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A Practical Approach to Starting Fission Surface Power Development

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July 2006

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ABSTRACT

The Prometheus Power and Propulsion Program has been reformulated to address NASA needs relative to lunar and Mars exploration. Emphasis has switched from the Jupiter Icy Moons Orbiter (JIMO) flight system development to more generalized technology development addressing Fission Surface Power (FSP) and Nuclear Thermal Propulsion (NTP). Current NASA budget priorities and the deferred mission need date for nuclear systems prohibit a fully funded reactor Flight Development Program. However, a modestly funded Advanced Technology Program can and should be conducted to reduce the risk and cost of future flight systems. A potential roadmap for FSP technology development leading to possible flight applications could include three elements: 1) Conceptual Design Studies, 2) Advanced Component Technology, and 3) Non-Nuclear System Testing. The Conceptual Design Studies would expand on recent NASA and DOE analyses while increasing the depth of study in areas of greatest uncertainty such as reactor integration and human-rated shielding. The Advanced Component Technology element would address the major technology risks through development and testing of reactor fuels, structural materials, primary loop components, shielding, power conversion, heat rejection, and power management and distribution (PMAD). The Non-Nuclear System Testing would provide a modular, technology testbed to investigate and resolve system integration issues.

I. INTRODUCTION

The Prometheus Power and Propulsion Program has been reformulated to address NASA needs relative to lunar and Mars exploration. Emphasis has switched from the Jupiter Icy Moons Orbiter (JIMO) flight system development to more generalized technology development addressing Fission Surface Power (FSP) and Nuclear Thermal Propulsion (NTP). Current NASA budget priorities and the deferred mission need date for nuclear systems prohibit a fully funded reactor Flight Development Program. However, a modestly funded Advanced Technology Program can and should be conducted to reduce the risk and cost of future flight systems. The proposed plan described in this paper represents the author's view on a logical and practical path forward.

A roadmap for Fission Surface Power technology development leading to possible flight applications is shown in figure 1. The technology development could include three elements: 1) Conceptual Design Studies, 2) Advanced Component Technology, and 3) Non-Nuclear System Testing. The Conceptual Design Studies would expand on recent analyses conducted by the JIMO Project (ref. 1), Naval Reactors (NR) (ref. 2), the NASA Exploration Systems Architecture Study (ESAS) Team (ref. 3), Glenn Research Center (GRC) (ref. 4), and Los Alamos National Laboratory (LANL) (refs. 5 to 7). The intent would be to increase the depth of study in areas of greatest uncertainty such as reactor integration and human-rated shielding. The Advanced Component Technology element would address the major technology risks through development and testing of reactor fuels, structural materials, primary loop components, shielding, power conversion, heat rejection, and power management and distribution (PMAD). Non-Nuclear System Testing would be conducted via a full-scale, electrically heated Technology Demonstration Unit (TDU). The TDU would provide a modular, technology testbed to investigate and resolve system integration issues. The three elements are highly coupled with component technology selections predominantly determined through the Conceptual Design Studies and TDU hardware elements provided from the Advanced Component Technology element. As new components are developed, they would be inserted and demonstrated within the TDU system context.

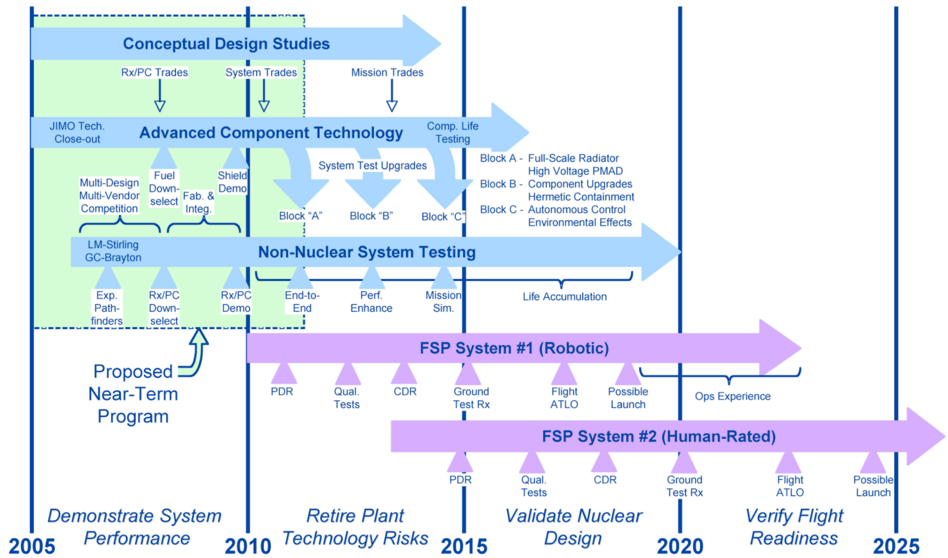


Figure 1.—Technology roadmap and relationship to flight system development.

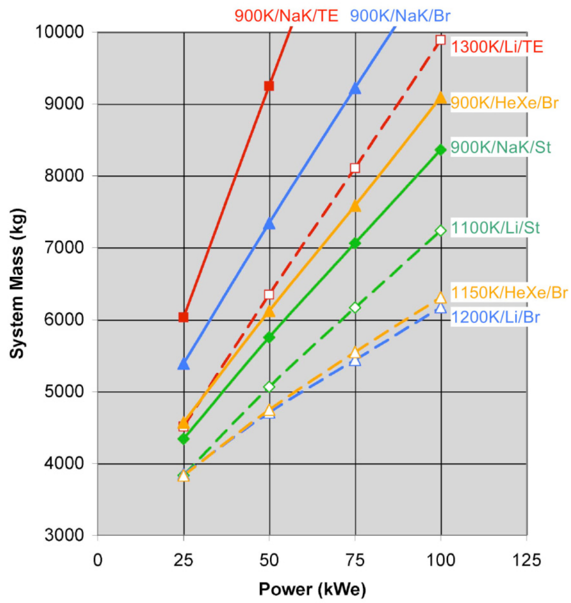
The technology development elements are well-suited to support a robotic FSP mission in the late 2010 and a human FSP mission in the mid-2020. The robotic mission might utilize a FSP system in a permanently-shadowed crater as part of a science payload to verify the existence of local water. The human mission might utilize a FSP system to support the initial lunar outpost providing power for crew life support, science experiments, and rover re-charging. The robotic mission is an excellent precursor for the human mission to validate technology readiness and provide valuable operating experience without the "human-rating" encumbrance. The proposed near-term program emphasis will retire many of the technology risks and assure a credible starting-point for the flight development.

II. TRADE STUDIES

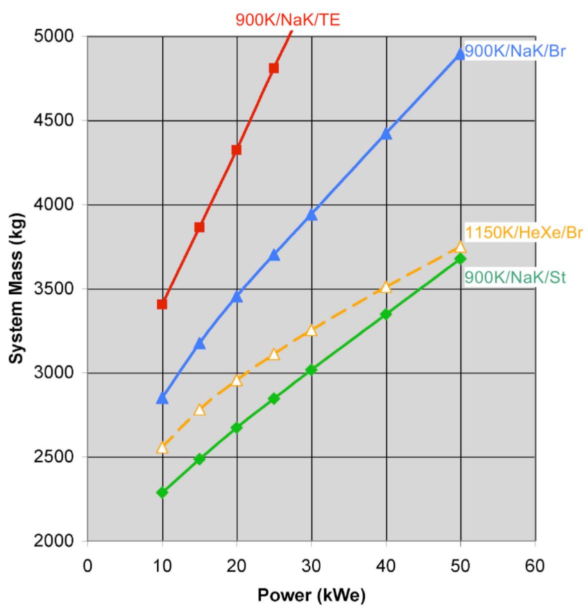
Recent trade studies by the JIMO/NR team and LANL have produced two distinct paths for space fission power systems. The JIMO/NR team conducted a rigorous study of reactor and power conversion technologies for 100 kWe-class Nuclear Electric Propulsion (NEP) missions and selected a gas-cooled reactor with direct Brayton conversion as the reference concept. The concept uses UN or UO2 fuel with refractory alloy cladding and helium-xenon coolant (1150 K max). The gas-cooled Brayton option was selected by NR over competing technologies based on performance, scalability, simplicity, deliverability, and testability. NR also concluded that the concept was amenable to a non-refractory pressure boundary making it extensible to surface missions with oxidizing environments.

The LANL team evaluated low temperature reactor options (900 K max) using more conventional reactor fuel and cladding materials as a means to reduce development risk and cost. LANL examined three different configurations for a 25 kWe-class system: UZrH fuel with pumped NaK cooling, UO2 fuel with pumped NaK cooling, and UO2 fuel with potassium heat pipe cooling. All of the configurations utilized Stirling power conversion, based on the potential for high efficiency at relatively low hot-end temperature. While the lower operating temperature helps to reduce reactor development risk, it also introduces considerable operating constraints on the power conversion and heat rejection that lead to system mass penalties. These mass penalties must be weighed against the anticipated cost savings to determine the preferred development path.

A parametric study was conducted to explore the reactor and power conversion trade-space for low and high temperature reactors and the results are shown in figure 2. The power conversion options that were considered include Brayton, Stirling, and thermoelectric. The human outpost mission application assumes in-situ reactor shielding, 10-year full-power life, 100 percent power conversion redundancy, vertical radiators (sized for lunar noon on the equator), long-distance (500 m) power transmission, and 30 percent mass margin. In-situ shielding is provided via installation of the reactor core in an excavated hole with an upper plug shield. Expected power levels range from 25 to 100 kWe. Results indicate that the high temperature reactor options (dashed lines, open markers) provide up to 35 percent mass savings. Among the low temperature reactors (solid lines, closed markers), the NaK/Stirling system offers the lowest mass. The HeXe/Brayton and Li/Brayton options provide the lowest mass overall. Power levels up to about 100 kWe could be delivered with a 6000 kg lunar cargo lander.



(a) Human outpost mission application



(b) Robotic science mission application

Figure 2.—Mass versus power for various FSP technology options.

The Robotic mission design assumptions include earth-delivered instrumentation shielding, 5-year full-power life, non-redundant power conversion, vertical radiators (sized for permanently-shadowed operation), short-distance (50 m) power transmission, and 30 percent mass margin. Given the anticipated earlier mission date, the design choices were reduced to include only the three low temperature liquid metal options and the high temperature gas-cooled Brayton. Shielding is provided via a borated-water containment vessel surrounding the core. Power levels range from 10 to 50 kWe. Here, the NaK/Stirling system proves to be the lowest mass option, but the high temperature gas-cooled Brayton is comparable. The results indicate that power levels up to 30 kWe could be considered for robotic landers that can deliver 3000 kg to the lunar surface. There would be a considerable advantage for the robotic FSP system to use the same reactor and power conversion technologies as anticipated for the human FSP system.

III. NEAR TERM TECHNOLOGY EMPHASIS

Significant progress can be made in FSP technology over the next few years with moderate funding. The proposed technology development would address both the reactor and balance-of-plant with the primary objective of reducing development risk and cost. A nominal budget of \$10M to \$20M per year over the next five years would be sufficient to sustain the proposed technology development activities. Conceptual design studies would be a key element providing direction on system requirements, mission integration, and technology selection. The trade studies would also help to identify and prioritize component technology investments. The component tasks would focus on hardware development and risk reduction.

It is imperative that NASA expand beyond studies into hardware demonstrations in order to establish technology viability for fission systems. Completion of the power conversion and heat rejection technology tasks that were started under JIMO provide an opportunity to accelerate the maturation of several key technologies. Many of the JIMO tasks are relevant to the surface power application, and represent meaningful hardware-based milestones that can be completed in 2006. Among the test hardware deliverables is a 50 kWe-class Brayton alternator test unit, an experimental 30 kWe twin turbine closed-loop Brayton power system, three full-scale multi-heat pipe radiator panels, and nine high temperature water heat pipes with various wick designs. The majority of materials and equipment costs were paid with previous-year JIMO funding and FY06 funds are being used to install the equipment, conduct the tests, and document the results.

The FSP Advanced Component Technology element would build on these activities while expanding the breadth to include reactor and shield related development. Additional component technologies that could be pursued specific to the FSP application include reactor fuels, structural materials, primary loop components, shield materials, high power Stirling conversion, and high voltage PMAD. On the nuclear side, initial irradiation tests could be performed on candidate fuel forms. In parallel, materials testing could evaluate radiation effects, and fill gaps in thermal-mechanical property databases. Additional reactor related items for development include primary pumps, heat exchangers, accumulators, control drive actuators, and instrumentation. Since shielding has a major influence on design and mass, several early experiments could be conducted to evaluate material and packaging options. On the plant side, component development activities could expand on JIMO efforts while focusing on lunar environment issues. Of particular interest would be radiators and transmission cabling that are suitable for the lunar surface and amenable to the various power conversion options. The component technology element would also include the further development of multi-kilowatt, 900 K Stirling converters.

A crucial element of the near-term technology plan is the design and test of a full-scale, end-to-end, electrically-heated Technology Demonstration Unit (TDU). A notional test layout for a 30 kWe TDU is presented in figure 4. Most of the current fission design concepts and trade studies are based on technology development conducted in the 1960's through 1980's. This test could provide a much-needed experimental validation of the overall power system, based on modern design and fabrication methods, in order to anchor flight reactor performance projections. The major test goals could include: 1) demonstrate system performance, 2) verify manufacturing capabilities, 3) obtain comprehensive temperature, pressure, and flow data under steady-state and transient conditions, 4) expose component interactions and interdependencies, 5) develop safe and reliable control methods, and 6) validate analytical models. The TDU activity will help to stimulate industrial infrastructure for component design and fabrication, and will provide critical as-built mass and cost data. In addition, the TDU will provide NASA and DOE personnel with valuable hands-on operating experience that will support a successful transition to flight development.

The TDU could include a high-fidelity reactor thermal simulator, developed jointly by MSFC and DOE. Specific issues to be addressed include non-fuel core materials (possibly a mix of stainless steel and superalloys), core support, core thermal hydraulics, performance, and safety. The thermal simulators will be designed to closely mimic heat from fission. Testing would measure reactor flow distribution and temperatures, and be used to benchmark design tools. Testing could also validate steady-state and transient reactor module behavior, including geometric effects that could affect operations and safety. High fidelity non-nuclear reactor module testing could increase confidence in cost, mass, and performance estimates of future flight reactors.

The proposed TDU implementation approach could include a multi-design, multi-vendor competitive development process as shown in figure 5. Initially, two parallel design concepts would be pursued: liquid metal-cooled Stirling and gas-cooled Brayton. Each concept could have two vendors conducting competing power conversion conceptual design studies. At the conclusion of the conceptual designs, one vendor could be down-selected for each design concept to complete a detailed design. In parallel with the detailed design studies, NASA could conduct experimental Pathfinder tests for each concept using existing, sub-scale hardware. At the conclusion of the design studies and Pathfinder tests, a single design concept, either LM-Stirling or GC-Brayton, could be selected for fabrication and test. Other component technologies, such as radiators and PMAD, could be developed separately under the Advanced Component Technology element and incorporated into the TDU as they are completed.

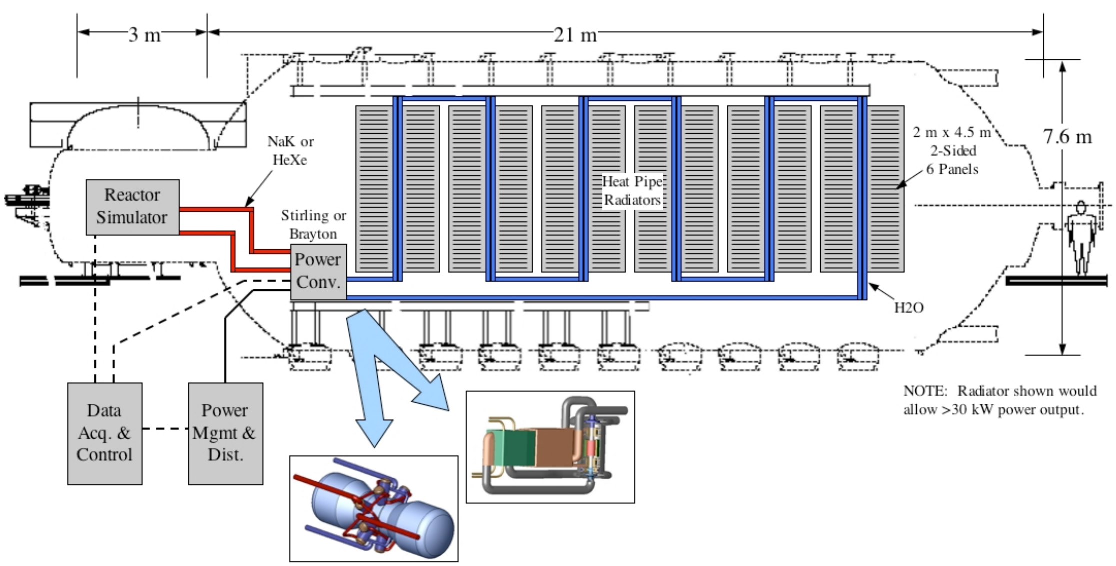


Figure 4.—Notional TDU test layout in GRC vacuum facility no. 6.

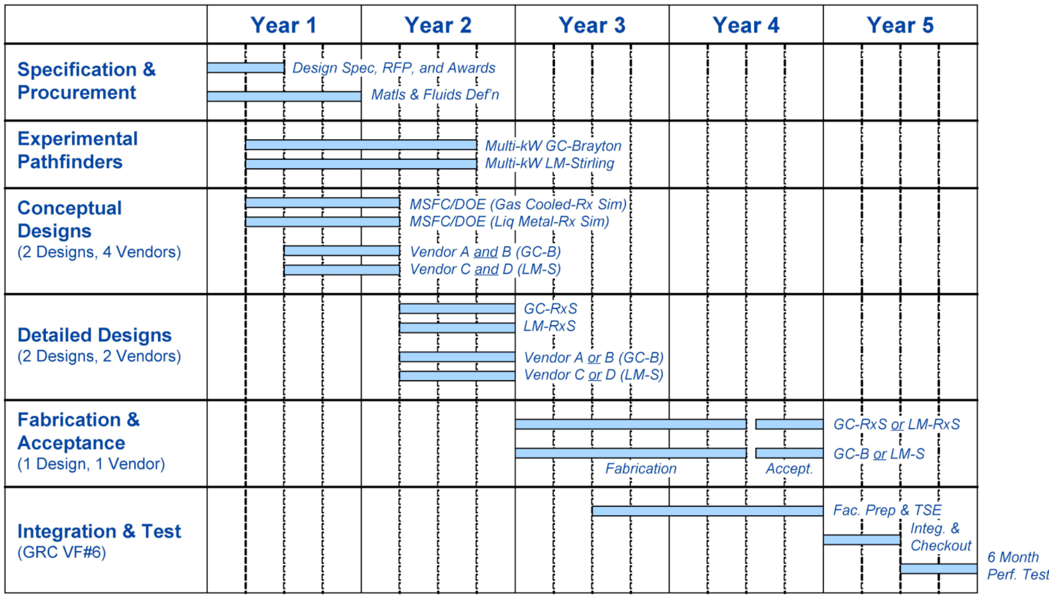


Figure 5.—TDU development schedule.

IV. CONCLUSIONS

The use of surface fission power systems is inevitable as NASA missions seek to establish a permanent human presence on the moon and Mars. Nuclear technology investments made today will reduce the development risk and cost of those future space reactors. An incremental development approach with component technology and integrated system testing is feasible in a constrained budget environment. A joint NASA/DOE team is available to address the long lead technology issues and establish the necessary infrastructure to permit a low-risk flight fission surface power system development.

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