and recent communication satellites are around  $10 \text{ kg/m}^2$ . Current studies target  $6 \text{ kg/m}^2$  or less for NEPP systems in the planetary class range. It should be noted that smaller

communications satellite radiators are not subject to the penalties of deployment mechanisms that larger systems are and larger systems must also consider stiffness/mass requirements driven by the natural frequency of the combined structural systems.

The *transport thermal energy function* is assumed to be decoupled from the energy conversion working fluid loops through a condenser or cooler that provides heat transfer to the radiator cooling loop or combination of heat pipes and loops. Although a directly coupled Brayton system option is possible is not included due to the mass increase associated with the heavier ducting required to deliver the waste heat to the radiator in gaseous versus liquid form. For a Brayton system this would mean transferring gaseous heat to and from the radiator, and in the case of a heat pipe radiator the length of the radiator, using a large diameter duct (e.g. 6-8 inch) rather than a smaller (e.g. 1-2 inch) fluid line. For the study power levels, Brayton systems will require radiator areas greater than  $150 \text{ m}^2$  with lengths at least that of the space station design (14.3 m deployed length and  $85 \text{ m}^2$ ). For these distances the mass difference associated with transporting a gas versus a liquid becomes very significant. Secondly, the pressure drop that results from the longer ducting in the directly coupled configuration negatively impacts Brayton efficiency due the change in pressure ratios across the turbine and compressor. Advanced radiator concepts such as liquid droplet, liquid belt, solid belt Curie point, filament and rotating membrane configurations were considered too technically immature to be included at this time.<sup>36</sup>

**Table 7: Concept Combination for Reject and Manage Waste Heat**

<b>Reject and Manage Waste Heat</b>		
<b>Thermal Transport</b>	<b>Radiator Thermal Transport</b>	<b>Radiator Geometry</b>
<i>Passive</i>	<i>Passive</i>	Fixed
Heat Pipe	Heat Pipe	Deployable
Loop Heat Pipe	Loop Heat Pipe	
<i>Active</i>	<i>Active</i>	
Pumped Loop	Pumped Loop	

### **5.1.4 Distributed Control and Environmental Protection**

Distributed control and environmental protection encompasses many attributes that are highly integrated across the NEPP system in addition to a few very specific environmental protection functions.

The function of protecting the spacecraft, payload and other parts of the NEPP system from neutrons and gamma rays produced by the reactor takes form as a radiation shield. The shield material may be relatively independent of reactor selection although the shield configuration, size and placement relative to the combined reactor and power conversion system can be dependent upon the reactor and mission. Mass and geometry are critical factors and may drive a layered design of shielding materials. The vacuum of space and a non-human mission allows for a shield design to be used on only one side of the reactor and is set to a specific cone half-angle for shadow protection. Lithium Hydride (LiH) was used as the neutron shield material for both the SNAP and SP-100 programs and can still be considered the preferential material, although Be could potentially be used. In shielding against gamma rays, high atomic number and high-density materials would be expected to result in a minimum mass shield.<sup>37</sup> Candidate

gamma ray shielding materials include tungsten, uranium and stainless steel alloys. The SP-100 reference radiation shield utilized W-Ni-Fe alloy for primary and secondary gamma attenuation.<sup>38</sup> Favorable architectures must minimize shield mass and protect other systems by minimizing total exposure, minimizing neutron scattering effects around the shield and minimizing neutron streaming through any penetrations in the shield.

This functional category also includes items that are dedicated to the safe operation of the system from transport to launch to in-space operation. This function also serves to protect the Earth environment during each of these respective phases. Transportation trades may impact the reactor assembly by requiring an architecture that can be fueled at the launch site allowing for separate reactor and fuel shipments. Protecting the Earth environment from inadvertent reentry of the system or launch accident is first accomplished by assuring that the reactor is not operated in a critical state prior to achieving a nuclear safe orbit. Second, the shield around the reactor core must be capable of surviving reentry and Earth impact in an intact state. The SP-100 design used a carbon-carbon heat shield for this purpose. Given the maturity of the concept designs it is difficult to assess if this is a discriminating factor among candidate reactors. Properties of the material include high heat tolerance for operation and re-entry and ductility for impact.

Controlling the NEPP system requires coordination within the NEPP system and spacecraft. This is accomplished through a variety of operational sensors. Because of the distances and associated time delays between Earth and the spacecraft, the system must possess autonomous detection, diagnostics and decision capabilities. The approach taken to control is a critical architectural decision that must integrate several distributed control

systems. This must encompass classic control methods or proportional-integral-derivative control with some type of advanced control methods. Architectures may include intelligent adaptive, fuzzy and neural type controls but would most likely include a more conservative hierarchical or supervisory control approach. Reactor systems are designed with independent protection and control systems although the control systems have inherent protection features. Deciding on the optimum control architecture is critical for mission success. This includes meeting all science and safety objectives and may become an influential factor when differentiating between the stability or ability to control subsystems and the interaction between subsystems.

**Table 8: Concept Combination for Control Operation and Protect Environment**

<b>Control Operation and Protect Environments</b>	
Radiation Shield	Control Logic
LiH and W	Distributed
Be or Other	Central
	Other Advanced

### **5.1.5 Distributed Power Management**

The functional components of the power management and distribution system are highly dependent on power conversion concept selection. Static systems produce a lower voltage direct current (DC) while dynamic systems are designed with an alternator that produces higher voltage alternating current (AC). The power conversion systems also vary in voltage and frequency output. Electric propulsion devices require high voltage and frequency input while the spacecraft bus, used for other spacecraft subsystems, requires a standard spacecraft operating voltage of 28 Volts DC. Distribution voltages to the spacecraft bus can range from the 28 V spacecraft standard to the International Space

Station 120 V DC design or to advanced higher voltage systems (e.g. Advanced aircraft designs at 270 V DC).

Electric propulsion input characteristics must also be integrated with the power conversion system output and distribution decision. As previously noted, dynamic Brayton and Rankine power conversion devices allow for a direct drive option that can produce a high voltage output (1000's of Volts) from the power conversion alternator directly to the electric propulsion device's power processing unit. This allows for the elimination of components required to step up voltages and/or frequencies. This option is captured in the power conversion table and directly impacts the power distribution and management functions. However, even if a high power direct drive option is not selected, the dynamic devices can deliver higher power to the PPU's than is required by the spacecraft bus. Essentially there are two separate power distribution decisions: Distribution to the spacecraft bus and distribution to the thruster PPU.

The functional components include inverters, rectifiers, filters, transformers, controllers and associated electronics necessary to convert, condition and distribute power. These elements are functions of concept and reliability requirements. Lifetime requirements drive reliability that may also lead to two parallel distribution systems that are cross-strapped for redundancy. This may result in multiple static or dynamic power conversion systems and corresponding power management devices.

Providing power for LEO reactor system start, radiator deployment and maintaining dormant spacecraft low power requirements introduces a secondary power generation function. This role could be fulfilled by a variety of solar array and battery designs or could potentially be addressed with RTGs. If batteries are used it is assumed

that they would be recharged by the operating reactor as the solar arrays would become increasingly less effective at greater distances from the sun. RTGs could remain autonomous for many years. The most pivotal systems independent elements are included in Table 9.

**Table 9: Concept Combinations for Manage Power and Enable Start and Shutdown**

<b>Manage Power and Enable Start and Shutdown</b>		
Distribution to Thruster	Distribution to Bus	Secondary Power
<i>Static Conversion</i>	<i>Static Conversion</i>	RTG's
28 V DC	28 V DC	Solar Array/Battery
120 V DC	120 V DC	
<i>Dynamic Conversion</i>	<i>Dynamic Conversion</i>	
120 V AC	28 V DC	
300-600 V AC	120 V DC	
> 3000 V DC (direct drive)		

### 5.1.6 Electric Propulsion Devices

Electric propulsion thrusters can be categorized as electrothermal, electrostatic and electromagnetic. Electrothermal devices electrically heat a propellant that is then expanded through a nozzle to provide propulsion. Examples include resistojets and arcjets with demonstrated specific impulses of  $\sim 300$  seconds and  $< 1,200$  seconds, respectively. Electrostatic thrusters use an ionized propellant that is accelerated through an electric field. Examples include the Hall thruster and ion thrusters. Hall thrusters have demonstrated specific impulse values of  $\sim 1,600$  seconds for flight articles and  $> 3,000$  seconds for development level articles. Ion devices have flight proven values of  $\sim 3,100$  seconds. Development of 4,000 to 6,000 second ion devices is being pursued for next generation propulsion applications with future generation devices seeking 6,000 to

10,000 seconds. Electromagnetic thrusters, also known as a Lorentz Force Accelerators (LFA), produce thrust by accelerating charged plasma through a magnetic field. Examples include the Magnetoplasmadynamic thruster (MPD) and Pulsed Plasma Thruster (PPT). These devices offer greater levels of specific impulse, 2,000 to 10,000 seconds or more, but operate at very high voltages. Important to all of these devices are the power level of operation and lifetime.

The PPU is usually associated with the EP subsystem because of the close electrical coupling and electrical tailoring for the specific EP device. The PPU must transform, for AC input, and convert for either AC or DC input, to high frequency, high voltage DC power for the thrusters. Depending on whether direct drive is selected or not will directly impact the PPU internal design. Reliability and the number of total thrusters used will determine the number of PPUs used.

The number of thrusters will be determined by the type, thruster size or power level, mission requirements and redundancy requirements. One architectural alternative is to combine different types of thrusters (e.g. Hall and Ion) in order to take advantage of their respective propulsion properties. Hall devices provide a greater thrust but are less efficient while ion devices are very low thrust but highly efficient.

Although “Propellant and Tanks” was identified at the equivalent level of decomposition as the NEPP system at the spacecraft level decomposition (Figure 6), transferring and regulating the propellant flow through a propellant feed system is part of the lower NEPP functional domain of “Producing Thrust from Electrical Power”. A variety of propellants can be used including xenon, krypton, argon, cesium or mercury

however the most influential architectural decision is whether or not to store and transfer the propellant at cryogenic or supercritical temperatures.

**Table 10: Concept Combination for Produce Thrust From Electrical Power**

<b>Produce Thrust from Electrical Power</b>	
Electric Propulsion Device	Propellant Delivery System
<i>Electrothermal</i>	Supercritical
Arcjets	Cryogenic
Resistojets	
<i>Electrostatic</i>	
Hall	
Ion	
Hall/Ion	
<i>Electromagnetic</i>	
Magnetoplasmadynamic (MPD)	
Pulsed Plasma Thruster (PPT)	

## 5.2 Concept Combination

The number of theoretical concept combinations that can be derived by completing a full factorial of the above six tables yields approximately 58,786,560 architectures. Fortunately not all of the possible combinations are feasible or desirable from a practical engineering standpoint. Chapter 6 moves through both filtering and screening to arrive at a promising subset of architectures. The concept or variables selected are the ones with the greatest leverage across the architecture in terms of impacting other subsystems and interrelationships. Other potential concepts deemed too technologically immature were not included at this time.

## 6.0 Filtering and Screening of Concept Architectures

The objective of this section is to narrow the candidate concept tables and resulting combined sets of concept architectures by filtering and screening, respectively. Filtering is performed on the individual concept tables prior to combining the tables together as end-to-end NEPP architectural concepts and applying the developed screening criteria. Mission planning and system level mass measures are also introduced.

### 6.1 Identification of Evaluation Criteria By Mission Phase

Several dimensions must be considered for evaluation criteria including the top-level system goals and objectives, architectural frameworks and influences and fundamental functional behaviors of the systems and subsystems. Although challenging, it is also important to distinguish between design requirements and the appropriate architectural discriminators. One approach is to apply a temporal perspective that identifies criteria along salient phases of a spacecraft system. Table 11 divides the criteria by the spacecraft phases of Development and Qualification, Transportation and Launch, Mission and Operations and Future Missions. Descriptions of the criteria are provided in the following sections.

**Table 11: Architectural Concept Discriminators by Mission Phase**

<b>Development And Qualification</b>	<b>Transportation and Launch</b>	<b>Mission Operations</b>	<b>Future Missions</b>
1) Technology Readiness Level 2) Infrastructure 3) Complexity 4) Strategic Value	5) Schedule 6) Launch Packaging	7) Power 8) Specific Mass 9) Lifetime 10) Payload Interaction	11) Adaptability

### 6.1.1 Development and Qualification

The Development and Qualification phase contains four discerning criteria. “Technology Readiness Level” (TRL) is a measure of technical maturity, as defined in Table 12, ranging from basic principles and observations to flight proven designs. Note that the Apollo era Saturn V rocket is a TRL 9, however, as with many large complex systems that encounter an appreciable hiatus, they become increasingly difficult to reproduce over time and the schedule to recapture the capability remains elusive. Reasons include changing or deteriorating infrastructure, facilities, knowledge capture, manufacturing methods and other effects of shifting investments and time. Because this phenomenon is very applicable to nuclear space power systems the criteria titled “Infrastructure” is included to capture and discriminate among concepts affected by loss in availability, producibility and changes in the government and commercial base. One other important aspect of the TRL scale is recognizing the amount of effort or risk involved in moving to the next TRL level. In some cases the physics of the problem are not as easily solved as they might be in other situations.

**Table 12: NASA Technology Readiness Level (TRL)**

TRL Level	Level Description
9	Actual system “flight proven” through successful mission operations
8	Actual system completed and “flight qualified” through test and demonstration
7	System prototype demonstration in a space environment
6	System/subsystem model or prototype demonstrated in relevant environment
5	Component and/or breadboard validation in a relevant environment
4	Component and/or breadboard validation in a laboratory environment
3	Analytical & experimental demonstration of critical function and/or proof-of-concept
2	Technology concept and/or application formulated
1	Basic principles observed and formulated

“Complexity” includes the inherent intricacy and physical implementation challenges associated with the concept NEPP subsystems, the ability to integrate the NEPP system and the ability to integrate the NEPP system with systems in external domains. This measure considers the engineering behaviors, producibility, manufacturability and testability. Cost is inherently reflected in this measure although it does not contribute to this measure. “Complexity” also includes the relative ability to qualify a design both analytically and physically.

“Strategic Value” reflects an understanding of the mission, political and organizational factors that impact architectural decisions independent of technical attributes. This measure is sensitive to customers and stakeholders and is inclusive of organizational factors. This element considers two of Brenda Foreman’s “Facts of Life” on the political process and systems architecting: “Technical problems become political problems” and “The best engineering solutions are not necessarily the best political solutions.”<sup>39</sup> This measure reflects the ability to implement the architectural influences in Chapter 4 such as “Corporate Strategy” and “Customer and Market Strategy” that may allow a program to pass or fail independent of technical attributes.

### **6.1.2 Transportation and Launch**

The “Schedule” criterion represents an assessment of the ability to deliver a flight-qualified system to the launch site within the 10-12 year target period assuming resource projections commensurate with the current NASA budget projections derived from Figure 23. “Launch Packaging” assesses the ability to integrate the system with the launch vehicle and stow the NEPP system within the payload fairing. Volume can become a factor with large heat rejection systems and is accounted for with this criterion.

This measure includes on-orbit deployment as it relates to stowage. Unique assembly or testing that may be performed at the launch site is considered.

### **6.1.3 Mission Operations**

“Power” is the key to meeting the fundamental mission requirements and addresses the capability of the architecture to operate within the 75-250 kW range. Directly related to this is the corresponding system “Specific Mass”. Having lower specific mass values allow for increased payloads and increased mission ranges. This is one of the most important parameters for an NEPP system and is also difficult to assess without actual designs or test hardware.

“Lifetime” is the capability to operate successfully over the mission lifetime of 8-12 years. Closely coupled to this is the ability to accommodate reliability requirements through redundancy. For example some power conversion, heat rejection and reactor concepts lend themselves to incorporating higher levels of redundancy.

“Payload Interaction” includes all types of detrimental effects caused by the NEPP system. This includes vibration, radiological, thermal, electromagnetic and propulsion effluents and the measures taken to mitigate the effects.

### **6.1.4 Future Missions**

“Adaptability” is inclusive of modularity and ability to scale within the power range of 75-250 kW. Scalability above 250 kW is not considered a discriminator although modularity that potentially allows for the development of other mission classes is a positive attribute. “Adaptability” is also addressed by placing value in the ability to

operate with different combinations of subsystems and respond to different mission scenarios.

### **6.1.5 Criteria Excluded**

Cost became very difficult to independently assess other than what is implied through complexity, advancement of TRL, reviving infrastructure and other attributes. Mass is simply limited to an expendable heavy lift launch vehicle and does not serve as an economic discriminator as it will be limited by the largest launch vehicle (e.g. EELV heavy class). Although conceivably an on-orbit assembly scenario is possible, involving two or more flights, the specified mass for this thesis limits the system to one flight on a U.S. expendable heavy lift launch vehicle.

Military requirements were also not considered as on previous programs such as SNAP and SP-100. Criteria such as survivability of enemy attacks, remote detection and various threat assessments are not considered. Extended LEO operational considerations such as dormancy, thermal cycling, and atomic oxygen were not considered. Protection from orbital debris at orbital insertion altitudes and interplanetary travel is considered as a design requirement for all systems in addition to space radiation environments. Maintainability, human factors, supportability or any type of on-orbit servicing are not considered to be discriminators.

Lastly, safety and surety are also not considered to be measures that can differentiate among concepts at this time. All concepts, if selected for flight, must ultimately meet the same flight and ground safety criteria regardless of design. While some concepts may be inherently more reliable, as a result of innate factors such as a lower level of complexity or reduced operating temperature, they cannot necessarily be

considered safer due to this dictum. This binary gate is the difference between flight and non-flight and does not make a good measure of merit, as other measures do, that can infer or incorporate both quantitative and qualitative information. Although this is applicable throughout the entire mission lifetime it is heavily weighted on potential accidents in the early part of the mission that involve the Earth or Earth's atmosphere. In all cases numerous and exhaustive requirements for safety and surety must be unequivocally addressed prior to flight.

## 6.2 Mission Planning

The Science Mission Domain depicted in Chapter 4, Figure 6, imposes considerable requirements on the selection of candidate concept architectures. Power, mass, specific mass and lifetime are attributes that become some of the most significant parameters traded during mission planning. Different trajectories and combinations of launch vehicles and upper stages can be considered for Earth escape. This directly impacts the architecture of the NEPP system by trading propulsion responsibilities between the spacecraft and launch vehicle. One mission concept may select a relatively low Earth injection altitude and use the low-thrust NEPP system to escape from Earth orbit. An alternative approach would be to use an upper rocket stage that would use a chemical stage to escape Earth orbit. The trade becomes one of time and mass. If the first concept were used more time, potentially over a year, would be required to perform the spiral escape maneuver. If the latter concept were used the NEPP vehicle mass would be significantly decreased because of the chemical upper stage and would result in decreased mission capability due to the less efficient use of mass and propellant. This option may also decrease the NEPP system mass to a point of infeasibility, at near term

technology levels, or necessitate a second flight for a complex and costly on-orbit assembly.

The more plausible trades occur between the NEPP system mass and the insertion altitude. NASA studies indicate that it will be challenging for the first NEPP systems to meet the launch mass requirements. This will drive the insertion altitude to whatever is determined to be an acceptable minimum. Early JPL studies indicated that an altitude of 700 km could be used for similar NEPP missions. This would correspond to a nuclear safe orbit where the spacecraft would not enter the Earth's atmosphere within 300 years.<sup>40</sup>

## 6.3 Critical Relationships and Application of Criteria

This section introduces critical behaviors, attributes and functional constraints of the NEPP system, subsystems and components that are then used in combination with the top-level goals and objectives to filter the concept combination tables.

### 6.3.1 NEPP System Level Considerations

One of the most often used measures of space power system performance is the specific mass, or alpha ( $\alpha_p$ ), measured in kg/kW. Alpha values are calculated in different ways depending on what is included in the mass portion of the ratio. Some calculations may include total vehicle dry mass minus the payload, while other calculations may only include those masses that scale with power. The danger in the latter method is that unless a complete understanding of the system interrelationships are understood, errors can be made in power scaling calculations. Lower values are more desirable as they allow for

reduced trip times and/or increased payloads. Alpha values are highly dependant upon the power level of operation of a system.

Total system mass is critical as there is a finite amount of lift capacity in U.S. launch systems. Total system mass can be approximated by the following equation:

$$M_t = \alpha_p P_0 + T M_{\text{propellant}} + M_{\text{fixed}} + M_{\text{payload}} \quad (5)$$

Where  $M_t$  equals the total spacecraft mass,  $\alpha_p$  equals the power system alpha,  $P_0$  equals the initial electric power of the system,  $T$  equals the total percentage of propellant required that includes “tankage” or margin/error factors,  $M_{\text{propellant}}$  equals the calculated propellant requirement,  $M_{\text{fixed}}$  equals the structures, mechanisms and adapters and  $M_{\text{payload}}$  is a nominal value that is reserved for the payload.

A NASA/DOE NEP Study Team was formed in July 2001 with representatives from Marshall, Glenn, JPL, and several DOE national laboratories including Sandia, Los Alamos, and Oak Ridge. In February 2002, the Study Team produced an initial report showing mass allocations of a conceptual 100 kW NEP (dry) vehicle to be 59% reactor power system, 7% ion propulsion system, 15% vehicle subsystems, and 19% payload. The significant mass contribution of the reactor power system reveals its relative importance to the NEP vehicle design.

### **6.3.2 Nuclear Reactor Subsystem**

Liquid metal reactors can be used with all candidate power conversion systems and are the only reactor systems that have ever flown in space. Liquid metal reactors have the greatest experience base although they have lost developmental momentum since SP-100. Issues still remain regarding lifetime, complexity and cold startup.

Heat pipe reactors offer passive cooling over active pumped loop liquid or gas systems, provide redundancy and eliminate mass transfer issues. Heat pipe reactors are the least mature technically of the reactor concepts. Heat pipes have a high degree of complexity and do not scale well above ~150 kW. Multiple shield penetrations are required and present concerns with radiation streaming to the other spacecraft systems.

Gas cooled reactors are not readily compatible with Stirling, Rankine or TE conversion systems due to poor heat exchange characteristics. Gas cooled systems are most advantageous in terms of specific mass in the direct connection heat exchange configuration with the Brayton system. This concept does introduce rotating machinery vibration and reliability concerns. The concepts scale well for the interplanetary power range and are adaptable to higher temperature fuel and material substitutions. A terrestrial experience base does exist for gas-cooled reactors.

The fuel selection has a significant impact on the subsequent architecture due to the direct effect on safety and reactor operating temperature. Although U-ZrH fuel was used for the early SNAP reactors and is space qualified there is currently no existing U.S. infrastructure to produce the U-ZrH. Also, U-ZrH outlet temperatures are limited to about 920 K (1200F), which limits higher power applications.<sup>41</sup> Table 13 provides a summary of some of the important characteristics of the other candidate fuels:<sup>42</sup>

**Table 13: Characteristics of NEPP Fuels**

Characteristic	UO <sub>2</sub>	UN	UC	UC <sub>2</sub>
U Density, g/cc	9.66	13.52	12.97	10.6
Melt Point, K	3100	3035	2775	2710
Thermal conductivity W/mK	3.5	25	23	18
Relative stability	Moderate	Low	High	High
Relative Swelling	Low	Mid	Mid	Low
Fission Gas Release	High	Low	Mid	Low
Fabricability	Easy	Moderate	Easy	Difficult

UC and UC<sub>2</sub> do not provide significant technical benefit over UN, other than high temperature stability, to warrant further pursuit. Qualification work performed on UN, as part of the SP-100 effort, created a significant database over UC fuels providing an advantage from an infrastructure and investment perspective. In a 1993 NASA / DOE report on Space Exploration Initiative Fuels, UN pin fuels ranked the highest for NEPP systems due to their potential to utilize SP-100 experience and the ability to flight qualify smaller systems (100-500kW).<sup>43</sup> Because of the length and costly process required to fully qualify fuel and fuel forms, it is prudent to consider only the most well established Uranium 235 fuel forms using either UN or UO<sub>2</sub>. The selection between UN, which has better properties, and UO<sub>2</sub>, which has a greater industrial base, availability and understanding, will be primarily based on time and the projected cost to bring the UN fuels to a fully qualified state. Lastly, while cermet fuels offer advantages for NTR or bimodal systems they are presently too immature for consideration at this time for a near term NEPP system.

Cladding selection is also highly coupled to fuel selection and system performance through increased operating temperature. Fuels interact with the cladding and liners by swelling against the material, releasing fission gases that result in

mechanical pressure and through chemical corrosion. Interaction between the fuel/cladding system and the coolant is also a factor when combining UO<sub>2</sub> with liquid metals. Although stainless steel is relatively easy to fabricate and can be used with both UN and UO<sub>2</sub>, the temperature is limited to around 950 K which inhibits system growth to the higher power levels in the planetary requirements range. Refractory materials with different liners can move operating temperatures to approximately >1400 K although they are more challenging to fabricate and qualify.

Selecting a low temperature system does little to advance the state of the art and introduces significant performance concerns. This limits the selection of the most compelling missions for NEPP and correspondingly reduces the necessary constituent and political advocacy. High temperature operation increases system efficiencies and decreases specific mass although introduces material manufacturing and lifetime issues. UN exhibits the best properties for high temperature operation and is selected over UO<sub>2</sub> for this option. A true assessment of manufacturing capability cannot be ascertained until the industrial base is reengaged again. Consequently initial pursuit of a high temperature system is warranted along with a medium temperature system. The filtered combination matrix results in the following:

**Table 14: Filtered Concept Combinations for Produce Thermal Energy**

Produce Thermal Energy		
Reactor	Fuel	Operating Temperature
Liquid Metal	UN	Low
Gas Cooled	UO <sub>2</sub>	Medium
Heat Pipe	UC	High (UN only)
	UC <sub>2</sub>	
	U-ZrH	
	Cermets	

### 6.3.3 Energy Conversion Subsystem

Specific mass versus power level is the most advantageous characteristic for Rankine systems beyond approximately  $\sim 400$  kW (Figure 25). This critical characteristic along with a terrestrial knowledge of the cycle has resulted in the consideration of these systems within the space reactor/ conversion cycle trade space over the years of intermittent studies. However, they are the most complex choice of the conversion systems. They require two-phase fluid management, which in low gravitational environments is problematic. Rankine systems have made very little progress since the 1960's SNAP program and suffer from a significant loss of infrastructure and knowledge base. Until a true assessment of the industrial base to produce this system can be completed this system should remain in the trade space due to its favorable specific mass characteristics.

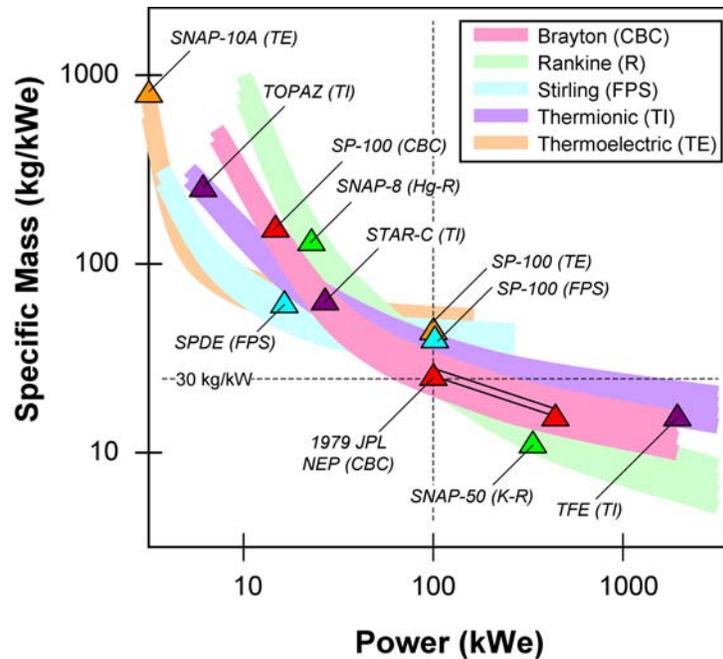
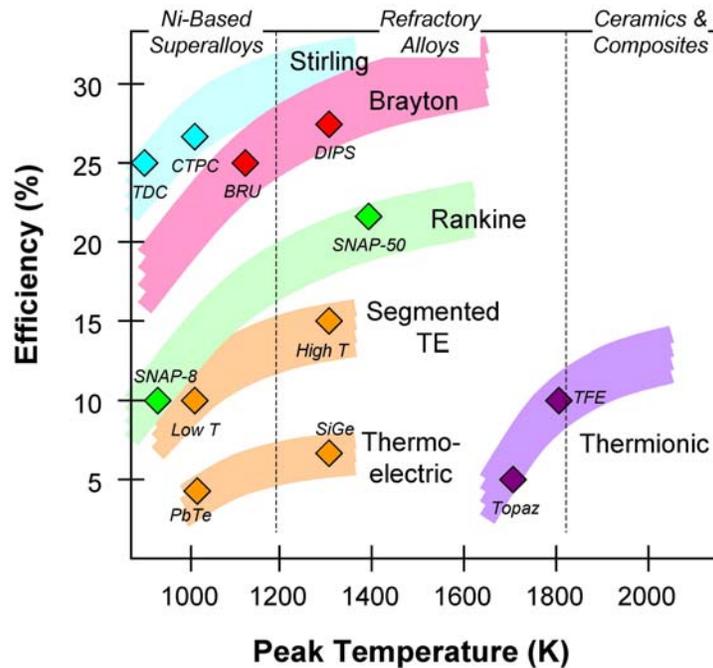


Figure 25: Specific Mass Versus Power Level<sup>44</sup>

Stirling cycles have a small commercial terrestrial market and are currently being pursued for lower power space radioisotope systems. When compared against Brayton for spacecraft systems applications, the crossover point for specific mass is around 30-40 kW at which time Brayton offers the lowest mass option.<sup>45</sup> Stirling devices produce low frequency output due to the linear alternator, which also negatively impacts the power management subsystem. Although these devices offer advantages over thermoelectric radioisotope systems and have advanced in technical maturity for the lower power ranges, it is difficult to include them among the most feasible dynamic conversion options for the 75-250 kW range NEPP application due to specific mass and integration scaling issues.

Brayton space systems have advanced since the 1960's through the development of several ground based demonstrators for both nuclear and solar dynamic systems. Open cycle systems have an extensive terrestrial use and limited space flight use (e.g. space shuttle auxiliary power unit) and can provide data on operational reliability. The system has very attractive specific mass values for the selected power range and has very good efficiencies (> 25%) in the medium temperature ranges (Figure 26). Brayton systems have a low rejection temperature that results in a greater radiator area than other dynamic systems. This sensitivity results in large, heavier radiators for low temperature systems. If rejection temperatures are increased too much then the Brayton cycle efficiencies decrease. Directly coupling a gas cooled reactor to the Brayton system reduces system mass and parts although may become more complicated to test and operate. One additional concern is that analysis has shown that xenon coolant will become activated

through neutron absorption and, although no changes in the physical properties occur, some level of radioactive sources will be present in the combined loop.<sup>46</sup>



**Figure 26: Converter Efficiency Versus Operating Temperature<sup>47</sup>**

Thermoelectric devices offer proven flight heritage, no rotating machinery and redundancy. Conversely, they also are very inefficient, do not scale well with in the 75-250 kW power range and have significant lifetime issues. The SP-100 program calculated that a total of 8,640 SiGe cells would be required for a 100 kW system.<sup>48</sup> Thermoelectric issues include: Increasing the thermoelectric figure of merit “Z”, maintaining the bond between the thermoelectric cell and heat source over the lifetime and maintaining electrical insulation over the lifetime. Further, the low voltage DC output impacts the power management and distribution subsystem by requiring additional equipment in order to significantly increase the voltages for EP devices. Radiatively coupled segmented designs offer increased efficiencies and longer lifetimes but are at a low TRL. Unfortunately reliability advantages of static systems decreases as higher

efficiencies are pursued through higher temperatures (Figure 26) and closer tolerances. SiGe thermoelectric devices will however remain in the trade space due to their proven flight heritage, inherent redundancy and static characteristics for potential use at the low end of the targeted power range. PbTe devices, while having flight heritage have been replaced with higher performing SiGe devices.

Thermionic systems while offering the advantages of compactness (e.g. Space Thermionic Advanced Reactor-Compact (STAR-C) concept) encounter significant issues with fuel swelling and venting of fission gases. The STAR-C thermionic reactor/power conversion system was mass competitive below about 15 kW but at higher power levels the scalability was relatively poor.<sup>49</sup> Thermionic fuel element and converter lifetime, overall technical maturity and the limited ability to scale to higher power levels remain the dominant restrictions on selecting both in-core and ex-core thermionic systems for further consideration. To achieve reasonable efficiencies also requires significant operational temperatures (Figure 26), which further limits lifetime. Thermionic systems do offer smaller radiators due to higher heat rejection temperatures, and hence smaller signatures, which made them attractive to earlier DOD missions.

Thermophotovoltaic conversion is not mass competitive in this power range, scales poorly and has a low TRL for higher efficiency devices. TPV is therefore also removed from the matrix.

The potential to eliminate the heat exchanger for the combined liquid metal reactor and Rankine system is eliminated due to technical maturity, control, corrosion and erosion issues associated with the coupled design. The combined gas cooled reactor and

Brayton conversion system combination is however kept in the trade space due to its potential to reduce specific mass at higher temperature operation.

Selecting a power management and distribution concept that allows for a directly connected electric propulsion module is also considered technically immature at this time. This would require that both the power conversion system alternator produce a very high voltage output, ~ 4,000 V DC, and the power management system components are capable of transferring the high DC power across the spacecraft to the electric propulsion power processing units. This option is also not applicable to static devices. The filtered combination matrix results in the following:

**Table 15: Filtered Concept Combinations for Convert Thermal Energy to Electrical Power**

<b>Convert Thermal Energy to Electrical Power</b>		
Device	Heat Exchange	High Power EP Drive
<i>Dynamic</i>	<i>Dynamic</i>	<i>Dynamic</i>
Rankine	Direct (Brayton only)	Direct
Brayton	Indirect	Indirect
Stirling		
<i>Static</i>	<i>Static</i>	<i>Static</i>
Thermoelectric (SiGe)	Indirect	Indirect
Thermoelectric (PbTe)		
Segmented Thermoelectric		
Thermionic in-core		
Thermionic ex-core		
Thermophotovoltaic		

### 6.3.4 Radiator and Thermal Management Subsystem

Rejection of waste heat in a space environment can be expressed by the Stefan-Boltzmann equation:

$$Q_R = \epsilon \sigma A (T_c^4 - T_s^4) \quad (6)$$

Where  $Q_R$  is the heat radiated,  $\varepsilon$  is the surface emissivity for thermal radiation,  $\sigma$  is the Stefan-Boltzmann constant,  $A$  is the area of the radiating surface,  $T_c$  is the absolute temperature of the radiating surface and  $T_s$  is the absolute temperature of the radiative sink. This equation illustrates that the surface area and related mass of the radiator are very sensitive to heat rejection temperature. This leads to the conclusion that high heat rejection temperatures will lead to lower radiator mass. However, power conversion device efficiencies are also sensitive to heat rejection temperatures. The power conversion cycle efficiency is expressed as:

$$\eta_P = \eta_D \eta_C \quad (7)$$

Where  $\eta_P$  is the power conversion efficiency,  $\eta_D$  is the device efficiency and  $\eta_C$  is the Carnot efficiency. The Carnot efficiency can be expressed as:

$$\eta_C = \frac{T_H - T_C}{T_H} \quad (8)$$

Where  $T_H$  is the power conversion inlet temperature and  $T_C$  is the power conversion rejection temperature. This illustrates that an optimal temperature must be derived that satisfies both power and mass requirements for the entire system. Higher operating temperatures are helpful in advancing device efficiency and increasing power levels however this impacts radiator size which can decrease overall specific mass and area constraints. Conversely, seeking to reduce the mass and area of the large radiators is desirable but impacts system performance. Summarizing, the sensitivity to radiator mass and area will drive the selection of a less efficient system than for terrestrial applications.

Both the amount of heat transport required and the difficult integration of a heat pipe transport system to a radiator system, that may also use a heat pipe system,

precludes the use of heat pipe devices as a mechanism to transport waste heat away from the power conversion device. Transport within the radiator system can be accomplished by either heat pipes or pumped loops. Heat pipes offer the advantage of greater redundancy and reliability than a pumped loop, passive transport and flight heritage on the International Space Station. Micrometeoroid damage and leakage is also a significant concern and multiple heat pipes offer greater redundancy over a few pumped loops. The International Space Station design, that uses a pumped loop transport and redundant heat pipe transport within the radiator, is the most likely concept selection. SP-100 also selected a baseline design that utilized a pumped loop for thermal transport and heat pipes for heat rejection. However, current performance ISS values of 15 kg/m<sup>2</sup> will have to be reduced by material substitutions, new deployment mechanisms or lightweight associated structures. Deployable geometries may be different depending on spacecraft configurations.

Radiator sizing studies show that the area required for NEPP systems is similar to the space station radiator area, which precludes the use of fixed radiator designs. This is also especially true for Brayton conversion systems with low rejection temperatures.

**Table 16: Filtered Concept Combinations for Reject and Manage Waste Heat**

<b>Reject and Manage Waste Heat</b>		
<b>Thermal Transport</b>	<b>Radiator Thermal Transport</b>	<b>Radiator Geometry</b>
<i>Passive</i>	<i>Passive</i>	Fixed
Heat Pipe	Heat Pipe	Deployable
Loop Heat Pipe	Loop Heat Pipe	
<i>Active</i>	<i>Active</i>	
Pumped Loop	Pumped Loop	

### 6.3.5 Control and Environmental Protection Subsystem

Radiation shielding geometry will be reactor and power conversion system dependent. Some concepts can transport heat through penetrations in the reactor shield and other concepts can route the thermal transport around the shield. In either case, previous work performed under the SP-100 program is relevant and applicable. The properties of LiH and Be for Neutron shielding and W for gamma shielding remain the most favorable candidates. The effect of neutrons streaming through the LiH shield or scattering at the edges, due to reactor to energy conversion thermal connections or heat pipe connections, is a concern that can worsen with power level. Determining the exact cone angle of coverage will also be dependant on the reactor as will reentry shielding. Safety concerns may also mandate the design of an auxiliary coolant loop in the reactor.

Control logic and integration with the spacecraft control systems should follow a conservative design that can be readily communicated. Distributing the functions would be highly advanced for a combined spacecraft and NEPP system at this time. First generation systems should follow a conservative control and software design due to the nuclear nature of spacecraft and desire to explain nominal, off-nominal and safe modes of operation to numerous external review committees.

**Table 17: Filtered Concept Combinations for Control and Operate Safely**

<b>Control Operation and Protect Environments</b>	
Radiation Shield	Control Logic
LiH and W	Distributed
Be or Other	Central
	Other Advanced

### **6.3.6 Power Management Subsystem**

As discussed in Chapter 5, power distribution concepts are highly dependent on the output characteristics of the power conversion device, which can be either high voltage (100's of Volts) AC for rotating dynamic systems or low voltage DC for static systems. The two main power requirements are for the thruster PPU and the spacecraft bus, which are a very high voltage DC (1000's of Volts), and 28 V DC, respectively. The objective in selection is to minimize mass and the number of total components while maintaining a high reliability through redundancy and controllable operating ranges. It is also highly desirable to limit the total amount of power electronics devices due to the sensitivity to the planetary and on-board reactor radiation environments that directly impact lifetime.

High voltage AC and DC are more efficient to transmit than low voltage DC and result in lower mass cabling. If dynamic devices are used it becomes favorable to use the higher voltage AC before converting to DC for longer cable distances. Notionally, the power management subsystem would be located adjacent to the spacecraft bus, however studies have shown the PPU and thrusters being located at various places around an NEPP vehicle.

For a dynamic system that produces a high voltage, the distribution to the thrusters should maintain the highest AC voltage practical to the thruster PPU's. Ideally this can be taken up to the high voltage direct drive concept but at this time the alternators, power electronics and controls are simply deemed too technically immature to pursue this option. The distribution to the spacecraft bus will most likely draw upon the flight heritage of the International Space Station and use the 120 V DC distribution

systems. Lower distribution voltages only increase the mass and higher distribution levels limit the amount of space-qualified devices that can be incorporated into architecture.

For static conversion systems with a low voltage output the choice is less clear. If a more compact architecture were selected, on the low end of the study power range (75 kW), there may be reason to use the standard 28 V DC systems or the ISS 120 V DC system for both distributions. However due to added components, probably not both.

For the initial phase of the mission, including reactor start-up and maintaining minimum S/C bus and instrument power, the secondary power requirements can be met using a small solar array and battery. This is the simpler, less costly and preferred approach. The operating reactor and battery combination can meet subsequent requirements as long as the reactor is operational. The key assumption is that the reactor is never shutdown but operated in a low power mode. Therefore the RTG is eliminated at this time. If the assumption changes this decision will have to be revisited.

**Table 18: Filtered Concept Combinations for Manage Power and Enable Start and Shutdown**

<b>Manage Power and Enable Start and Shutdown</b>		
Distribution to Thruster	Distribution to Bus	Secondary Power
<i>Static Conversion</i>	<i>Static Conversion</i>	RTG's
28 V DC	28 V DC	Solar Array/Battery
120 V DC	120 V DC	
<i>Dynamic Conversion</i>	<i>Dynamic Conversion</i>	
120 V AC	28 V DC	
300-600 V AC	120 V DC	
> 3000 V DC (direct drive)		

### 6.3.7 Electric Propulsion Subsystem

NASA studies have indicated that for NEPP interplanetary missions,  $I_{sp}$  values of greater than 6,000 seconds will be required. Electrothermal systems, although flight demonstrated, do not provide high enough exhaust velocities and are therefore significantly less efficient when applied at a primary propulsion level over long trip distances. Specific impulse values for these systems are correspondingly too low (< 1,200 seconds) to serve as primary propulsion for interplanetary travel.

Since propulsion system power is proportional to the product of  $I_{sp}$  and thrust, high specific impulse systems require high power levels to generate thrust. This increases the requirement for higher power devices. While electromagnetic devices offer the promise of higher power and higher  $I_{sp}$  values, they are unfortunately considered to be at too low of a technology readiness level to be included for consideration for a relatively near term NEPP mission.

Electrostatic systems, both Hall and ion, have flight heritage and are advancing technologically due to ongoing industry, government and university development programs. Hall thrusters produce greater thrust and offer an advantage over ion devices when escaping planetary gravitational wells but do so with less  $I_{sp}$  than ion devices. Because the  $I_{sp}$  values for current flight systems are only ~1600 sec, ion devices, with flight proven values of > 3,000 seconds, offer the most promise of meeting and exceeding the estimated 6,000+ second target values required for NEPP systems.

Propellant systems have flight heritage in the supercritical regime but not cryogenic. While cryogenic systems offer lower volume and a corresponding reduction in tank mass, they also require more insulation and the management of gas venting,

propellant stratification and sloshing. Supercritical systems have flight heritage but require higher pressures and temperatures and require heaters. Although cryogenic systems offer promise for volume and mass reduction, their lack of flight heritage removes them from further consideration given the goals and objectives in Chapter 4.

**Table 19: Filtered Concept Combinations for Produce Thrust from Electrical Power**

<b>Produce Thrust from Electrical Power</b>	
Electric Propulsion Device	Propellant Delivery System
<i>Electrothermal</i>	Supercritical
Arcjets	Cryogenic
Resistojets	
<i>Electrostatic</i>	
Hall	
Ion	
Hall/Ion	
<i>Electromagnetic</i>	
Magnetoplasmadynamic	
Pulsed Plasma Thruster	

## 6.4 Summary of Filtering

In addition to the individual elements of the concept subsets that were filtered, several combinations of reactors and power conversion devices were also eliminated in the preceding discussions. For clarity, Figure 27 provides a summary trace of the filtered concepts for the combined reactor and power conversion tables. The remaining concepts are used for the screening table.

Reactor	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	LM	
Fuel	UO <sub>2</sub>	UN	UO <sub>2</sub>	UN	UN	UN	UN	UN																
Temp	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H
Conversion	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE
Exchange	D	D	D	D	D	D	D	D	D	D	D	D	D	I	I	I	I	I	I	I	I	I	I	I
Reactor	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC	GC
Fuel	UO <sub>2</sub>	UN	UO <sub>2</sub>	UN	UN	UN	UN																	
Temp	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H
Conversion	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE
Exchange	D	D	D	D	D	D	D	D	D	D	D	D	D	I	I	I	I	I	I	I	I	I	I	I
Reactor	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP
Fuel	UO <sub>2</sub>	UN	UO <sub>2</sub>	UN	UN	UN	UN	UN																
Temp	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H	M	M	M	H	H	H
Conversion	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE	B	R	TE
Exchange	D	D	D	D	D	D	D	D	D	D	D	D	D	I	I	I	I	I	I	I	I	I	I	I

<input checked="" type="checkbox"/>	Direct HP and LM	<input type="checkbox"/>	Liquid Metal	<input type="checkbox"/>	Brayton
<input checked="" type="checkbox"/>	Direct TE and Rankine	<input type="checkbox"/>	Gas Cooled	<input type="checkbox"/>	Rankine
<input checked="" type="checkbox"/>	GC with TE and Rankine	<input type="checkbox"/>	Heat Pipe	<input type="checkbox"/>	Thermoelectric
<input checked="" type="checkbox"/>	High Temperature UO <sub>2</sub>	<input type="checkbox"/>	Medium	<input type="checkbox"/>	Direct
<input checked="" type="checkbox"/>	Remaining Concepts	<input type="checkbox"/>	High	<input type="checkbox"/>	Indirect

**Figure 27: Summary of Filtered Reactor and Power Conversion Combinations**

## 6.5 Screening of Candidate Architectures

This section draws upon both the Pugh concept selection method and an adaptation of the concept-screening methods outlined in Product Design and Development by Ulrich and Eppinger<sup>50</sup>. The remaining filtered subsystem components, which were not already filtered to a single concept, are combined at the NEPP systems level and ranked against a baseline using the derived screening criteria. One exception is the possible choice between the 28 V DC and 120 V DC distribution functions for the static power conversion option within *Manage Power and Enable Start and Shutdown*. This decision is considered dependent upon spacecraft configuration and can be made

independent of the combined concept screening table. This option would add six additional concepts to the table and derive little, if any, benefit of being evaluated when combined with other architectural concept attributes.

The SP-100 system architecture, to the degree that it is applicable, was selected as the baseline and is highlighted (solid dark shading) in the Figure 28 matrix. The combined architectural concepts are rated with a “+” if the concept is better than, “0” if it is the same as and “-” if it is worse than the baseline concept in the associated screening category. The net score equals the sum of “+” and “-” values by concept architecture. A ranking is then tabulated based upon the net scores.

Grouping the concepts together at the systems level allows for the screening to consider the interrelationships illustrated in Chapter 4 in addition to the emergent properties that may result at the NEPP systems level. Figure 28 presents the ranked results of the screening. Concepts ranking from 1-3 (circled) out of a range of 1- 8 are considered the most promising candidate architectures for further quantitative study and technology investment. Concepts ranking from 4-8 are considered less promising at this time for the stated goals and objectives. Recombining the concepts that are constant to all of the selections from the filtering process with the most promising candidates from the screening yields the promising architectures.

Concept Combinations																									
Reactor	LM	LM	LM	LM	LM	LM	LM	LM	LM	HP	HP	HP	HP	HP	HP	HP	HP	HP	HP	GC	GC	GC	GC	GC	GC
Conversion Device	B	B	B	R	R	R	TE	TE	TE	B	B	B	R	R	R	TE	TE	TE	TE	B	B	B	B	B	B
Heat Exchange	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	D	D
Fuel	UO <sub>2</sub>	UN	UN	UO <sub>2</sub>	UN	UN	UO <sub>2</sub>	UN	UN	UO <sub>2</sub>	UN	UN	UO <sub>2</sub>	UN	UN	UO <sub>2</sub>	UN	UN	UN	UO <sub>2</sub>	UN	UN	UO <sub>2</sub>	UN	UN
Operating Temp.	M	M	H	M	M	H	M	M	H	M	M	H	M	M	H	M	M	H	M	M	M	H	M	M	H
Criteria																									
TRL	0	0	-	-	-	-	+	0	0	-	-	-	-	-	-	-	-	-	-	0	0	-	-	-	-
Infrastructure	+	0	0	-	-	-	+	0	0	+	0	0	-	-	-	+	0	0	0	0	0	0	0	0	0
Complexity	0	0	-	-	-	-	+	+	0	0	0	0	-	-	-	0	0	0	0	0	0	0	0	0	-
Strategic Value	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Schedule	+	0	-	-	-	-	+	+	0	+	0	-	-	-	-	+	0	0	+	0	0	+	0	0	0
Launch Packaging	-	-	0	0	0	0	0	0	0	-	-	-	0	0	0	0	0	0	0	-	-	0	-	0	-
Power	+	+	+	+	+	+	-	-	0	+	+	+	+	+	+	-	-	0	+	+	+	+	+	+	+
Specific Power	0	+	+	+	+	+	-	-	0	0	+	+	+	+	+	-	-	+	+	+	+	+	+	+	+
Lifetime	+	+	0	0	0	0	0	0	0	+	+	0	0	0	0	0	0	0	+	+	+	0	0	0	0
Payload Interaction	-	-	-	-	-	-	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Adaptability	0	+	+	0	+	+	-	-	0	-	0	0	0	0	0	-	-	-	-	0	0	-	-	-	-
Sum "+"	4	4	3	2	3	3	4	2	0	4	3	2	2	2	2	2	0	0	4	3	2	2	2	2	2
Sum "0"	5	5	4	4	3	3	4	6	11	3	5	4	4	4	4	4	6	7	5	6	5	4	4	4	4
Sum "-"	2	2	4	5	5	5	3	3	0	4	3	5	5	5	5	5	5	4	3	2	4	5	5	5	5
Net Score	2	2	-1	-3	-2	-2	1	-1	0	0	0	-3	-3	-3	-3	-5	-4	1	1	-2	-3	-3	-3	-3	-3
Rank	(1)	(1)	4	6	5	5	(2)	4	(3)	(3)	(3)	(3)	6	6	6	6	6	8	7	(2)	(2)	5	6	6	6

LM = Liquid Metal      B = Brayton      I = Indirect      M = Medium  
 HP = Heat Pipe        R = Rankine      D = Direct        H = High  
 GC = Gas Cooled      TE = Thermoelectric

= SP-100 Reference  
 = Promising Concepts

Figure 28: Concept Screening Matrix

## 7.0 Results, Recommendations and Conclusions

### 7.1 Discussion of Results

The filtered concept combination tables represent the best concepts for meeting the top-level goals and objectives identified in this thesis, Chapter 4.5, at the time of writing. Advancements in some of the individual technologies could potentially change the feasible concepts that would be included in the Concept Screening Matrix at a future date. Also, on a cautionary note, the filtered tables represent the author’s best attempt to assess the current technological state of the concepts and may unintentionally contain some level of personal bias or omission based on partial information. This does present some level of risk to potentially excluding a concept that should have warranted further

consideration in the screening matrix. However changes can be readily amended in future assessments if necessary.

Several observations can be made from the results presented in the Figure 28 Concept Screening Matrix. First, selecting only concepts ranking “1” for further study would eliminate all reactors except liquid metal cooled, all conversion systems except Brayton, and any high temperature option. Expanding the promising candidates to rankings of “2” would allow for subsequent evaluations to include the gas cooled reactor, thermoelectric power conversion and a second option that also uses UN fuel. Further expansion to rankings of “3” adds the heat pipe reactor, reinforces the consideration of UN fuel and introduces one high temperature option. Consideration of rankings of “4” includes two more UN concepts with one utilizing the high temperature option. Levels “5” and “6” introduce multiple combinations of Rankine power conversion and heat pipe reactors. Two remaining heat pipe thermoelectric concepts scored “7” and “8”. Break points could potentially be drawn at the rankings of “1”, “2” or “3”, however, given the intended usage of the matrix and the associated shortcomings in quantitative resolution it is prudent to include the first three levels that are at least rank equivalent to, or exceed, the reference SP-100 concept architecture.

It should be noted that the category of “Strategic Value” was given an even weighting of “0” across the concept set. This was included in the matrix to emphasize the potential consideration of this important criterion but is also left neutral due to conflicting strategies that currently exist. For example, if the strategy is to launch a mission as soon as possible then medium temperature concepts with  $\text{UO}_2$  fuel become “+” values in this category. Conversely, if higher power, low specific mass systems are

avored in order to achieve truly new levels of mission capability, then high temperature UN fueled dynamic power conversion systems would receive the “+” and medium temperature, UO<sub>2</sub> systems with static power conversion would receive “-” values.

Some values are more difficult to apply than others. Specific mass values are difficult to determine due to aggressive technical promises made by concept advocates. Significant variation exists in the literature although useful relative assessments can be made without detailed models. Lifetime is also difficult as only a few elements of the concepts actually have empirical data. Some values are also dependent on a preliminary design concept for better resolution.

## 7.2 Recommendations for Future Work

### 7.2.1 Further Concept Refinement

Weighting the criteria and performing supplementary rankings may serve to determine sensitivities, however further concept reduction should not be pursued without a greater understanding of the underlying concept performance capabilities and characteristics. This can only be achieved through refined modeling that incorporates quantitative information grounded in technology development and testing. Premature assignment and use of detailed numerical values will result in the computational obfuscation of recommendations given the present fidelity of test data. Industrial participation beyond the current government studies is also required to fully address infrastructure, schedule and producibility questions.

The filtering and screening process used in this thesis could also be applied to a single mission with specific attributes. This could be repeated for a select group of missions considered the most promising from a scientific and political valuation. This

process would allow for the most frequently chosen architecture to emerge that would best suite the near term set of interplanetary missions. This orthogonal view of the architectures based on a series of individual mission assessments, rather than collective, would serve as a check against the results of this thesis assuming the same current technical information.

Parametric cost modeling could also be used to supplement the thesis work. Although reactor cost data is limited by SNAP and SP-100 efforts, subsequent efforts on power conversion, thermal management, power management and distribution and electric propulsion are relevant. This would enable the formulation of relative cost relationships, cost functions and the ability to discern recurring from non-recurring costs. Cost estimating relationships can be developed by subsystem using constant, linear and device specific functional relationships for different power levels and reliability.<sup>51</sup> These relationships can be incorporated into multidisciplinary design models discussed in the next section.

Lastly, a detailed Design Structure Matrix (DSM) analysis on each of the promising concepts, both within the NEPP system and between the successive domains of influence, should be completed in order to reveal other considerations necessary for further evaluation and selection.

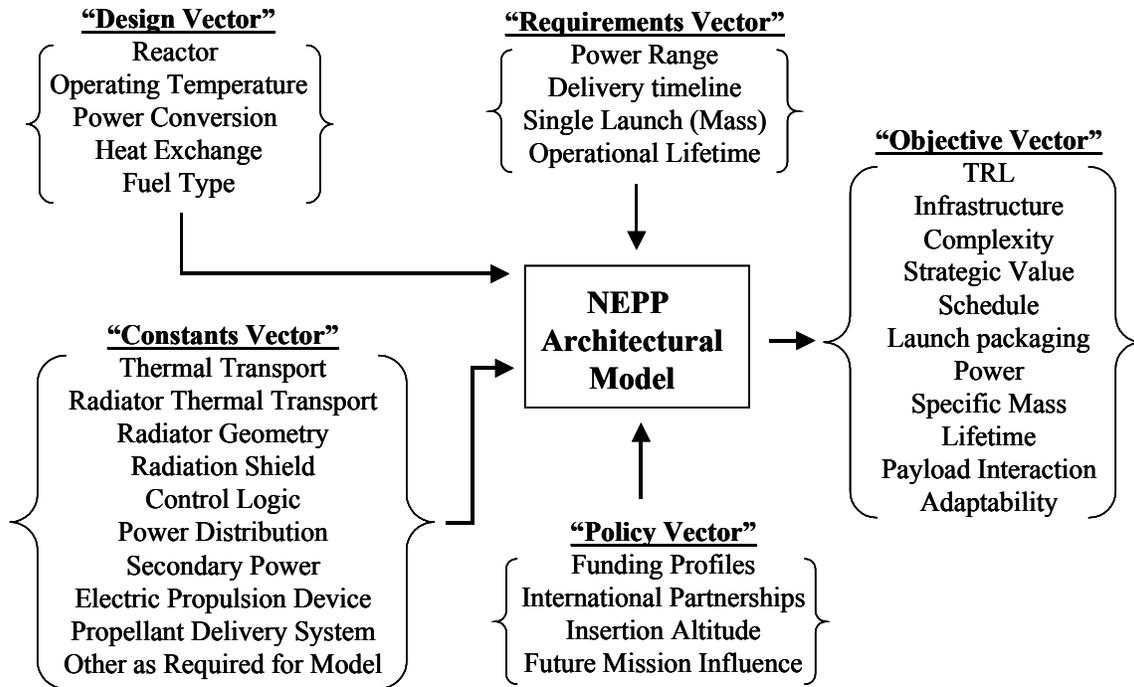
### **7.2.2 Introduction of Multidisciplinary Design**

Multidisciplinary design can be used as a subsequent quantitative methodology to refine architectural trade and selection studies. This methodology can incorporate technical performance, economic and policy factors that together influence the final architecture. One approach presented by de Weck and Chang is to define a “Design

Vector”, “Constants Vector”, “Requirements Vector” and “Policy Decision Vector” that provide the input to a simulator in order to produce the desired “Objective Vector”<sup>52</sup>.

This methodology provides a depiction of decision space to objective space.

An example formulation is provided in Figure 29. The “Design Vector” represents the feasible concepts identified after filtering in this thesis. The “Constants Vector” represents the selections made during both the concept definition and filtering processes. Other constant factors discussed in the thesis that are common to all architectures can be added to this matrix as necessary. The “Requirements Vector” captures the goals and objectives outlined in Chapter 4 or can reflect specific mission requirements. The “Policy Decisions Vector” may be used to reveal a variety of contemporary political and societal issues that may emanate from the outer domains in Figure 6 in addition to the architectural influences presented in Chapter 4. Examples include Administration and Congressional funding levels and timelines, launch and on-orbit safety (e.g. LEO insertion altitude), international partnerships and the degree that future human missions influence the planetary architectures. Finally the “Objective Vector” contains the evaluation factors to which the architectures are assessed.



**Figure 29: Example Formulation of Architecture Trade Methodology**

### 7.3 Concluding Remarks

It is important to discern between 10, 20 and 30-year systems. There is a propensity to design for all nuclear cases too soon. This all-encompassing approach, while noble, will lose focus, diffuse limited resources and fail the effort. Merging rocket science and nuclear engineering is a quintessential challenge in complex systems. Given the myriad of engineering and management factors that will ultimately contribute to the success of bringing a complex system like this to fruition, there is probably more than one concept that equally satisfies the targeted goals. Consequently, at some point after adequate technology investment and quantitative architectural study, a concept should be selected and flown before another ephemeral decade of paper studies passes.

## 8.0 References

- <sup>1</sup> NASA, *FY 2003 Performance Plan*, NASA 2002.
- <sup>2</sup> Jet Propulsion Laboratory, *Solar Cell Array Design Handbook*, JPL SP 43-38, Vol. I, 1976, pg. 2-4.
- <sup>3</sup> Angelo, J., and Buden, D., *Space Nuclear Power*, Orbit Book Company, Inc., 1985, pg. 35.
- <sup>4</sup> de Weck, O. and Crawley, E., “System Architecture Trade Studies”, 16.882/ESD.34J, Systems Architecture Lecture 17, 26 November 2001.
- <sup>5</sup> El-Genk, M., *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 223.
- <sup>6</sup> Ibid, pg. 225.
- <sup>7</sup> Perry, R., *Origins of the USAF Space Program 1945-1956*, History Office, USAF Space and Missile Systems Center, 1997, <http://www.fas.org/spp/eprint/origins/index.html>, pg. 30.
- <sup>8</sup> Ibid, pg. 31.
- <sup>9</sup> El-Genk, M., *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 271.
- <sup>10</sup> Angelo, J., and Buden, D., *Space Nuclear Power*, Orbit Book Company, Inc., 1985, pg.159.
- <sup>11</sup> Ibid, pg. 245.
- <sup>12</sup> El-Genk, M., *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 382.
- <sup>13</sup> Bennett, G., “Space Nuclear Power”, *Encyclopedia of Physical Science and Technology*, Third Edition, Volume 15, 2002.
- <sup>14</sup> Angelo, J., and Buden, D., *Space Nuclear Power*, Orbit Book Company, Inc., 1985, pg.223.
- <sup>15</sup> Ibid, pg. 245.
- <sup>16</sup> Ibid
- <sup>17</sup> El-Genk, M, Buden, D, *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 22.
- <sup>18</sup> Ibid, pg. 21.
- <sup>19</sup> Massachusetts Institute of Technology © de Weck/Crawley 2001
- <sup>20</sup> Ibid
- <sup>21</sup> Office for Outer Space Affairs, United Nations Office in Vienna, “United Nations Treaties and Principles on Space Law”, 2001.  
<http://www.oosa.unvienna.org/SpaceLaw/treaties.html>
- <sup>22</sup> Committee on the Peaceful Uses of Outer Space, “Principles Relevant to the Use of Nuclear Power Sources In Outer Space”, 1992.  
<http://www.oosa.unvienna.org/SpaceLaw/nps.html>
- <sup>23</sup> Ibid
- <sup>24</sup> National Research Council, Space Studies Board, “New Frontiers in the Solar System an Integrated Exploration Strategy”, National Academy of Sciences, 2002, <http://www.nationalacademies.org/ssb/newfrontiersfront.html>.

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- <sup>25</sup> Rayman, M. et. al., “Results from the Deep Space 1 Technology Validation Mission”, 50<sup>th</sup> International Astronautical Congress, IAA-99-IAA.11.2.01, Acta Astronautica 47, pg. 475, 2000.
- <sup>26</sup> El-Genk, M., et. al. *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994.
- <sup>27</sup> Oleson, S., et. al., “Radioisotope Electric Propulsion For Fast Outer Planetary Orbiters”, American Institute of Aeronautics and Astronautics, Paper AIAA-2002-3967, 2002.
- <sup>28</sup> Dudzinski, L., Borowski, S., “Bimodal Nuclear Electric Propulsion: Enabling Advanced Performance with Near-Term Technologies”, AIAA 2002-3653, 2002.
- <sup>29</sup> Meisl, Claus J., “Parametric Cost Modeling for Nuclear Space Systems”, NTSE-92, Nuclear Technologies for Space Exploration, American Nuclear Society, 1992.
- <sup>30</sup> Office of Management and Budget presentation on the 2003 Federal Budget
- <sup>31</sup> El-Genk, M., et. al. *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 38.
- <sup>32</sup> Ibid, pg. 45.
- <sup>33</sup> Angelo, J., and Buden, D., *Space Nuclear Power*, Orbit Book Company, Inc., 1985, pg. 167.
- <sup>34</sup> Bennett, G., “Space Nuclear Power”, *Encyclopedia of Physical Science and Technology*, Third Edition, Volume 15, 2002.
- <sup>35</sup> El-Genk, M., *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 349.
- <sup>36</sup> Reid, R. and Merrigan, M., “Advanced Space Heat Rejection Concepts for High Power Systems”, NTSE-92, Nuclear Technologies for Space Exploration, American Nuclear Society, 1992.
- <sup>37</sup> Rockwell International, “Space Reactor Electric Systems, Subsystem Technology Assessment”, Rockwell International, ESG-DOE-13398, Contract DE-AT03-82SF11687, 1983, pg. 190.
- <sup>38</sup> Bhattacharya, S. et. al., “Space Exploration Initiative Fuels, Materials and Related Nuclear Propulsion Technologies Panel Final Report”, NASA Technical Memorandum 105706, 1993.
- <sup>39</sup> Maier, W. and Rehtin, E., *The Art of Systems Architecting*, CRC Press, 2000, pg. 244-245.
- <sup>40</sup> Jet Propulsion Laboratory, “SP-100 Planetary Mission/System Preliminary Design Study, Final Report”, NASA JPL D-2544, 1986.
- <sup>41</sup> Rockwell International, “Space Reactor Electric Systems, Subsystem Technology Assessment”, Rockwell International, ESG-DOE-13398, Contract DE-AT03-82SF11687, 1983, pg.151.
- <sup>42</sup> El-Genk, M., et. al. *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 180.
- <sup>43</sup> Bhattacharyya, S. et. al., “Space Exploration Initiative Fuels, Materials and Related Nuclear Propulsion Technologies Panel Final Report”, NASA Technical Memorandum 105706, 1993, pg. 119.
- <sup>44</sup> Mason, L., “Power Technology Options for Nuclear Electric Propulsion”, IECEC 2002 Paper No. 20159, 2002.

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- <sup>45</sup> Mason, L., “ A Comparison of Brayton and Stirling Space Nuclear Power Systems for Power Levels from 1 Kilowatt to 10 Megawatts”, NASA TM-2001-210593, 2001.
- <sup>46</sup> El-Genk, M., et. al. *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 359.
- <sup>47</sup> Mason, L., “Power Technology Options for Nuclear Electric Propulsion”, IECEC 2002 Paper No. 20159, 2002.
- <sup>48</sup> El-Genk, M., et. al. *A Critical Review of Space Nuclear Power and Propulsion*, American Institute of Physics, 1994, pg. 29.
- <sup>49</sup> Gallup, D., “The Scalability of Out-of-Core Thermionic Reactor Space Nuclear Power Systems”, Department of Energy, Sandia Report SAND90-0163, 1990.
- <sup>50</sup> Ulrich, K. and Eppinger, S., *Product Design and Development*, Irwin McGraw-Hill, 2000, Chapter 7.
- <sup>51</sup> Meisl, Claus J., “Parametric Cost Modeling for Nuclear Space Systems”, NTSE-92, Nuclear Technologies for Space Exploration, American Nuclear Society, 1992.
- <sup>52</sup> de Weck, O. and Chang, D., “Architecture Trade Methodology for LEO Personal Communications Systems”, 20<sup>th</sup> International Communications Satellite Systems Conference, AIAA 2002-1866, 2002.