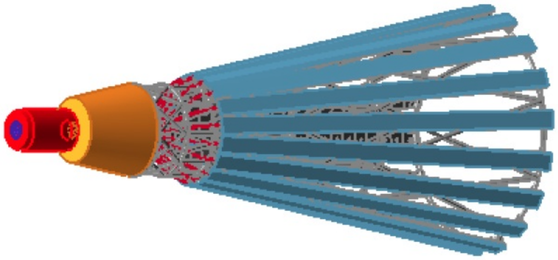

Small Fission Power System Feasibility Study
Final Report

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The results of a 6-week study performed by a NASA/DOE Study Team for the Decadal Survey Giant Planets Panel and the NASA Science Mission Directorate

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This report contains preliminary findings,
subject to revision as analysis proceeds.

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Executive Summary

In early March 2010, the Decadal Survey Giant Planets Panel (GPP) requested a short-turnaround study to evaluate the feasibility of a small fission power system (FPS) for future unspecified National Aeronautics and Space Administration (NASA) science missions. FPS technology was considered a potential option for power levels that might not be achievable with radioisotope power systems. A study plan was generated, and a joint NASA/Department of Energy (DOE) study team was formed. The team developed a set of notional requirements, which were accepted by the GPP and which included 1 kW electrical output, 15-year design life, and 2020 launch availability. After completing a short round of concept screening studies, the team selected a single concept for further study and analysis. The selected concept is a uranium-molybdenum fueled, heat pipe cooled reactor with distributed thermoelectric power converters coupled directly to aluminum radiator fins. The team generated a preliminary configuration, mass summary, development schedule, and cost estimate. The system mass is 772 kg (including margin) and the rough order-of-magnitude cost for the 10-year flight system development program is $690M. The study results were presented at a preliminary review on April 8 to NASA and DOE management with no significant modifications requested. The final review with the GPP was held on April 16, 2010.

1. Study Description

1.1. Study Objectives

The main study objectives were to evaluate the feasibility of a small Fission Power System (FPS) for NASA science missions and to provide information to the Decadal Survey Giant Planets Panel (GPP) that will guide their recommendations to NASA concerning an investment in small FPS. The primary motivation was to identify a power system option for the larger flagship science missions whose power requirements may exceed what is practical with the current suite of 100-watt class Radioisotope Power Systems (RPS).

1.2. Study Process

The study was initiated in early March 2010 after some preliminary scoping studies performed by the Jet Propulsion Laboratory (JPL). At the beginning of the study, the NASA Science Mission Directorate (SMD) requested an extended study scope to cover a range of power levels up to 10 kWe and to examine a range of power conversion approaches. The GPP reiterated their preference for the originally requested scope and so the study was focused specifically on the 1 kWe class system with some top-level assessment of extensibility to higher power. SMD agreed to proceed with the focused short study of the 1 kWe class in order to accommodate the GPP needs and schedule, and decided to defer the broader scope to an expanded second phase of the study. This report covers only the scope requested by the GPP and funded by the Decadal Survey. The second phase would be funded by SMD.

The study was assigned to Glenn Research Center (GRC) and a basic study plan was generated and agreed upon by the study sponsors. A study team was formed that included participants from JPL; Marshall Space Flight Center (MSFC); DOE Headquarters; and the DOE National Laboratories at Idaho (INL), Los Alamos (LANL), Oak Ridge (ORNL), and Sandia (SNL). A short turnaround was necessary to support the Decadal Survey planning needs. The study team agreed to complete the feasibility assessment within approximately six weeks, culminating in a presentation to the GPP in mid-April and a narrative report by the end of April. An intense and expedited process was followed in order to meet the schedule, with the expectation that if the initial results were favorable, a more detailed follow-on study could be commissioned. The study schedule is provided in Appendix A.

A step-wise process was followed to identify a preferred concept and define its basic design parameters and development needs. An initial kick-off teleconference was held to review the Study Plan and identify the next steps. A team meeting was held at GRC on March 17-18. The team generated a notional set of requirements, reviewed past space nuclear power systems of similar scale (see Appendix B), and identified a set of technology options for each of the major subsystems. Since no specific mission was identified, the requirements derived for the study were selected to encompass a wide range of potential space science missions. By the conclusion of the GRC meeting, the team had developed a set of candidate system concepts that were considered credible based on the requirements and ground rules.

The next week was spent performing screening studies on reactor, shielding, and power conversion options. A second team teleconference was held on March 25 during which the various concepts were discussed and a single concept was selected for further analysis. A follow-on team meeting was held March 31–April 1 at JPL to flesh out the selected concept. While at JPL the team determined the system performance, configuration layout, mass summary, and operations approach for the selected concept. Additional time was spent evaluating the extensibility of the concept to higher power by simple scaling or modest design changes. The team also defined a verification strategy and development schedule that was used as the basis for a rough-order-of-magnitude (ROM) cost estimate.

All of these results were incorporated into a presentation package that was reviewed with NASA and DOE management and the study team via teleconference on April 8. The management review resulted in general agreement on the findings and an affirmation that the results sufficiently addressed the study objectives. The presentation underwent some minor improvements and was delivered via teleconference to the GPP on April 16. The rules of engagement in place for Decadal Survey studies limited participation in that review to the GPP members only.

1.3. Study Participants

The study was led by Lee Mason from GRC. JPL personnel included John Elliott, Bill Nesmith, Duncan MacPherson, Jean-Pierre Fleurial, and Tom Moreno. Mike Houts was the MSFC participant. The DOE was represented by Ryan Bechtel (HQ), Jim Werner (INL), Dave Poston, Rick Kapernick (LANL), Lou Qualls (ORNL), Ron Lipinski, and Ross Radel (SNL). Two expert consultants were also members of the study team: Sterling Bailey (former SP-100 Program Manager and liquid metal reactor expert at General Electric and

Lockheed Martin) and Abraham Weitzberg (former SNAP 10A program participant and expert in space and terrestrial nuclear power systems). The Giant Planets Panel is chaired by Heidi Hammel and the GPP representative for this study was John Casani from JPL. The NASA Headquarters sponsor was Len Dudzinski from SMD and the DOE Headquarters lead was Scott Harlow.

1.4. Study Groundrules and Assumptions

At the GRC meeting, a set of notional requirements was developed and concurred upon by the GPP study representative and GPP chairperson. The requirements were broadly defined to cover a range of potential Giant Planet science missions. A primary goal was to select requirements that would bound technology choices without over-constraining the trade-space. An over-arching requirement was that the FPS would be safe for launch and operations. This translated to a requirement that the reactor remain subcritical until commanded to start via Earth telemetry. Neutronic calculations were performed to verify that the design would not achieve criticality under a range of credible launch accidents. After startup, the reactor would operate based on inherent negative temperature reactivity feedback. This ensures that the reactor responds to temperature increases with an automatic decrease in reactivity and a corresponding reduction in thermal power to minimize the consequence of adverse transients.

The major parameters that affect technology selection are power level, lifetime, and launch date. For this study, these were chosen as 1 kWe continuous output, 15-year design life, and 2020 launch availability. Several spacecraft integration requirements were also adopted. These included the reactor-induced radiation dose ($1\text{x}10^{11}$ n/cm^2 and 25 krad), payload envelope size (4.5 m diameter), and electrical bus voltage (28 Vdc). The radiation limits were selected to allow the use of commercially available electronics at the payload dose plane. To better accommodate the radiation dose limits, the payload was assumed to be located at a specified separation distance from the reactor within a defined cone angle. This geometry set the parameters required to determine the dimensions and mass of the radiation shielding.

In addition to the assumptions stated above, the study participants agreed on several goals for the FPS. While no mass or volume metric was set, minimizing these parameters would make the system more attractive to potential missions. At the same time, the team judged that low cost and low risk (both developmental and operational) were even more important than mass. An additional goal was to minimize the system-related accommodations imposed on the spacecraft. These might include the need for control actions, operational constraints, additional power sources, or extension booms. Another key FPS goal expressed by the team and echoed in the study objectives was the potential for mission extensibility, especially as it relates to upward power scalability.

2. Study Context

2.1. Study Foundation

This study draws on more than 60 years of nuclear engineering and technology development by DOE, industry, the U.S. Navy, and the U.S. Air Force as well as over 55 years of space nuclear power and propulsion technology development by NASA, DOE, industry, and the Air Force. Throughout this period, DOE, the Navy, and industry have continued to invest heavily in nuclear engineering and technology. Specific areas of emphasis have included nuclear databases, reactor physics, fuels, material property databases, test capabilities, and operational experience. A testament to these efforts is the hundreds of reactors operating today in commercial power plants, university research reactors, and in Navy sea vessels. There are now more than 30 robust nuclear engineering undergraduate and graduate programs offered at U.S. universities. These resources and experiences provide a strong foundation for this study. Nuclear engineering and technology is well established in the U.S. and the world, and developing space-qualifiable nuclear system hardware is not unusually challenging compared to other NASA endeavors. An overview of space and terrestrial nuclear power systems is provided in Appendix C.

2.2. Rationale for Radioisotope and Fission Systems

Radioisotope power systems (RPSs) using plutonium-238 (Pu-238) heat sources are safe and reliable, as evidenced by the more than 40 radioisotope thermoelectric generators (RTGs) that have been flown by NASA and other U.S. agencies. However, Pu-238 has become very scarce and expensive. In response, NASA and DOE have invested in Stirling power conversion technology with a projected fourfold increase in power output over thermoelectric conversion systems for the same amount of Pu-238. Stirling-based systems are also lighter, but require a dynamic heat engine with moving parts as compared to the static thermoelectric devices used in the past.

The U.S. has a very limited supply of Pu-238 and foreign supplies have become less dependable and more costly. The DOE is planning to re-establish production of Pu-238 to better support NASA missions, and this study team strongly endorses this activity as a means to achieve a reliable source of Pu-238 for future RPS. The proposed new U.S. production capability would be expected to provide approximately 2 kg/yr of Pu-238 beginning in 5 or 6 years. This would be a sufficient production rate to fuel RPSs for a potential series of small Discovery or New Frontiers missions that could use 140-watt Advanced Stirling Radioisotope Generator (ASRG) systems. However, the larger kilowatt-class Flagship science missions may be better served by an alternative approach that does not require so many units to meet the power demands and does not detract from the Pu-238 supply.

A small fission-based power system provides a potential option. With a reasonable development program, NASA and DOE could produce power systems in the 1 to 10 kWe range that provide many of the same advantages as RPS. Fission power systems are not suitable for small missions because they are significantly heavier than radioisotope systems at power levels less than 1 kWe. However, fission systems offer a practical solution for power levels of 1 kWe and higher, and may offer a cost benefit, from a recurring unit cost perspective, as compared to using a large number of RPS for those missions. In other words, development of fission systems could allow NASA to reserve radioisotope systems for the smaller class missions where the lower mass is imperative and the Pu-238 needs are manageable, and fission-based systems for the larger missions where the higher power is needed.

3. Technology Options

3.1. Reactor Technologies

Since the advent of the nuclear age, researchers, engineers, and scientists have been exploring and testing many forms of nuclear fuels, structural materials, shielding materials, and design configurations. A wealth of knowledge and performance capabilities has been established and is available for consideration in design options.

Typical uranium fuel forms range from oxides (i.e. UO_2), the most commonly used form of fuel in terrestrial power reactors, to metal fuels (i.e. UMo, UZr), common to fast reactor technologies, to other chemical fuel forms that have specific performance or material characteristics e.g., nitride (UN), carbide, cermet, UZrH. These fuels have been tested both from a mechanical/physical standpoint to performance under nuclear irradiation conditions in the form of pins, plates, blocks, and microspheres. Consequently, a number of fuel types and configurations could be considered for this application.

The U.S. experience with mixed oxide and metal fuels is substantial, comprising irradiation of over 50,000 oxide fuel rods and 130,000 metal fuel rods in the Experimental Breeder Reactor-II (EBR-II) and the Fast Flux Test Facility (FFTF) alone. Most types of fuel have been demonstrated capable of fuel utilization exceeding 10% fuel burnup. To varying degrees, life-limiting phenomena for all types have been identified and investigated. For this study there are no disqualifying safety-related fuel behaviors that would reduce the viability of any of the fuels for use. However, fuel density becomes a dominant factor when designing very small reactor systems. Likewise, reactor configurations utilizing different neutron spectra for maintaining nuclear criticality have been studied and well established. Nuclear reactor designs basically fall into three categories: 1) Thermal: fission neutrons are rapidly slowed down to thermal energy ranges before the next fission reaction occurs (e.g., water-moderated reactors), 2) Epithermal: neutrons lose most of their energy before next fission (e.g., graphite-moderated gas-cooled reactors), and 3) Fast: neutrons are absorbed with minimal loss of energy prior to the next fission (e.g., sodium-cooled reactors). The most “neutron efficient” reactors are thermal systems; however, the smallest, most lightweight reactors have fast spectra.

Most nuclear fuel cladding and structural materials are made out of zirconium alloys and stainless steels. nickel-based superalloys have also been extensively tested in the nuclear industry where higher temperatures and operating pressures are desired and applications in variety of reactor systems have been established. Refractory alloys have been explored and a large amount of data exists regarding performance of these materials under high temperature high radiation environments, but their use would require additional development and fabrication investments.

Control of a nuclear reactor system is achieved by utilizing materials that reflect materials back into the core [e.g., water, graphite, beryllium (Be), or beryllium-oxide (BeO)] and materials that absorb neutrons [e.g., boron (B), boron carbide (B_4C)]. For small lightweight reactors, Be or BeO are more suitable reflector materials, and B_4C is more suitable for the neutron absorber. A variety of combinations of these two materials have been employed in test reactors as well as previous space designs. Typical control options include the use of rods (pins are inserted in the reactor), drums (a section of the drum surface has absorbing material and is located outside the reactor core), shutters (reflector or absorbing materials are arranged outside the reactor core and their position adjusted to either allow more neutron leakage or exposure to neutron absorbing material), or sliders (reflector or absorbing materials are arranged outside the reactor core and the materials are made to slide around the core to either allow more neutron leakage, reflection, or exposure to neutron absorbing material)

Reactor heat transport is typically accomplished by flowing a liquid or a gas through the core. Coolant options for this type of system include using sodium (Na), potassium (K), NaK, lithium (Li), helium-xenon (He-Xe), or carbon dioxide (CO_2) as the heat transfer fluid. All reactors that transport heat from a reactor core using liquid or gas require a circulation pump or rely on gravity to induce circulation by convection. A novel approach of using heat pipes for primary heat transport has been investigated over the past 30 years and a significant amount of testing has been accomplished in both radiation and non-radiation test environments. However, a heat pipe-cooled reactor has not yet been built or operated.

A large variety of shielding materials have also been developed and tested over the years. Effective shielding requires the use of a specific class of materials to reduce the radiation from neutrons using low-mass elements [e.g., hydrogen (H), Li, B], and from beta and gamma radiation using higher-mass elements [e.g., tungsten (W), depleted uranium (DU), lead (Pb)]. The shielding material selections are also influenced by other design requirements such as operating temperature, heat load, structural stability, and material compatibility.

3.2. Balance-of-Plant Technologies

Four potential power conversion technologies were considered for the small space FPS application: dynamic energy conversion using the Brayton, Stirling, or Rankine cycle and static thermoelectric conversion. The use of stainless steel or superalloy materials for the hot-end limits the maximum operating temperature to approximately 1100 K or less. If refractory alloys are utilized, this limit could be extended to 1300 or 1400 K.

Space Brayton converters are a closed-loop derivative of an air-cycle gas turbine in which an inert gas working fluid (such as HeXe) is recirculated through a turbine and compressor coupled to a rotary alternator. Thermal input is achieved by either direct heating of the gas in the reactor (gas-cooled reactor) or through an intermediate heat exchanger. A recuperative heat exchanger improves cycle efficiency using the hot turbine exhaust gas to pre-heat the working fluid before it returns to the heat source. Space Rankine converters are derived from conventional steam power plants, in which the working fluid is superheated in a boiler, expanded in a turbine, and liquefied in a condenser before being pumped back to the boiler. Systems using either an organic (e.g., toluene) or an alkali-metal (e.g., K) working fluid have been built and operated in ground tests. Space Stirling converters produce electrical power via a linear alternator coupled to a reciprocating power piston and displacer that oscillate in a pressurized cylinder containing helium gas. Thermal energy is introduced at the heater head, waste heat is removed from the cooler, and a regenerator transfers energy between the heater head and cooler.

Thermoelectric converters generate a voltage potential by exposing dissimilar semiconductor materials to a temperature difference, similar to the operation of a thermocouple. This type of static power conversion has been used extensively in RTGs since the early 1960s with demonstrated lifetimes in excess of 30 years, and it was baselined for the SP-100 Program in the 1980s. Thermal energy is provided to the hot-end, by either radiative or conductive coupling, and waste heat is rejected at the cold-end to a radiator. Some common semiconductor materials used in thermoelectric devices in the past 50 years include lead-telluride (PbTe) and silicon germanium alloys (SiGe). Potentially, more efficient thermoelectric materials are available today in the temperature range of interest such as skutterudites based on $CoSb_3$ and refractory rare earth compounds, $Yb_{14}MnSb_{11}$, Zintl, and $La_{3-x}Te_4$. A promising approach is to segment the thermoelectric legs using a material combination of Zintl, $La_{3-x}Te_4$, and skutterudites (Zintl/LaTe/SKD).

There are numerous methods to remove the waste heat from the power conversion. The simplest is to directly attach a radiating surface to the cold-end of the power converter. However, this becomes more difficult as the waste heat load increases and other methods must be employed. Options include single-phase pumped liquid loops, two-phase heat pipes, and two-phase capillary pumped loops. The expected range of heat rejection temperatures for this small FPS application is about 350 to 500 K. In this range, heat transfer coolants such as water, ammonia, fluorocarbons, and hydrocarbons could be utilized. Above 500 K, liquid metal coolants such as NaK could be considered. Likely radiator construction materials include aluminum (Al), titanium (Ti), or polymer matrix composites.

4. Candidate System Concepts

To explore the attractiveness of several possible technical approaches for obtaining the desired characteristics, the study team identified four candidate system concepts with two variants.

4.1. Conduction Reactor with Body-Mounted Thermoelectric Conversion

As an initial concept, modeled closely after the technical approach used for the very successful general-purpose heat source (GPHS)-RTG, the team identified a concept with thermoelectric elements mounted directly to the body of a low power reactor. This is the same approach used in the Romashka reactor that was ground tested by the USSR from 1964 to 1966; the approach was also proposed in 1992 as an early flight demonstration of a low-power variant of the SP-100 concept. The team's approach to this concept uses block UMo fuel, a Be reflector, B_4C control rods, a superalloy structure, lithium hydride (LiH)/W shield, SiGe thermoelectric elements on the outside of a radial reflector, and a liquid-metal heat pipe radiator, with the entire system forward of shield and within the shield cone angle. To minimize the mass of the system, a very compact core was necessary, which limited the amount of reactor surface area for mounting the thermoelectrics. Also, because of the nuclear radiation from the reactor core, space reactor configurations necessarily have the spacecraft payload separated from the reactor by a tapered shield in the shape of a frustum of a cone, with the apex of the cone away from the payload. This arrangement severely limits the amount of radiator area that can be accommodated in front of the shield. Because of these constraints, it was estimated that the power level of this concept would be limited to about 0.5 kWe. Even with the use of alternate reflector configurations, or higher temperature core materials, the power level possible from this concept would remain substantially below the study target of 1 kWe.

4.2. Heat Pipe Reactor with Distributed Thermoelectric Conversion

This concept uses the same reactor and shield technologies as the conduction reactor concept, but uses in-core liquid-metal heat pipes to transport heat from the core through the shield to Zintl/LaTe/SKD thermoelectric elements distributed along the heat pipes and directly coupled to individual aluminum radiator surfaces at the thermoelectric cold-end. Moving the power conversion and heat rejection components behind the shield eliminates the volume and area constraints that limited concept 4.1, and increases the radiation margin for the already radiation-hard thermoelectric materials. Although the Zintl/LaTe/SKD thermoelectric materials are less mature than the SiGe, their use yields improved efficiency at the lower temperature available at the heat pipe condenser. This concept was judged to be a good choice for a 1 kWe class system.

4.3. Heat Pipe Reactor with Compact Thermoelectric Heat Exchangers

This concept uses the same reactor, shield, and heat pipe technologies as concept 4.2, but replaces the distributed thermoelectric elements with Zintl/LaTe/SKD thermoelectric elements integrated into compact heat exchangers. Additionally, secondary water heat pipes are used to transfer waste heat from the cold-end of the thermoelectrics to an aluminum radiator. This concept is more complex than the previous system, but would be scalable up to perhaps 5 kWe.

4.4. Heat Pipe Reactor with Stirling Power Conversion

This variant of concept 4.3 uses the same reactor, shield, and heat pipe technologies, but replaces the compact thermoelectric heat exchangers with Stirling converters to increase power output. This concept is possibly more complex than the system with compact thermoelectric heat exchangers, but would be scalable up to about 10 kWe.

4.5. Pumped Liquid Metal Reactor with Compact Thermoelectric Heat Exchangers

This concept uses the well-understood reactor and primary heat transport technologies from terrestrial fast reactors and the Fission Surface Power (FSP) concept, now being studied by NASA's Exploration Systems Mission Directorate (ESMD). The reactor system utilizes UO_2 pin fuel, a Be reflector, rotating Be/B_4C control drums, stainless steel structure, a LiH/W shield and a pumped NaK primary loop using a thermoelectric electromagnetic pump. The reactor system would provide heat to Zintl/LaTe/SKD thermoelectric elements in compact heat exchangers, rejecting heat through pumped NaK secondary loops to composite radiators. This concept was assessed to be too heavy for a 1 kWe class system, but could be a viable option for 10 kWe or 20 kWe.

4.6. Pumped Liquid Metal Reactor with Stirling Power Conversion

This variant of concept 4.5 concept uses all of the technologies of the FSP system including the same reactor technologies, but would use an annular linear induction pump to transport the NaK coolant to multiple Stirling converters. Waste heat would be rejected via pumped water secondary loops to water heat pipe radiators. While too heavy for the 1 kWe class, this concept is well suited for power levels from about 10 kWe up to perhaps 100 kWe.

5. Selected System Concept

5.1. Rationale for Selection

The study team selected the heat pipe reactor with distributed thermoelectric conversion (concept 4.2) for further study and analysis. The main factors leading to this selection were design simplicity, reasonable system mass, and low development risk.

The selected concept represents a best effort at minimizing the complexity of fission systems and making them competitive with RPS on a mass basis. The compact nature of the block UMo core and BeO radial reflector allows the reactor diameter to be as small as practical while still meeting the neutronic and thermal power demands. This directly translates to reduced shield mass since the reactor diameter dictates the footprint of the radiation shield. The use of LiH and W provides a mass-efficient material combination for meeting the radiation requirements at the spacecraft. The reactor control is simplified through the use of a single, core-centered control rod whose operation is only required during reactor startup. The use of heat pipes offers a straightforward primary heat transport approach using proven liquid-metal heat pipe technology. Further, the elimination of complex heat transport components, both at the reactor side and radiator side, contributes to reducing the total part-count and lowering system mass. The thermoelectric technology, albeit using relatively new materials, has heritage tracing to a long history of successful and long-lived space power systems. The direct integration of the thermoelectric converters with the heat pipes combined with the direct coupling of the thermoelectric converters to the radiator makes this concept very simple from a heat transfer perspective. The simple thermal interfaces serve to minimize the temperature drop that would otherwise degrade system performance and necessitate a bigger reactor and a larger radiator.

Low development risk results from the use of available technology. The selected concept uses a reactor fuel form based on metal fuels that are currently in production by DOE. The structural materials are conventional nickel-based superalloys that have been thoroughly tested at the temperatures and radiation fluences required for this system. Liquid metal heat pipe technology is also well established, with several vendors capable of designing and delivering the required heat pipes. The thermoelectric configuration is based on past designs that have been successfully operated, although the new materials introduce some risk. Therefore, a long-term development and demonstration program is planned to verify the thermoelectric materials, including their performance in the space and reactor environment where they would be operated. The only significant development issue for the aluminum radiator is thermal integration with the thermoelectric cold-end.

It should be noted that a heat pipe-cooled reactor has never been built and operated. It would require rigorous analysis and testing to verify the design and establish a statistical database of reliability and performance. Fission power reactors (of any type) at this scale are not common. However, the small size, low fuel burnup, and low irradiation fluences offer a significant advantage because robust margins can be incorporated into this design relative to those assumed for larger power reactors.

The relatively small scale of the system and the availability of test facilities to validate the design also help to reduce development risk. The reactor core is the size of a large coffee can. The entire reactor and shield assembly is about the height of an average adolescent child. An individual heat pipe along with the distributed thermoelectric converters and radiator panel can be tested as a modular assembly to validate performance. At this scale, numerous test facilities exist within the NASA community to conduct thermal-vacuum performance and mechanical vibration testing. The reactor fuel can be fabricated in existing production facilities, and the reactor neutronics can be verified in existing nuclear criticality test facilities within the DOE complex.

5.2. System Design

The system can be divided into two major subsystems: the reactor and balance-of-plant. The reactor includes the fuel, core, reflectors, heat pipes, shield, and instrumentation and control (I&C). The balance-of-plant includes the thermoelectric converters, radiators, power cabling, and truss structure. These two sub-systems are mechanically attached to each other, with the balance-of-plant mechanically attached to the spacecraft structure.

5.2.1. Reactor Design

The selected reactor concept utilizes a metallic fuel that conducts fission-generated heat to in-core heat pipes, which then transfer the power through the shield to the power conversion system. The reactor is controlled by an in-core control rod. An annular safety collar is used to satisfy expected pre-startup launch safety requirements. The reactor and shield axial cross-section is shown in Figure 5.2-1. The reactor radial cross-section is depicted in Figure 5.2-2. As part of the six-week study, SNL fabricated a full-scale plastic model of the reactor based on this design layout. A photograph of the model and the SNL fabrication team is provided in Figure 5.2-3.

The FPS reactor was designed using standard engineering and reactor physics design practices. Limited structural and nuclear analyses were performed to show that physical integrity and nuclear performance objectives including safety could be achieved. Sufficient excess reactivity was included to ensure that the reactor would operate well beyond its 15-year mission requirement with margin. Also, because the only significant radiological risk from a fission reactor would be the possibility of inadvertent criticality resulting from a launch accident, the design was confirmed to remain safely subcritical for likely accident scenarios. A number of launch accident configurations were evaluated as part of this study, and the reactor design was shown to be subcritical with sufficient margin for all cases analyzed (k-eff < 0.985, where k-eff of 1.00 is a self-sustaining fission reaction). Additionally, the reactor analyses confirmed that the temperature coefficients of reactivity are strongly negative, which ensure a safe thermal power response to adverse temperature transients. The key reactor design features are described in the proceeding paragraphs.

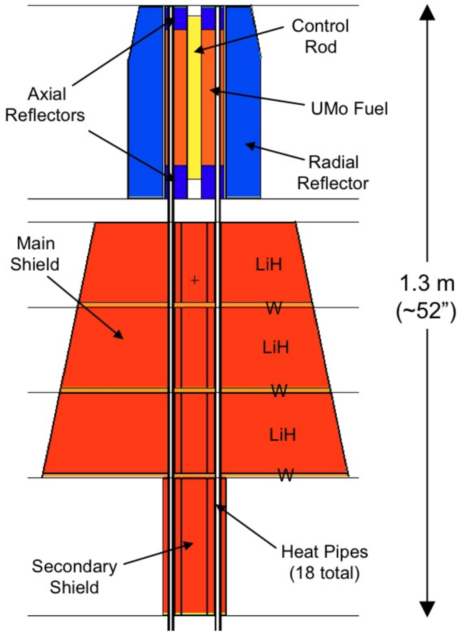


Figure 5.2-1 Reactor and Shield Concept

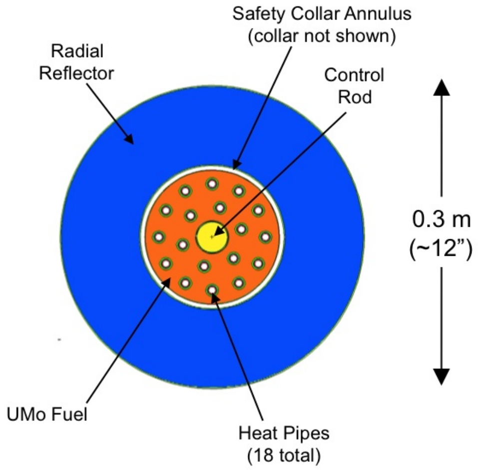


Figure 5.2-2 Reactor Radial Cross-Section

Figure 5.2-3 SNL Reactor Model and Fabrication Team

Fuel: The fuel selected for the FPS reactor concept is the alloy U10Mo (uranium with 10 weight percent molybdenum). This fuel was selected for its high uranium density, high thermal conductivity, and excellent neutronic characteristics for this application (very low neutron capture at fast energies, modest capture at moderated energies, and inherent gamma shielding). One concern with U10Mo is material swelling at relatively low fuel burnup (~1%); however the burnup in this application is so low (~0.1%) that swelling is not a significant technical risk. The anticipated form of the U10Mo fuel is cylindrical plates, with the thickness defined by manufacturing and assembly considerations. These plates would contain holes for a central control rod and in-core heat pipes. The fueled region is 12.9 cm in diameter and 30 cm tall. For this study, a maximum fuel temperature of 1200 K was imposed on the fuel, which significantly influences the core and heat pipe geometry.

Core Internal Structure: One of the key features of the selected concept is that the fuel can provide its own structural support. The fuel assembly would be contained in a can or a liner to prevent material interactions and inhibit fission gas release (which should be negligible due to the low burnup), but this envelope is not needed to maintain physical fuel integrity. The low fuel burnup minimizes possible mechanical changes in the fuel that would necessitate structural containment and hurt core performance. The advantages of this approach are that it minimizes the amount of neutron absorbing structural material in the core (keeping the core compact), and it reduces the heat conduction losses through the fuel structure. Molybdenum is a good candidate material for the liner. If some minimal structural material is required, a nickel-based superalloy (e.g., Hastelloy-X) could be used.

Heat Pipes: The FPS reactor is cooled by liquid metal heat pipes. The configuration uses 18 heat pipes: six in an inner ring and twelve in an outer ring. A “ring” geometry provides symmetry and simplifies PCS integration. The spacing of the heat pipes minimizes the distance that heat must travel through the fuel; which keeps the fuel temperature below 1200 K, and the temperature gradients and thermal stresses relatively low. The heat pipe vapor temperature is 1100 K, which led to the selection of a sodium working fluid and superalloy wick and shell. Each heat pipe is specified to be 1.11 cm in diameter and approximately 4 m long. The heat pipe design has more than a factor of two throughput margin, given the nominal heat pipe power of about 750 W, and the peak axial and radial heat fluxes are also well within the established limits. Similar heat pipes have also proven to be reliable at neutron fluences more than an order of magnitude higher than produced within the FPS core. There are several possible options for thermal integration of the heat pipes with the fuel, including brazing, hot isostatic pressing, or a liquid-metal or gas bonding. As the design evolves, each option would have to be evaluated for technical risk, cost, and reliability.

Neutron Reflectors: The neutron reflector material is very important to the FPS concept design. A reflector with a high-reactivity worth is needed not only to keep system size small, but also to make launch safety accidents relatively easy to accommodate. The reflector material specified for most space reactors is Be or BeO: no other candidate material has sufficient reactivity worth to meet the currently assumed launch accident criticality requirements. For the FPS, a compact geometry is highly desirable; thus BeO was chosen because it is a denser, higher-worth material per unit thickness than Be. The FPS concept assumes the BeO in brick form within a stainless-steel (or superalloy) container. The neutron fluence is expected to be low enough that BeO swelling and cracking should not be a significant technical issue. If later, more-detailed design studies indicate that material degradation is an issue, then BeO powder may be substituted; however, the lower density of the powder would necessitate a thicker reflector. The radial reflector surrounding the core is 7.7 cm thick. The upper axial reflector is 5 cm thick and the lower axial reflector is 7 cm thick. The lower reflector optimizes to the thicker geometry because it also provides shielding benefits.

Control Rod: Nominal reactor control is performed with a central boron carbide (B_4C) control rod that is clad with Hastelloy-X. The rod would be moved by a drive mechanism on the backside of the shield, with a drive-shaft penetrating straight through the shield. The control rod contains the required reactivity worth to ensure the reactor can be started from a cold subcritical condition and progress to full-temperature critical operation. One of the significant advantages of the FPS concept is that further reactor control is not required after startup. If there is no control rod movement, the reactor temperature would slowly degrade with time, by approximately 3 K per year or 45 K over the entire 15-year mission. The hot-end temperature drop would cause a small decrease in reactor thermal power over time, although the drop in effective heat sink temperature in the outer solar system may counteract this effect, allowing full power throughout the mission. A possible alternative approach would be to design the system for control rod adjustments throughout the mission lifetime, to counteract this small temperature drop and possibly respond to other unanticipated issues.

Safety Collar: The simplest design approach to meet the assumed launch accident safety requirements is to place an annular B_4C collar between the reactor and the radial reflector. This collar would be removed from the core once the probability of Earth return became negligible. The collar mechanism design would ensure that the safety collar remains in place during launch, but is extracted prior to reactor startup.

Radiation Shield: The FPS shield utilizes LiH (canned in stainless steel) as the neutron shield material and W as the gamma shield material. The LiH is enriched in ^{6}Li to reduce the gamma source from neutron capture in the stainless-steel and tungsten, and because ^{6}Li is naturally lower mass than ^{7}Li. Tungsten or any other high-Z material serves as a better gamma shield because it reduces the thickness and therefore, the geometric expansion of the shield diameter into the shield cone. The shield utilizes three layers of LiH and W, with each layer of LiH being placed in a stainless-steel can. The shield contains full penetrations for the heat pipes and the control rod shaft. A gap is provided around each heat pipe in which multi-foil insulation would be placed to prevent shield heating and parasitic power loss. Shielding calculations showed that the streaming dose through these penetrations accounted for approximately 50% of the payload dose. Consequently, a secondary “plug” shield (see Figure 5.2-1) was added behind the main shield to substantially reduce this streaming dose, with a relatively small mass addition.

5.2.2. Balance-of-Plant Design

To accommodate the targeted electrical power output of 1 kWe and the planned reactor heat pipe operating temperature of 1100 K, the selected concept uses a distributed thermoelectric converter approach integrated with a passive heat rejection radiator structure. The concept is very similar to approaches developed for prior RTGs in that it uses a mostly radiative thermal coupling of thermoelectric devices along the length of each of the 18 heat pipes and rejects the heat directly through a finned radiator surface. The key power system performance characteristics are summarized in Table 5.2-1.

Table 5.2-1 Small FPS Performance Summary

Heat from fission reactor	13,000 W
Heat pipe temperature	1100 K
Number of heat pipes	18
Heat per pipe	722 W
Heat loss	10%
Temperature drop from heat pipe to TE couple	50 K
TE hot-end temperature	1050 K
TE cold-end temperature	525 K
Converter efficiency	9.83%
Electrical wiring losses	10%
Temperature drop from TE couple to radiator	50 K
Effective radiator temperature	475 K
Radiator size required	5.035 m^2
Radiator panel width (1 panel per heat pipe)	11.7 cm
Radiator length required	240 cm
System net electrical power output	1035 W
Overall system efficiency	7.96%

The power conversion assembly consists of 18 panels, each about 12 cm x 250 cm for a total radiator surface area of 5 m^2. Each panel is composed of 21 thermoelectric converters with attached radiator fin as shown in Figure 5.2-4. Each converter is coupled to the reactor heat pipe by means of a highly efficient but mechanically compliant heat pipe saddle and radiation coupler that would accommodate thermal expansion of the heat pipe upon power system startup. This type of radiation coupler approach has been successfully used in other space systems, including the International Space Station. The materials selected for the thermoelectric couples include n-type conductivity $La_{3-x}Te_4$ / double-filled $CoSb_3$ skutterudite with p-type conductivity $Yb_{14}MnSb_{11}$ Zintl / filled $CeFe_{3.5}Co_{0.5}Sb_{12}$ skutterudite. These materials are stacked in a segmented device configuration similar to that used in proven heritage RTG technology (such as $Si_{0.8}Ge_{0.2}/Si_{0.63}Ge_{0.37}$ materials). The rare earth compounds are currently baselined for operation in next generation RTGs at temperatures up to 1275 K, well in excess of the requirement for the small FPS application. All of these materials are produced through metallurgy techniques in large batches, and skutterudites are currently targeted for large-scale waste heat-recovery power systems. Efficiencies of approximately 9 to 13% have been demonstrated for devices based on these materials.

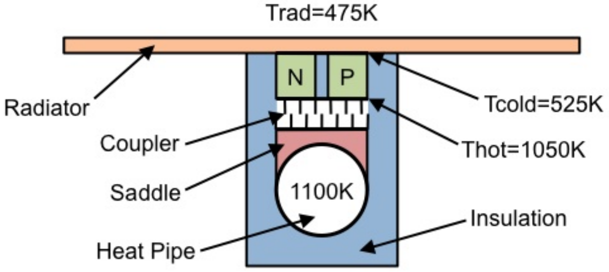


Figure 5.2-4 Thermoelectric Converter Concept

Taking into account the thermal resistances on both the hot- and cold-end of the thermoelectric device, the couples would operate with a 525K temperature differential (1050K minus 525K) with a projected efficiency close to 10%. The predicted overall system efficiency would be about 8%, with a net power output of 1035 W. The thermoelectric devices would be connected in series/parallel strings to match the spacecraft bus voltage of 28 Vdc.

5.2.3. System Configuration and Mass

The basic power system layout and geometry is shown in Figure 5.2-5. The reactor is mounted to a truncated-cone radiation shield designed to meet the radiation dose limits assumed in this study (1x10^{11} n/cm^2 and 25 krad) at a dose plane 10 m from the reactor/shield interface as shown in the figure. The shield provides a conical shadow of radiation protection with a half angle dictated by the separation distance and the diameter of the desired area to be protected at the dose plane, assumed for this study to be 4.5 m. The power conversion and radiators are located behind the shield within the cone angle. A support structure would provide mounting for the power conversion and radiator panels as well as provide the load path from the reactor to the spacecraft. The FPS would interface with the spacecraft through an adapter flange at the base of this support structure. The extension boom that connects the power system to the spacecraft is not included in the FPS mass estimate.

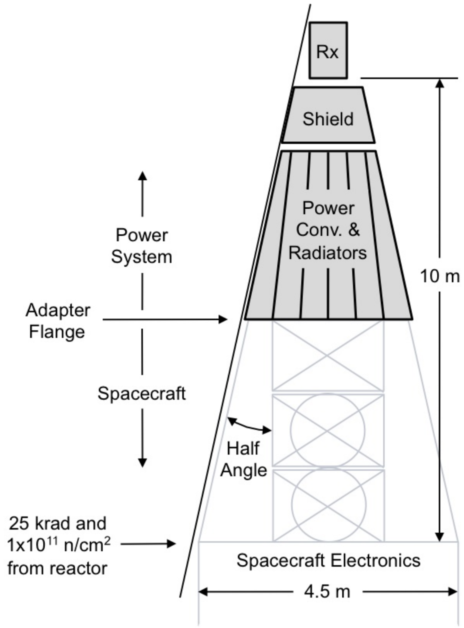


Figure 5.2-5 Concept Layout

The FPS design configuration is shown in Figure 5.2-6 and additional views are provided in Appendix D. The power system that resulted from this design study has a total length of about 4 m, including the 2.5 m long radiator panels. The reactor heat pipes extend from the core straight through the shield (shown as partially transparent) and then flare outward to where the radiator panels begin. The secondary plug shield discussed earlier is not shown, but would be inserted behind the main shield to attenuate heat pipe radiation streaming down the straight section of heat pipes. The aluminum radiator panels are rectangular, but are angled to form a conical structure to improve structural rigidity and radiator view factor. A tubular aluminum truss structure supports the radiator panels and extends to the backside of the radiation shield. The truss structure and radiators are fixed and do not require any in-space deployment. The 1.7 m-diameter end skirt would include an adaptor flange to permit mating to the spacecraft.

The system mass summary is presented in Table 5.2-2 and a full Master Equipment List (MEL) is included in Appendix E. The total current best estimate (CBE) mass is 604 kg, or about 1.7 W/kg. The shield assembly has the greatest individual mass at 271 kg, approximately 45% of the total. This could be reduced if the radiation limits are relaxed or the separation distance is increased. A 30% mass margin was applied to all components with the exception of the reactor fuel. The fuel mass was calculated specifically to meet the required criticality and safety conditions, and a mass margin of 5% (which translates to a large reactivity margin) was deemed appropriate for the 56 kg of UMo fuel. The total FPS mass with margin is 772 kg, or about 1.3 W/kg.

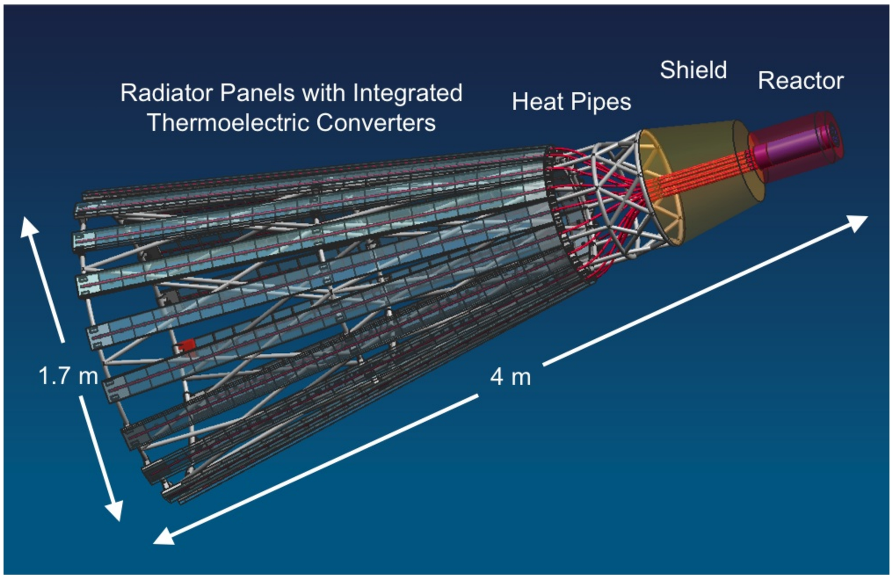


Figure 5.2-6 Small FPS Design Configuration

Table 5.2-2 Small FPS Mass Estimate

	Current Best Estimate (kg)	CBE + Margin* (kg)
Core Assembly	133	159
Heat Pipe Assembly	19	25
Shield Assembly	271	353
Thermoelectric Assembly	89	115
Truss Assembly	60	78
Inst. & Control Assembly	32	42
Total Small FPS	604 (1.7 W/kg)	772 (1.3 W/kg)

*Margin is assumed as 30% for all components except reactor fuel (5%)

Since the shield represents a significant fraction of the total system mass, the team performed a mass sensitivity analysis relative to reactor separation distance, as shown in Figure 5.2-7. As expected, the analysis shows that greater separation distances result in lower shield mass. In theory, an optimum separation distance results when shield and boom mass are properly balanced. In practice, a larger boom length introduces numerous integration issues including greater difficulty in packaging the spacecraft within the launch vehicle shroud, the possible need for post-launch deployments, and the potential for unstable science-orbit dynamics. Based on the sensitivity analysis performed and the possible spacecraft integration issues that arise with longer booms, it appears that the 10 m separation represents a reasonable design choice.

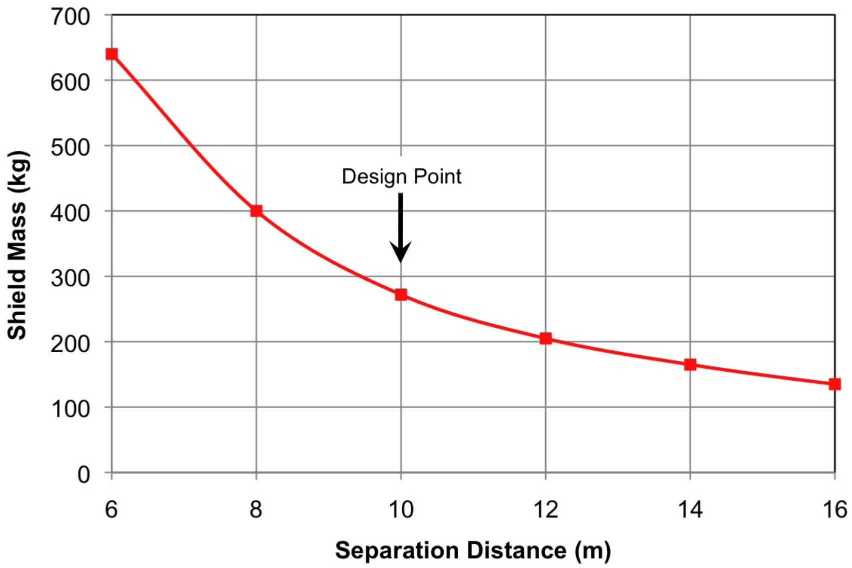


Figure 5.2-7 Shield Mass Sensitivity with Separation Distance

5.2.4. Spacecraft Integration

The design concept for the FPS results in a conical package in common to all space reactors flown thus far. This packaging lends itself to a relatively straightforward integration into a spacecraft design; the base of the FPS radiator array structure is simply attached to the upper portion of the spacecraft structure. Separation distance of the dose plane from the reactor is most easily achieved through a simple extension of the spacecraft body. This extended structure would provide ample room for propulsion tanks and other equipment that are less susceptible to the elevated levels of radiation and thus can be closer to the reactor. An example spacecraft configuration, based on the Europa Orbiter mission, is shown in Figure 5.2-8. The launch configuration, in a standard evolved expendable launch vehicle (EELV) 5-m fairing, is shown in Figure 5.2-9.

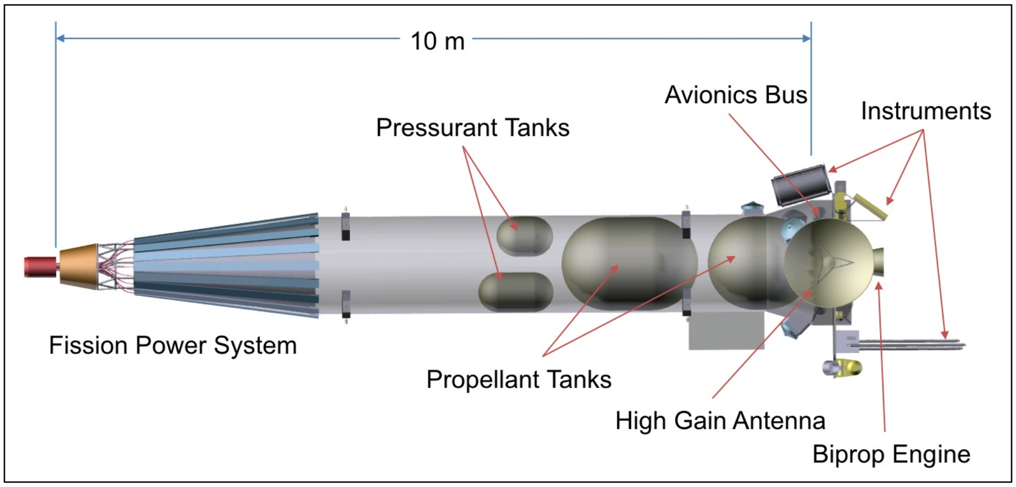


Figure 5.2-8 Notional FPS-based Europa Orbiter Configuration

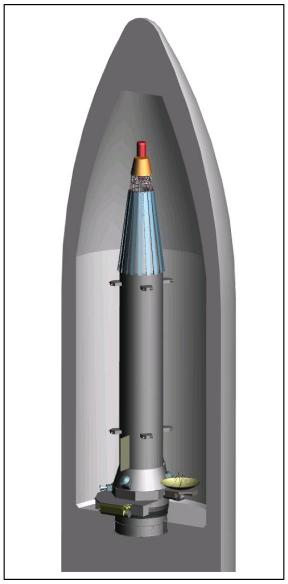


Figure 5.2-9 Notional Launch Configuration in EELV Fairing

The notional spacecraft configuration is representative of a typical orbiter spacecraft, incorporating a large bipropellant propulsion system for deep space maneuvers and an orbit injection. Radiation-sensitive avionics are centrally located in the avionics bus, which begins at the defined dose plane distance of 10 m from the back of the reactor. Instruments are grouped around the aft end of the spacecraft, which would be nadir-pointed when operating in science orbit. This design lends itself to gravity gradient stabilization and this is easily accommodated by the configuration. The high gain antenna (HGA) is located on a fixed mount, sufficiently separated from the spacecraft body to allow full articulation while remaining within the confines of the reactor shield cone. A feature of this design concept is that the higher power available from the FPS can increase telecommunications radio frequency (RF) power output, facilitating high data return from a relatively small HGA. This feature has a number of benefits, including eliminating the need for antenna booms and deployment, and greatly reducing the tight spacecraft pointing and stability requirements imposed by larger HGAs typically used for such missions.

5.2.5. Concept-of-Operations

The reactor is launched at ambient temperature and at zero-power. The reactor core is not a radiological hazard during launch processing and can be approached by personnel without concern of radiation effects. The reactor is maintained subcritical with essentially no fission activity because it has a neutron-absorbing control rod inserted in the core, and a neutron-absorbing sleeve between the reactor fuel and the reflector. The sleeve must be removed and the rod must be withdrawn to initiate reactor operation. Once the spacecraft is on the appropriate trajectory, the sleeve is removed from its position between the fuel and the reflector using a fault-tolerant ejector mechanism. To start the fission process, the control rod is then gradually withdrawn from the core using a redundant motor drive. A sustained fission reaction would initiate spontaneously once a critical configuration is achieved.

The position of the control rod is adjusted within the core to control the reactor thermal power level. The reactor can sustain a critical reaction at very low power levels. The control rod is adjusted slowly until a statistically significant response is recorded on system neutron detectors. To increase the thermal power level, the control rod is further withdrawn while neutron flux is monitored, until enough power is generated to produce the required thermal response.

Due to the nature of the reactor design, the thermal power output is self-regulating once the fuel temperature begins to rise. This negative temperature feedback effect causes the reactor power level to automatically decrease if the reactor temperature increases and to increase if the reactor temperature decreases (in the absence of a control rod adjustment). Once the reactor fuel temperature begins to increase, the temperature feedback mechanisms begin to function and the reactor is then brought to full power and temperature. Increase to full reactor power is expected to occur over a period of approximately 8 hours, but it could be done faster if required.

Heat removal from the core to the power conversion system is the only significant source of heat loss; thus, the reactor power would inherently and correctly respond to changes in the system power demand (intended or otherwise). Therefore once the reactor is started additional reactivity control is not required for short-term power changes. The reactor power density is low enough that the fuel can be cooled with a combination of passive conduction and heat pipe operation. Therefore, no active control systems related to core cooling are required. Another beneficial feature of low-power operation is related to the fact that very little fissionable material is consumed. This fact, coupled with the negative temperature coefficient of reactivity allows the reactor to operate at essentially full power and temperature over extended periods without a reactivity adjustment. Current estimates suggest that the electrical power output of the power system would decrease by only 5% during a 15-year mission without reactivity adjustment after full power has been achieved.

Reactor startup would be initiated using battery power within a few hours after launch. Once the heat pipes begin operation, the thermoelectric converters would begin producing electrical power to meet spacecraft power needs. The reactor would operate under steady-state full-power conditions throughout the mission and any electrical power not needed by the spacecraft would be shunted to a parasitic radiator and rejected to space. While the study requirement called for continuous power output from the FPS, reactor power adjustments could be accommodated if desired. A possible benefit of reducing thermal power during the mission is the corresponding reduction in reactor-induced radiation at the spacecraft electronics bus.

5.2.6. Extensibility

The design of the small FPS concept is optimized to provide 1 kWe for approximately 15 years. The system is extensible to lower power levels; however, there would be a relatively small mass difference between a 0.5 kWe system and a 1 kWe system because the reactor is already near the minimum size needed to sustain a fission reaction. Extensibility to higher power levels can be divided into two categories – use of the same reactor (e.g., identical core and reflector) and use of the same reactor technology and approach but with some modifications.

In the first category, the same reactor could be used with longer heat pipes and additional distributed thermoelectrics to produce power up to about 1.5 kWe. The use of a more advanced heat pipe wick would allow an additional power increase up to about 2 kWe. A 2 kWe system could also be developed by using thermoelectrics in a compact heat exchanger with secondary heat pipes. The power limit using the same reactor but different power conversion appears to be about 5 kWe; the principal change would be the use of high-efficiency Stirling power conversion instead of thermoelectric conversion.

For power levels above 5 kWe, several small reactor design changes would be needed. In this second category of extensibility, increasing power to 10 kWe would require a slight change in core volume and the number (or size) of heat pipes. Increasing power beyond 10 kWe would require at least two changes: additional and larger diameter heat pipes, and possibly lower density UMo fuel to accommodate increased uranium burnup. These two changes would result in an increase in reactor size and system mass. Other options for increasing power beyond 10 kWe could include changing to a high temperature fuel block (e.g., W/UN or Mo/UN cermet) or changing to pin-type fuel.

At power levels above 10 or 20 kWe, the use of superalloy heat pipes to provide primary core cooling may become limiting. For these power levels, a different reactor cooling methodology could be utilized. Pumped alkali metals, refractory metal heat pipes, or direct gas cooling with Brayton power conversion are all possible options. More advanced, higher-temperature fuels, heat transport systems, and power conversion technologies would allow fission systems to scale to considerably higher power levels. Although these high-power systems would use different technologies, they would still greatly benefit from the knowledge and experience gained from designing, developing, testing, and flying the 1 kWe FPS.

5.3. System Development

5.3.1. Roles and Responsibilities

While the FPS project organization, roles, and responsibilities have not yet been defined, the study team envisions the following roles and responsibilities for system development.

DOE would be responsible for the reactor integration, assembly, and test. Early on, DOE would lead the development of a FPS conceptual design and establish the fuel and shielding fabrication processes. Following concept review, DOE would award and manage a FPS system design contractor. During the development program, DOE would lead all the nuclear irradiation testing required to verify the system. DOE would also furnish the nuclear material and shield material. The DOE contractor would be responsible for the overall system integration, assembly, and test of all the remaining components (less the reactor). The contractor would lead the system engineering and FPS design activities. The contractor would also be responsible for the fabrication of hardware elements other than the nuclear fuel and shielding materials.

NASA would be responsible for spacecraft design and integration. After a specific mission is defined, NASA would coordinate FPS integration with the spacecraft prime contractor. NASA would also perform the non-nuclear system testing (including thermal-vacuum testing) of the power conversion and heat rejection elements.

5.3.2. Verification Strategy

Development and verification of the system design and the flight hardware would follow the "test as you fly, fly as you test" maxim to the extent practical. Specifically, the components would be subjected to mechanical, thermal, vacuum, vibration, launch loads, material compatibility, radiation, nuclear, functional, electrical, instrumentation, and controls testing. In order to achieve the required test results and provide the most cost-effective approach for system verification, the system testing would be split into two categories: "zero-power" ground nuclear tests and electrically heated system tests.

Ground-based nuclear testing would confirm the nuclear design. Tests that are of particular interest include: 1) verify the amount of subcriticality margin at launch for nominal and accident conditions (e.g., surrounded by water), 2) verify the negative thermal feedback coefficient for the nuclear power as the reactor temperature rises, and 3) verify the control rod position for initial criticality and the rod margin for accommodating heat-up. The first is needed for the launch safety analysis. The second and third are needed for operation and design verification. None of these tests require full-power reactor operation (i.e. 13000 watts-thermal); they can be done with zero-power critical tests using external electrical heaters to achieve the desired temperatures and temperature gradients. In a zero-power critical test, the reactor is in a critical state and is producing a self-sustaining nuclear reaction, but the amount of nuclear power is kept at a very low level (nominally 1 to 10 watts-thermal) so that the buildup of radioactive fission products is negligible. This greatly reduces the safety concerns and the cost of the experiment, and permits repeated access to the hardware during testing.

The first zero-power critical test can be performed early in the program with a mock-up to verify the nuclear material cross sections, the neutron spectrum, and the leakage fraction of the FPS reactor concept. The second set of criticality experiments would be done with a higher-fidelity reactor prototype that includes the shield and heat pipes. Electrical heaters wrapped around the core, and heaters and cooling systems on the heat pipes themselves, would allow test engineers to alternately drive heat into the core and remove heat from the core in a manner that could exercise the reactor over a full range of temperatures and temperature gradients that might be encountered with nuclear heating. The nuclear feedback and the nuclear controls could be fully evaluated under these conditions. A zero-power critical acceptance test would also be performed on the flight reactor to verify the control rod position required to achieve criticality.

In the electrically heated tests, the full system would be evaluated with the nuclear heat of the core represented by electrical resistance heaters. Electrically heated testing would include startup, full power operation, and a wide range of operational transients. This approach has been developed over the past decade as a complement to nuclear testing for space fission power systems. The simulated core, possibly made using depleted UMo, would have embedded electrical heaters to generate the heat. The design would mimic the heat transfer conditions anticipated at the heat pipes, with similar thermal inertia and materials interactions as expected in the actual nuclear core. The main differences relative to the real core are the radiation environment and the nuclear feedback behavior. However, the heaters can be programmed to simulate the reactor behavior based on analytical models for reactivity feedback. Testing would be used to demonstrate adequate performance margin over an operational range that includes all significant reactivity feedback coefficients, the potential range of values for those reactivity feedback coefficients, and all potential effective delayed neutron fractions. Lifetime testing would also be performed on components to confirm long-term performance and degradation characteristics, using accelerated test methods as practical.

The electrically heated system testing would allow thorough evaluation of the heat transport, power conversion, and heat rejection subsystems in a thermal-vacuum environment while demonstrating control algorithms for both transient and steady-state operations. For the engineering unit, it would lead to design verification that would help ensure the success of the flight system. For the flight unit, it would ensure proper functionality prior to launch. Nuclear feedback effects on the flight unit would be shown to be within acceptable margins by coupling measured reactivity feedback coefficients with full-power electrically heated tests.

This two-pronged approach of zero-power nuclear testing and electrically heated system testing provides a robust verification strategy for the FPS. The testing would provide all the required data to confirm the flight design prior to launch. The key elements would be fully characterized under expected nuclear, thermal, mechanical, and electrical conditions. The combination of this test approach, the low thermal power and energy density of the reactor, the extensive suite of available analytical tools, and the broad nuclear experience base provides confidence that the flight system would meet the intended mission requirements.

5.3.3. Test Facilities

The FPS development effort would employ a number of existing DOE and NASA facilities and test capabilities to support the nuclear design and verification. Existing NASA facilities would permit the non-nuclear mechanical, thermal, vacuum, vibration, launch loads, material compatibility, electrical, instrumentation, and controls testing of individual components or the entire system.

DOE facilities would also be utilized to support the design, development and fabrication of the nuclear fuels, conduct nuclear irradiations testing, and perform the zero-power critical testing. DOE laboratories and fuel manufacturing capabilities at INL and ORNL would be utilized to develop the fuel manufacturing process and FPS reactor core assembly. Because the flight unit would be fueled with highly enriched uranium (HEU), specialized and dedicated security facilities would be needed. A number of nuclear irradiation facilities are available for use to perform irradiation experiments on various components, instruments, and materials using neutron or gamma irradiation capabilities. The SNL Gamma Irradiation Facility (Figure 5.3-1) and the fuel fabrication equipment at the INL (Figure 5.3-2) are examples of such existing capabilities within the DOE complex. In addition, DOE has recently established capabilities at the Nevada Test Site (Figure 5.3-3) to perform zero-power critical testing of nuclear reactor cores.

Figure 5.3-1 SNL Gamma Irradiation Facility

Figure 5.3-2 UMo Fuel Fabrication Press at INL

Figure 5.3-3 Device Assembly Facility (DAF) at the Nevada Test Site

Because of the size and type of materials selected for the FPS design, and because other DOE projects have established relevant fuel fabrication, testing, and experimental facilities, it is anticipated that no new facility-related infrastructure would be required for this system. Some facility and process fabrication equipment would need to be installed or modified within the existing facilities to support the FPS fabrication and testing requirements. The project would also explore available university or industrial test capabilities to reduce costs or improve schedule considerations.

5.3.4. Development Program

The FPS development program is summarized in Figure 5.3-4. The 10-year program is organized into three phases: Development (3 years), Engineering (3 years), and Flight Qualification (4 years). A basic set of program-related milestones is shown on the “Program” line. Within each phase, a listing of the key system engineering and testing activities is presented along with the expected National Environmental Policy Act (NEPA) and Launch Approval (LA) products. A more comprehensive, but still very notional, FPS development schedule is included in Appendix F.

Prior to beginning the Development phase, a Concept Development (CD) activity would be conducted to generate a FPS conceptual design and address some of the possible technology risks. The major areas identified for technology risk reduction during this period are: 1) fabricate a 4 m potassium heat pipe and demonstrate power throughput at FPS operating temperatures and irradiation levels, 2) fabricate a Zintl/LaTe/SKD thermoelectric module with integral radiator fin and demonstrate power output and efficiency at FPS operating temperatures and irradiation levels, and 3) fabricate UMo fuel coupons and characterize mechanical properties and evaluate core fabrication methods. These activities would be conducted in parallel and can be completed within 6 to 8 months at an estimated cost of approximately $1M. Starting this technology effort in the latter part of 2010 or early 2011 would enhance the ability to meet a 2020 flight readiness opportunity.

	Development Phase 2011 – 2013 (3 yrs)	**Engineering Phase 2014 – 2016 (3 yrs)**	**Flight Qualification Phase 2017 – 2020 (4 yrs)**
Program	CD ▲CR ▲CA	▲PDR ▲CDR	ATLO
System Engineering	• System Engineering Plan • Requirements Formulation • Analytical Tool Development • Detailed Equipment List	• Quality Assurance Plan • Requirements Verification • Model Validation • Detailed Design Drawings	• Final Documentation • Final Approvals • Launch Processing
NASA Tests	• TE materials testing • Elect-heated single panel HP/TE performance test with follow-on life test • 4 couple TE vibe test • 4 couple TE radiation test	• Elect-heated 18 panel HP/TE performance verification with boom and spacecraft simulator • 2 panel HP/TE life test • 18 panel HP/TE vibe test • 4x 4 couple TE radiation test	• Elect-heated qual unit test • Flight unit spacecraft and launch vehicle integration
DOE Tests	• Fuel mechanical testing • Single HP core radiation test • LiH thermal/radiation test • BeO reflector fab mockup • DU core fab mockup • Zero-power critical nuclear mockup test	• Shield thermal verification test • Reactor/shield structural mockup test • Control rod drive assembly test • Safety collar assembly test • Control S/W verification test • Zero-power critical nuclear prototype test	• Flight unit assembly and zero-power critical acceptance test
NEPA/LA	• Program & Mission EIS	• Preliminary & Draft SAR	• Final SAR & INSRP

CD=Concept Development
CR=Concept Review
CA=Contract Award

PDR=Preliminary Design Review
CDR=Critical Design Review
ATLO=Assembly, Test, and Launch Operations

EIS=Environmental Impact Statement
SAR=Safety Analysis Report
INSRP=Interagency Nuclear Safety Review Panel

Figure 5.3-4 Small FPS Development Program

The FPS Development phase would focus on concept validation. Design requirements would be fully defined and analytical models would be developed. Testing would be performed on components and sub-assemblies to evaluate performance. An electrically heated power generation test would be completed in thermal-vacuum using a single heat pipe and thermoelectric panel assembly. Material properties and design standards would be formulated and manufacturing processes would be established. The Development phase would culminate with a zero-power critical test of a reactor mock-up.

The Engineering phase would verify FPS form, fit, and function. Detailed design drawings would be completed and analytical models would be fully validated with test data. Thermal-vacuum performance testing would be conducted on a full-size, 18-panel engineering model using an electrically heated reactor simulator and spacecraft mockup. Comprehensive vibration and radiation testing of the panel would also be performed. The reactor instrumentation and control elements would be tested to verify performance in an operational environment and the flight software would be validated. A full-size reactor prototype would be fabricated and characterized in a series of zero-power critical tests.

The Flight Qualification phase would deliver the flight system to the launch site. It would include an electrically heated qualification test unit and the actual flight system. The flight system would be fueled and assembled at a DOE facility and delivered to the launch site ready for installation on the spacecraft. Prior to spacecraft integration, a final zero-power critical acceptance test would be performed on the flight reactor. A 1-year spacecraft and launch vehicle integration period was assumed as part of the 10-year development program.

5.3.5. ROM Costs

It was not possible for the team to develop a thorough cost estimate in the six-week period allocated for the study. At the same time, the team recognized that the feasibility of the selected FPS concept is heavily weighted by affordability. A simple methodology was developed to generate a ROM cost estimate for the FPS concept. The costs were organized into three phases that mirror the development program phases in Figure 6.3-4. Within each phase, best-guess engineering estimates were made as to the number of people required, materials/facilities/support equipment (i.e., support) costs, and system contract costs. The results are provided in Table 5.3-1. The total cost for the three phases, including the first flight unit, is $690M. The ROM flight unit recurring cost was estimated at $145M based on 25% of the total Engineering and Flight Qualification costs.

Table 5.3-1 ROM Development Costs by Phase

	Development Phase 2011 – 2013 (3 yrs)	**Engineering Phase 2014 – 2016 (3 yrs)**	**Flight Qual. Phase 2017 – 2020 (4 yrs)**
NASA People incl. FTE & WYE	20/yr	40/yr	30/yr
NASA Materials, Facilities, and Support Equip.	$2.5M/yr	$5M/yr	$15M/yr
DOE People incl. Labs	25/yr	20/yr	15/yr
DOE Materials, Facilities, and Support Equip.	$10M/yr	$15M/yr	$20M/yr
Contract Design & Fabrication	$20M/yr beginning in Year 3	$50M/yr	$30M/yr
ROM Cost	$110M	$265M	$315M

FTE=full-time equivalent (civil servants), WYE=workyear equivalent (contractors)

The workforce levels and support costs were estimated separately for NASA and DOE. It was projected that the NASA workforce would start at 20/yr during the Development phase, peak at 40/yr during the Engineering phase, and drop to 30/yr during the Flight Qualification phase. A flat rate of $250K/workyear was assumed for the NASA workforce, accounting for the mix of managers, engineers, and technicians that would be needed. NASA support costs would generally increase with time as facilities and testing expand to accommodate larger and higher fidelity hardware. The DOE workforce is expected to start at a relatively high number during the development phase and gradually reduce as the contractor assumes more design and fabrication duties. A flat rate of $400K/workyear was assumed for the DOE workforce including managers, engineers, and technicians. The DOE support costs would increase, similarly to NASA's, as the test requirements become more stringent. DOE's support costs would be somewhat higher than NASA accounting for the cost of nuclear materials, safety, and security. The system contractor costs are the most difficult to project using this methodology. The values presented in Table 5.3-1 represent a consensus best-guess estimate from the members of the team who have experience with contracts of similar scope with comparable deliverables. The contractor costs are expected to peak during the Engineering phase when the majority of test hardware is designed and fabricated.

To check the reasonableness of the ROM cost, the total was compared with actual and estimated costs from previous programs and studies as discussed below.

SNAP 10-A Flight System: In the early 1950s, the U. S. Atomic Energy Commission started the System for Nuclear Auxiliary Program (SNAP) to develop compact UZrH-fueled reactors for space applications. This technology program included the SNAP 2, 8 and 10A reactor concepts and looked into both Rankine and thermoelectric power conversion options. In December 1961, the SiGe direct radiating thermoelectric concept was selected for the 0.5 kWe SNAP 10A flight system, resulting in the April 1965 launch of the only space power reactor flown by the U. S. By combining the actual technology development and flight hardware cost elements of that program, a total cost of $61M in 1965-dollars is obtained. Adjusting these costs using NASA's New Start Inflation Index calculator available at http://cost.jsc.nasa.gov/inflate.html yields an estimate of $506M in 2010-dollars. These costs covered an 8-year period for development and flight hardware production and testing, but the time from the decision to fly a specific concept to launch was only a little more than four years.

SP-100 Flight Demonstration Study: In the early 1980s, NASA, DOE, and the Department of Defense (DOD) joined together to conduct the SP-100 Program. The original objective was to develop and demonstrate technology for a high-temperature, Li-cooled reactor with thermoelectric conversion to produce 100 kWe for a wide range of civilian and national defense missions. In the early 1990's, the program emphasis shifted, and the project shifted to a lower power flight demonstration mission that could be launched in a relatively short time frame. The contractor proposed a compact reactor core conductively coupled to surface-mounted SiGe thermoelectric elements that radiate directly to space. The cost to produce, assemble, test, and launch the 5 kWe flight system in a 6-year program was estimated to be $360M in 1992-dollars. The equivalent cost would be $546M in 2010-dollars after accounting for inflation using the NASA website calculator.

Affordable Fission Surface Power (FSP) System Study: In 2006 and 2007, NASA and DOE conducted a feasibility study of a surface reactor power system that would use low-risk technologies for application on the lunar surface with extensibility to Mars. A system capable of producing 40 kWe with a UO_2 pin-type core, stainless-steel construction, pumped-NaK cooling, Stirling power conversion, and water heat rejection was developed. A bottoms-up cost estimate was generated that included all of the typical NASA work breakdown structure elements and cost burden factors. The cost for the 11-year program through the first flight unit was estimated to be $1069M in 2007-dollars, which inflates to $1136M in 2010-dollars using the NASA website calculator.

The three cost estimates cited above cover a range of concepts, power levels, technical complexities, and time frames. One of the estimates reflects the actual costs for the only space reactor flown by the U.S. Taken together, these costs bound and support the FPS study team estimate to design, build, test and fly a small power reactor for NASA science applications in the 2020 time frame.

5.3.6. Program Leveraging

If undertaken within the near term, the small FPS can gain a substantial cost and schedule advantage in utilizing and building on other current DOE and NASA projects. Major cost-saving examples are as follows:

NASA Exploration Technology Development Program (ETDP) Fission Surface Power (FSP) Project: Extensive work has been under way to define, build, and test a technology demonstration unit of a lunar/Mars power system. The design and modeling tools for a small, compact reactor have been established including the requisite shielding and instrumentation and control systems. Extensive work has already been accomplished in defining the test programs as well as developing test hardware, all of which can be applied to facilitate the design, fabrication, and testing of a small FPS.

DOE Reduced Enrichment for Research and Test Reactors (RERTR) Program: DOE has an ongoing program to design and test UMo fuels for terrestrial nuclear research and test reactors. Extensive characterization and fuel irradiation evaluations have been completed on this fuel form. This work has provided sufficient data to understand how to fabricate fuel elements as well as to determine their performance under normal operating, transient, and accident conditions. Design margins and performance characteristics have been established for power generation levels and burnups that far exceed what is needed for the FPS. Fabrication techniques are well established and some capability exists to manufacture small HEU fuel samples. Investments in UMo fuel manufacturing capabilities have been made at both INL and ORNL to handle HEU fuels.

NASA/SMD RPS Technology Development Program: The thermoelectric materials and the assembly approach that has been selected for the FPS converter is a technology currently under development for potential use in high temperature (up to 1273 K hot-end operating temperature) next generation RTGs. This work will help provide enhanced margins in terms of lifetime performance and reliability. The processes and procedures for assembling and testing flight units and for conducting launch support activities have been established. While the existing procedures and processes would need adjustment to accommodate variations between the RPS and small FPS, the basic process and support activities are well established for handling power sources containing special nuclear material.

DOD and DOE Thermoelectric Materials and Systems Development: Ongoing technology development programs are aimed at demonstrating the viability and performance of thermoelectric converters harvesting vehicle exhaust waste heat or directly using combustion heat sources for auxiliary electric power sources. The technology is based on similar thermoelectric materials baselined for the selected converter approach, and will significantly reduce risks related to the production of materials in sufficient quantities with attention to thermal/mechanical converter integration challenges.

DOE National Nuclear Security Administration (NNSA) Device Assembly Facility (DAF): Work is almost completed for establishing the capability to perform zero-power critical reactor testing at the DAF at the Nevada Test Site. The required safety analyses and operational procedures to conduct reactor experiments at the facility have been prepared. The DAF is in the process of obtaining the needed fuel and structural elements (reflector material, shielding materials, etc.) to assemble a physics-based mock-up of the reactor to conduct the first set of zero-power critical experiments including the safety tests of water and sand immersion.

DOE INL and ORNL Critical infrastructure for Fuel and Shield Materials: INL and ORNL have existing facilities and security protocols to permit handling and fabrication of the highly-enriched nuclear core materials as well as the capabilities to process the required shielding materials (LiH, depleted uranium, etc.) that would be used for the FPS.

6. Conclusion

The team successfully developed a viable, low-risk fission power system concept that can be delivered for launch by 2020 and meet the 1 kWe power output and 15-year lifetime requirements defined for the study. The power system concept consists of a UMo-fueled, heat pipe-cooled reactor with distributed thermoelectric converters integrated with an aluminum radiator. The system mass is 772 kg (including margin); and the ROM cost, including the first flight unit, is $690M. The basic concept can be readily scaled to several kilowatts with thermoelectric conversion or up to 10 kWe using Stirling power conversion with minimal changes to the reactor design. This power system would provide an enabling capability for potential future space science missions that may otherwise be power limited. The technology is highly adaptable to provide significantly greater power using alternative, but similarly mature design approaches.

Although the team completed this study in only 6 weeks, the conclusions are based on a solid foundation of more than 50 years of nuclear engineering and technology development by DOE, NASA, the Navy, the Air Force, and private industry. Hundreds of commercial, military, and university reactors are operating safely in the U.S. today, and hundreds more worldwide, as a result of the nation's investment in nuclear technology. The materials, components, and test facilities needed to develop the selected FPS are readily available within the existing U.S. nuclear infrastructure.

Space reactors are not new or particularly complicated. The U.S. successfully built and launched a space reactor in 1965, and the Russians launched over 30 systems in the years between 1976 and 1988. This type of development has been done before and does not present a major challenge beyond what is routinely done in other space flight systems. For missions requiring 1 kWe or more, fission systems offer the potential for a reliable, low-cost power source that can be reproduced to meet the demands of outer planetary science spacecraft for the next century.

APPENDIX A. Small FPS Study Schedule

MON	TUE	WED	THU	FRI
Mar-8 Finalize Study Plan	9	10 Finalize Team	11 11:00 Kick-off Telecon	12 Review
15 Requirements and Past Concepts	16	17 GRC Face-to-Face Meeting	18	19 Propose
22 New Concepts	23	24	25 11:00 Concept Selection Telecon	26 Refine
29 Down-selected Concept	30	31 JPL Face-to-Face Meeting	Apr-1	2
5 Prepare Draft Presentation	6	7	8 Mgmt Review	9 Update
12 Presentation and Generate Report Outline	13	14	15 11:00 Team Telecon	16 GPP Review
19 Prepare Draft Report	20	21	22 11:00 Team Telecon	23 Update
26 Report	27 Distribute Report to Team	28 Final Team Comments Due	29 11:00 Team Telecon	30 Final Report

APPENDIX B. Relevant Space Nuclear Power Systems

System	Fuel (Coolant)	Thot/ Tcold	Power Conv.	Thermal Power	Electrical Power	System Mass	Design Life
GPHS RTG*	Pu-238	1273/ 573 K	SiGe TE	4.5 kW	285 W	56 kg	10+ yrs
MMRTG	Pu-238	811/ 483 K	PbTe/ TAGS TE	2 kW	110 W	45 kg	14 yrs
ASRG	Pu-238	1123/ 363 K	Stirling	500 W	140 W	25 kg	14 yrs
SNAP 10A*	UZrH (NaK)	790/ 560 K	SiGe TE	40 kW	500 W	432 kg	1 yr
BUK/ RORSAT*	UMo (NaK)	973/ 623 K	SiGe TE	100 kW	3 kW	1200 kg	6 mo
Topaz I*	UO_2 (NaK)	1723/ 923 K	Thermionic	150 kW	6 kW	1000 kg	1 yr
Topaz II	UO_2 (NaK)	1800/ 743 K	Thermionic	135 kW	5.5 kW	1060 kg	3 yrs
SP-100	UN (Li)	1350/ 850 K	SiGe TE	2400 kW	100 kW	4500 kg	7-10 yrs
JIMO (TB2.5)	UN (Li)	1300/ 500 K	Brayton	500 kW	135 kW	6200 kg	15-20 yrs
JIMO (PB1)	UO_2 (HeXe)	1150/ 400 K	Brayton	1000 kW	200 kW	6800 kg	15-20 yrs
FSP	UO_2 (NaK)	850/ 425 K	Stirling	200 kW	40 kW	5800 kg	8 yrs

* These systems have been launched and operated in space.

APPENDIX C. Nuclear Power System Background

Terrestrial Nuclear Power: The United States has actively developed and deployed terrestrial nuclear power technology since the early 1940s. The first nuclear electric power produced in the U.S. was by the Experimental Breeder Reactor (EBR-I) fast-spectrum reactor in Idaho in 1951. Currently there are 104 commercial nuclear power plants operating in the U.S., and there are a total of 439 power reactors operating around the world in 31 countries. The U.S. generates approximately 20% of its electric power from nuclear power plants, similar to the one shown in Figure C-1. In addition, there are more than 40 research reactors operating, primarily at universities.

Figure C-1 Tennessee Valley Authority-Watts Bar Nuclear Power Plant

Although commercial nuclear power plants are many orders of magnitude larger than the small reactors required for NASA missions (e.g., gigawatts compared to kilowatts) the technology and operating experience from terrestrial power plants provides an invaluable foundation for space fission power systems. In fact the fuel performance for small NASA reactors based on the burnup fraction of the fissionable atoms is roughly a factor of ten less demanding than for terrestrial plants.

The U.S. Naval Reactors program began in parallel with commercial nuclear power development and the first nuclear powered submarine was launched in 1954. Since then, Naval Reactors has consistently supplied power plants for submarines and surface ships. In recent designs, the reactors for these ships operate for the life of the ship without refueling or replacement. Currently there are more than 80 U.S. nuclear powered vessels operating, such as those shown in Figures C-2 and C-3.

Figure C-2 USS Seawolf

Figure C-3 USS Enterprise

Space Nuclear Power: Since 1961 the U.S. has flown more than 40 Radioisotope Thermoelectric Generators (RTGs) with an essentially perfect operational record. The specifics of these RTGs and the missions they have powered have been thoroughly reviewed in the open literature. The U.S. has flown only one reactor, which is described below. The Soviet Union has flown only 2 RTGs and had shown a preference to use small fission power systems instead of RTGs. The USSR had a more aggressive space fission power program than the U.S. and flew more than 30 reactors. Although these were designed for short lifetime, the program demonstrated the successful use of common designs and technology.

During the late 1950s and early 1960s the Atomic Energy Commission (predecessor to DOE), the Air Force, and NASA with selected contractors conducted an aggressive space nuclear power technology development program that resulted in the launch of the only operational U.S. space reactor, SNAP 10A, in April 1965. This system is shown in Figure C-4. The SNAP 10A reactor performed as designed; however, an electrical failure on the spacecraft caused the system to shut down after 43 days of operation. The successful development, launch, startup and operation of the SNAP 10A nuclear power system demonstrated the U.S. capability to effectively utilize fission power systems in space.

Although the U.S. has not flown a reactor since SNAP 10A, there have been three other significant reactor power system development programs: SP-100, JIMO, and FSP. The SP-100 program objective was to develop the technologies needed for a broad range of space missions requiring a high power-to-weight ratio with nominal 100 kWe power output. The program began in 1982 and was terminated by Congress in 1994. A high temperature (1350 K) refractory alloy heat transport system with thermoelectric power conversion was designed, uranium nitride fuel was fabricated and irradiated to 6% burnup, and significant amounts of hardware and electronics were successfully tested. The Jupiter Icy Moons Orbiter (JIMO) nuclear power program was conducted from 2003 to 2005 with the objective of developing a nuclear electric propulsion system for the long duration mission. The Naval Reactors branch of DOE led the nuclear system development that utilized a gas-cooled reactor and Brayton power conversion to generate 200 kWe power output. The Fission Surface Power (FSP) technology development project is a current NASA and DOE activity focused on developing and demonstrating a nominal 40 kWe power system to support human exploration missions. The FSP system concept uses conventional low-temperature stainless steel, liquid metal-cooled reactor technology coupled with Stirling power conversion. Significant component hardware testing has been successfully completed, and a non-nuclear system demonstration test is being fabricated.

Figure C-4 SNAP 10A

Radioisotope Power Systems (RPS): RPS generate electricity by using the natural decay of a radioisotope, usually plutonium-238 (Pu-238), to provide heat to either thermoelectric devices or Stirling engines which convert the heat into electrical power. The most common type of RPS is the RTG; the Multi-Mission RTG planned for use on the Mars Science Laboratory mission is shown in Figure C-5. The United States has flown over 40 RTGs in space since 1961 with excellent performance histories.

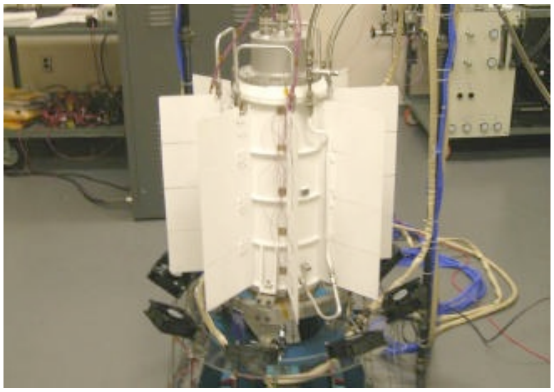


Figure C-5 Multi-Mission RTG

At launch the RPS necessarily contains a significant quantity of radioactive material, Pu-238 which decays by emitting alpha particles. The potential risks associated with the launch of nuclear materials are thoroughly evaluated by an expert panel as required by Presidential Directive/NSC-25 (May 1996) prior to receiving launch approval.

Pu-238 is not a naturally occurring material; it must be produced by irradiating another target isotope and then processing the product. At the current time the U.S. does not have a Pu-238 production capability. However, DOE and NASA are working to reestablish this capability.

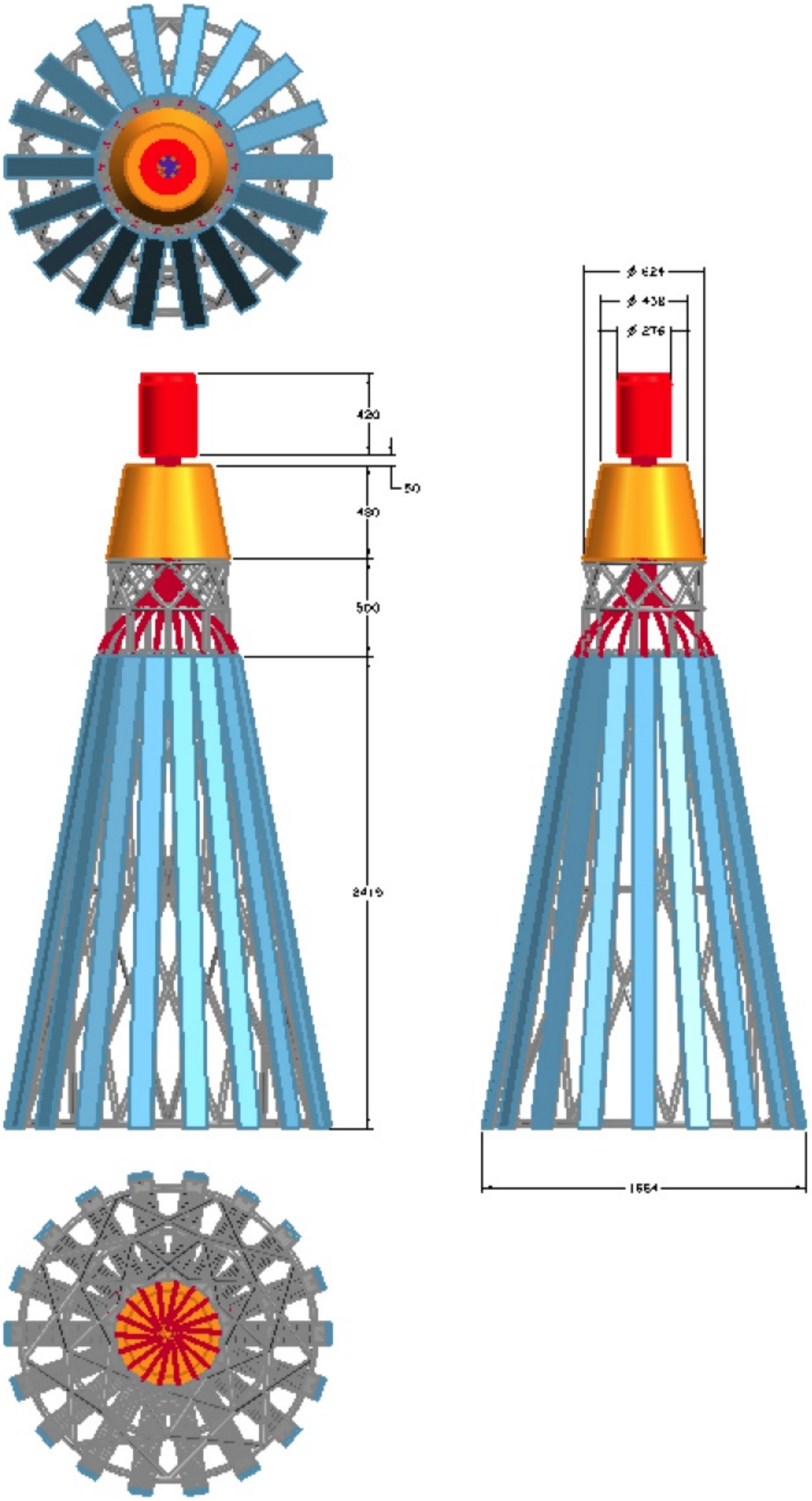
There is a limited stockpile of material and the availability of the international supply is under evaluation.

Fission Power Systems (FPS): FPS generate heat by neutrons colliding with atoms of a fissionable isotope, usually uranium-235 (U-235), and causing the isotope to undergo fission, splitting into two fission fragments plus additional neutrons. The kinetic energy of the resulting fission fragments and the accompanying radiation heat the fuel material. This thermal energy is then transferred to a power conversion subsystem that converts the heat into electricity. The magnitude of the neutron population is determined by the reactor configuration, and may be controlled to increase or decrease over time or to remain at a constant level. The fission rate, and therefore the thermal power level, depends linearly on the neutron population level. Thus the thermal power can be controlled from zero to a desired operational power setting. This control is usually provided by movement of neutron absorbing material or neutron reflectors. The reactor may be operated with a very low neutron population which results in very low or essentially “zero” power.

The uranium-235 fuel material is produced by enriching naturally occurring uranium ore. Uranium is readily available. Highly enriched uranium (HEU) that could be utilized for space reactors is also available from existing stockpiles. The initial radiation level from this fuel is very low, comparable to many other common earth-derived materials. No personnel protection or shielding is required for anyone around the fuel or the reactor prior to its operation. The fuel only becomes significantly radioactive after operation, when radioactive fission products have been produced. A space fission power system would not be operated on the ground and would be designed to remain subcritical, that is non-operating, during ground handling, launch and orbit until a command is received for startup. Therefore, it would contain only a small quantity of fission products during launch. The probability of unintentional brief operation during launch accidents, i.e. a criticality event, and the associated risk would be evaluated in the same basic manner as the risk evaluation process used for radioisotope power systems.

After launch and acquiring an escape trajectory, the reactor would be started and slowly brought to the desired operating power. Operation of the reactor would generate neutron and gamma radiation; thus, the fission power system includes shielding to protect the payload equipment from degradation.

APPENDIX D. Small FPS Design Layout



APPENDIX E. Small FPS Master Equipment List

WBS			Unit, kg	No. Units	CBE, kg	Margin	Total, kg	Provider	Materials
1.0	**Small Fission Power System**				**604.4**	**28%**	**771.7**		
1.1	**Core Assembly**				**132.8**		**158.5**		
	1.1.1	Fuel	56.2	1	56.2	5%	59.0	DOE	U10Mo
	1.1.2	Liner	0.4	1	0.4	30%	0.5	Contractor	Moly
	1.1.3	Fuel Container (Structure)	2.2	1	2.2	30%	2.9	Contractor	Hast-X
	1.1.4	Heat Pipe Sleeve	0.07	18	1.3	30%	1.6	Contractor	Hast-X
	1.1.5	Control Rod	0.8	1	0.8	30%	1.0	Contractor	B4C in Hast-X
	1.1.6	Safety Collar	2.3	1	2.3	30%	3.0	Contractor	B4C in Hast-X
	1.1.7	Radial Reflector	65.8	1	65.8	30%	85.5	Contractor	BeO in Hast-X
	1.1.8	Upper Axial Reflector	2.2	1	2.2	30%	2.9	Contractor	BeO in Hast-X
	1.1.9	Lower Axial Reflector	1.6	1	1.6	30%	2.1	Contractor	BeO in Hast-X
1.2	**Heat Pipe Assembly**				**18.9**		**24.6**		
	1.2.1	Heat Pipe	0.9	18	16.2	30%	21.1	Contractor	Hast-X and K
	1.2.2	Heat Pipe Hanger	0.1	18	1.8	30%	2.3	Contractor	SS
	1.2.3	Insulation	0.05	18	0.9	30%	1.2	Contractor	MFI
1.3	**Shield Assembly**				**271.6**		**353.1**		
	1.3.1	Reactor Attachment	6	1	6.0	30%	7.8	Contractor	SS
	1.3.2	Heat Pipe Sleeve	0.2	18	3.6	30%	4.7	Contractor	SS
	1.3.3	Heat Pipe Insulation	0.04	18	0.7	30%	0.9	Contractor	MFI
	1.3.4	Neutron Shield	88.7	1	88.7	30%	115.3	DOE	LiH
	1.3.5	Gamma Shield	154.5	1	154.5	30%	200.9	Contractor	W
	1.3.6	Main Container (Structure)	13.9	1	13.9	30%	18.1	Contractor	SS
	1.3.7	Plug Shield	3.7	1	3.7	30%	4.8	Contractor	LiH
	1.3.8	Plug Container (Structure)	0.5	1	0.5	30%	0.7	Contractor	SS
1.4	**Thermoelectric Assembly**				**88.9**		**115.6**		
	1.4.1	Saddle	0.0009	378	0.3	30%	0.4	Contractor	POCO
	1.4.2	Radiation Coupler	0.0005	378	0.2	30%	0.2	Contractor	Graphite
	1.4.3	Thermoelectric Couple	0.01	378	3.8	30%	5.0	Contractor	Zintl/LaTe/SKD
	1.4.4	Insulation	0.01	378	3.8	30%	4.9	Contractor	Aerogel
	1.4.5	Interconnects	0.005	378	1.9	30%	2.5	Contractor	Copper
	1.4.6	Radiator Panel	3.88	18	69.9	30%	90.8	Contractor	Aluminum
	1.4.7	Power Cable	0.5	18	9.0	30%	11.7	Contractor	Copper
1.5	**Truss Assembly**				**60.0**		**78.0**		
	1.5.1	Shield Attachment	5	1	5.0	30%	6.5	Contractor	SS
	1.5.2	Truss (Structure)	50	1	50.0	30%	65.0	Contractor	Aluminum
	1.5.3	Spacecraft Attachment	5	1	5.0	30%	6.5	Contractor	SS
1.6	**Instrumentation & Control Assembly**				**32.2**		**41.9**		
	1.6.1	Rod Drive Motor	1.2	2	2.4	30%	3.1	Contractor	
	1.6.2	Rod Drive Gear Mount	3.41	1	3.4	30%	4.4	Contractor	Hast-X
	1.6.3	Rod Drive Shaft	0.45	2	0.9	30%	1.2	Contractor	
	1.6.4	Motor Power Supply	1.3	2	2.6	30%	3.4	Contractor	
	1.6.5	Collar Mechanism	1	1	1.0	30%	1.3	Contractor	
	1.6.6	Collar Ejector	1	1	1.0	30%	1.3	Contractor	
	1.6.7	Sensor Package	3.78	1	3.8	30%	4.9	Contractor	
	1.6.8	Neutron Detector	1.5	2	3.0	30%	3.9	Contractor	
	1.6.9	Sensor Cable	5.13	1	5.1	30%	6.7	Contractor	
	1.6.10	Computer	1	3	3.0	30%	3.9	Contractor	
	1.6.11	Data Bus	1	1	1.0	30%	1.3	Contractor	
	1.6.12	Battery	5	1	5.0	30%	6.5	Contractor	500 Whr Li-ion

APPENDIX F. Notional FPS Development Schedule