Hardware Based Technology Assessment in Support of Near-Term Space Fission Missions

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Abstract. Fission technology can enable rapid, affordable access to any point in the solar system. If fission propulsion systems are to be developed to their full potential; however, near-term customers must be identified and initial fission systems successfully developed, launched, and utilized. Successful utilization will most likely occur if frequent, significant hardware-based milestones can be achieved throughout the program. Achieving these milestones will depend on the capability to perform highly realistic non-nuclear testing of nuclear systems. This paper discusses ongoing and potential research that could help achieve these milestones.

INTRODUCTION

The fission process was first reported in 1939, and in 1942 the world's first man-made self-sustaining fission reaction was achieved. Creating a self-sustaining fission chain reaction is conceptually quite simple. All that is required is for the right materials to be placed in the right geometry - no extreme temperatures or pressures required - and the system will operate. Since 1942 fission systems have been used extensively by governments, industry and universities. Fission systems operate independently of solar proximity or orientation, and are thus well suited for deep space or planetary surface missions. In addition, the fuel for fission systems (highly enriched uranium) is essentially non-radioactive, containing 0.064 curies/kg. This compares quite favorably to current space nuclear systems (Pu-238 in radioisotope systems contains 17,000 curies/kg) and certain highly futuristic propulsion systems (tritium in D-T fusion systems would contain 10,000,000 curies/kg). An additional comparison is that at launch a typical space fission propulsion system would contain an order of magnitude less onboard radioactivity than did Mars Pathfinder's Sojourner Rover, which used radioisotopes for thermal control. The primary safety issue with fission systems is avoiding inadvertent system start – addressing this issue through proper system design is quite straightforward. The energy density of fission is seven orders of magnitude greater than that of the best chemical fuels, and if properly utilized is more than adequate for enabling rapid, affordable access to any point in the solar system.

Despite the relative simplicity and tremendous potential of space fission systems, the development and utilization of these systems has proven elusive. The first use of fission technology in space occurred 3 April 1965 with the US launch of the SNAP-10A reactor. There have been no additional US applications of fission systems in space. While space fission systems were used extensively by the former Soviet Union, their application was limited to earth-orbital missions. Early space fission systems must be safely and affordably utilized if we are to reap the benefits of advanced space fission systems.

Table 1 gives a partial list of major US space fission programs that have failed to result in flight of a system (Angelo, 1985). There are a variety of reasons why these programs failed to result in a flight. The fact that so many programs have failed indicates that a significantly different approach must be taken if future programs are to succeed. In many cases, space reactor programs were cancelled because the proposed mission was cancelled. However, in many of those cases mission cancellation was partially due to the fact that the reactor required by the mission was taking too long and costing too much to develop.

Near-term space fission systems must capitalize on experience gained from previous fission programs. The development of new nuclear technology has historically been costly and time consuming. Nuclear technology developed by previous programs should thus be utilized, and no new nuclear technology should be required. This means that all in-core components should operate within demonstrated fuel burnup capability and demonstrated neutron damage limits for the given reactor environment (temperature, chemistry, power density, etc.). The construction of new nuclear facilities or the extensive modification of existing facilities has historically been costly and time consuming. Near-term fission systems should thus use only existing nuclear facilities in their development. No new or significantly modified facilities should be required. Flight qualification of any space system requires an extensive test program; thus near-term fission system flight units must be highly testable. Because of the expense and difficulty associated with performing realistic full-power ground nuclear tests, previous programs have considered the option of foregoing full-power ground nuclear testing in favor of a flight test. For example, in Josloff (1993) (referring to the SP-100 program) it is stated that "There has been recent interest among government agencies in establishing an early flight mission that would provide the catalyst needed to enable confident planning for subsequent operational missions. This first flight would validate the total system performance, obviate the need for costly ground nuclear testing, demonstrate safety features and facilitate safety approval through the INSRP process for the subsequent operational missions." Full power nuclear ground test facility requirements may also dictate that the unit tested on the ground be significantly different than the actual flight unit. Any differences between what is tested and what is flown will limit the benefit from full-power ground nuclear tests. It should also be noted that for NASA missions no safety-related data is obtained from a full-power ground nuclear test, and that the only potential benefit from that test is data related to system reliability. The cost effectiveness of a potential full-power ground nuclear test must thus be compared with other less expensive and time consuming methods for improving overall mission reliability. Highly testable systems that utilize established nuclear technology incur the least technical risk if full power ground nuclear testing is not performed. The ability to quickly and affordably establish the safety and reliability of any proposed space fission system will be critical to its programmatic success.

Additional innovative approaches will have to be used to ensure that the next space fission system development program results in system utilization. Safety must be the primary focus of the program, but cost and schedule must also be significant drivers. System performance must be adequate, but the desire to make performance more than adequate should not be allowed to drive system cost and schedule. Near-term space fission systems must be safe, simple, and as inexpensive to develop and utilize as possible.

TABLE 1. Partial list of major US space fission programs that have failed to result in flight of a system.

- Solid-Core Nuclear Rocket Program
- Medium-Power Reactor Experiment (MPRE)
- Thermionic Technology Program (1963-1973)
- Space Nuclear Thermal Rocket Program
- SP-100
- SNAP-50 / SPUR
- High-Temperature Gas-Cooled Electric Power Reactor (710 Reactor)
- SPAR / SP-100
- Flight Topaz
- DOE 40 kWe Thermionic Reactor Program
- Advanced Liquid Metal Cooled Reactor
- Advanced Space Nuclear Power Program (SPR)
- Multi-Megawatt Program
- Thermionic Fuel Element Verification Program
- Air Force Bimodal Study

One method for ensuring that a space fission system development program is "on track" is to require frequent, relevant hardware-based milestones. When possible, these milestones should include subsystem or system-level testing. Successful development of individual components is obviously necessary, but in no way ensures that an integrated system can be developed and flight qualified. Highly realistic testing of integrated subsystems and systems is the best way to demonstrate that a proposed approach is viable.

The difficulty, schedule, and expense associated with performing realistic, full power ground nuclear testing of an integrated space fission system will eliminate such testing as a potential early milestone. Development and flight qualification testing will thus rely heavily on realistic, non-nuclear testing. This in turn will require development of an adequate facility and thermal simulators capable of matching axial and radial power profiles, as well as fuel pin thermal conductivity. A viable space fission system development program must include development of highly realistic non-nuclear test capability.

POTENTIAL NEAR-TERM SPACE FISSION SYSTEMS

At least three potential near-term space fission systems have been proposed: a fast-spectrum, highly enriched uranium fueled reactor cooled by a noble gas mixture (GCR), a fast-spectrum, highly enriched uranium fueled reactor cooled by pumped NaK (NaK-LMR), and a fast-spectrum, highly enriched uranium fueled reactor cooled by heat pipes. In addition to similarities in fuel and operating neutron spectrum, these three potential near-term space fission systems have numerous other commonalities. All use ex-core control (e.g. drums or sliding reflectors), beryllium or beryllium oxide neutron reflectors, lithium hydride neutron shielding, and are designed for highly-autonomous operation. Although many of the technologies used by the three systems are quite similar, differences related to the method of primary heat transport can result in differences associated with development and flight qualification.

Hardware-Based Technology Assessment of Gas Cooled Reactors

Engineers at Sandia National Laboratories have devised a "testable" gas cooled reactor cooled by a noble gas mixture of helium and xenon (Wright and Lipinski, 2003). Additionally, the gas flow path is designed to cool the pressure vessel to the extent that stainless steel or superalloys can be used for the pressure boundary even if the reactor is providing turbine inlet temperatures in excess of 1150 K. The Sandia approach eliminates all single-point failure refractory metal vessels, eliminates the need for a high temperature, primary heat exchanger, and eliminates the need for hermetic refractory metal to superalloy (or stainless steel) transition joints.

A potential three-step program for hardware-based technology assessment of the gas cooled reactor concept would involve single-channel hot flow testing followed by core segment testing and then by full-core testing. The single-channel flow test would utilize an accurate scale model of one flow channel in the GCR design and would be used to benchmark flow predictions. Pressure drop would be measured under a variety of flow and temperature conditions.

A 37-channel test could then be performed to verify performance predictions related to a significant segment of the core. A realistic flow configuration could be tested, including pressure, flow rate, and core temperature increase. Specific tasks would include the following:

1. Benchmark thermal-hydraulic correlations that are used in the design of the gas cooled reactor.
2. Investigate the effects of radially dependent power loads and the viability of flow control via flow orifices at the exit end.
3. Measure the gas exit temperature at several different channel locations to determine the flow rate through the channel and validate the flow resistance correlations. Repeat for a variety of mass flow rates.
4. Perform a variety of power transients and measure the time dependence of gas temperature. Use data to benchmark GCR correlations. Repeat for various mass flow rates.
5. Vary the local heating rate (in one or two rows) to determine the stability of the flow field.
6. Search for evidence of flow vibration in the pins (such as wear, sonic noise, etc) and quantify if possible.
7. Develop and demonstrate techniques for low-cost electrically heated testing, and for acceptance testing of flight hardware, for gas-cooled reactor systems.
8. Identify any potential showstoppers early in the program.

The final task in the three step program would be to fabricate and test a pre-prototypic, full core gas cooled reactor operating at the desired thermal power for an early flight system. For this task it would be highly desirable to accurately match noble gas inlet and exit conditions. Prior to performing this test, it would also be highly desirable to fully quantify the effects of impurities in the noble gas on refractory metal fuel cladding and other components in the gas loop. A drawing of a potential 37-pin Test article is shown in Figure 1.

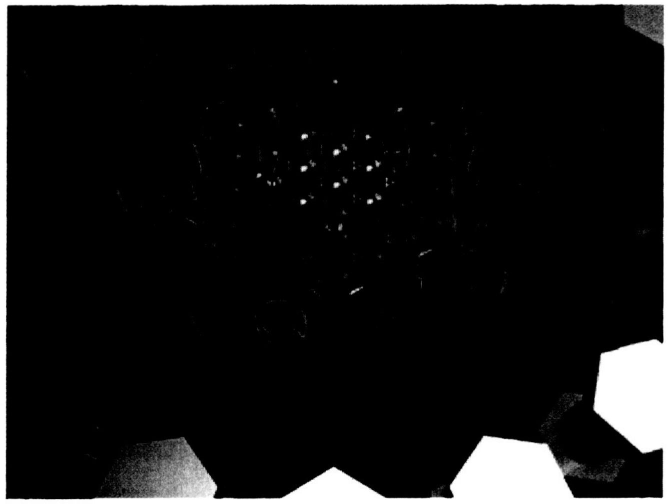

FIGURE 1. Potential 37-Channel Gas Cooled Reactor Test Article.

Hardware-Based Technology Assessment of Heat Pipe Cooled Reactors

Engineers at Los Alamos National Laboratory have devised numerous heat pipe cooled reactor concepts, ranging in power level from 15 kWt to > 800 kWt. Heat pipe systems do not require that a hermetic vessel surround the core. This allows ready access to one end of the core, providing a very high level of testability. Other potential advantages of heat pipe cooled systems are discussed in Poston, 2003.

Because of their high level of testability and other attributes, heat pipe cooled systems were the first of the three potential systems considered in this paper to undergo hardware-based technology assessment. Fabrication and test of a molybdenum heat pipe module was completed in 1996 via $75K funding provided by NASA's Marshall Space Flight Program. The module was fabricated by Los Alamos National Laboratory and tested at the New Mexico Engineering Research Institute using equipment originally purchased from the Former Soviet Union for use by the Thermionic Systems Evaluation Test (TSET) program. The test demonstrated operation at full rated power, restart capability, and the soundness of the modular approach (Houts, 1997). A "bimodal" module was fabricated in 1998 and tested in 1999. Module testing demonstrated very high temperature operation, fast start capability, and the potential for generating modest amounts of thrust by directly heating a propellant gas. Data from the test was also used to benchmark thermal predictions. Details concerning this particular test series are given in Van Dyke, 2000. The next step in the hardware-based technology assessment of heat pipe cooled systems was the fabrication and test of a full-core, 30 kWt system. Initial testing provided information concerning the operation of a full reactor core. A Stirling engine was then procured and coupled to the 30 kWt core, and both steady state and transient testing performed. Upon completion of the coupled core / Stirling engine tests, the coupled system was sent to the Jet Propulsion Laboratory, where it was integrated with an ion thruster. Steady state and transient testing of the integrated system was then performed. Details on the SAFE-30 test series and experimental results are given in Van Dyke, 2002 and Hrbud, 2003.

Experience gained from the SAFE-30 test series was used to design a 100 kWt stainless steel heat pipe cooled reactor core, and higher power refractory metal cores. Proposed improvements were made to both module geometry and thermal bonding techniques. Heat exchangers have been designed to enable heat to be transferred from the heat pipes to the noble gas coolant of a Brayton power conversion subsystem.

Future heat pipe cooled reactor research could include fabrication and test of the 100 kWt core and heat exchanger, or a significant portion thereof. Thermal bonding techniques for refractory metal heat pipe modules could be demonstrated, as well as integration of those modules with a representative heat exchanger. An extremely significant milestone for heat pipe cooled reactor development would be the successful fabrication and test of a pre-prototypic reactor core coupled to a pre-prototypic heat exchanger, operating at the thermal power and temperature required by a flight unit. Figure 2 is a picture of a coupled SAFE-30 /Stirling engine test. Figure 3 is a picture of a SAFE-100 thermal simulator test.

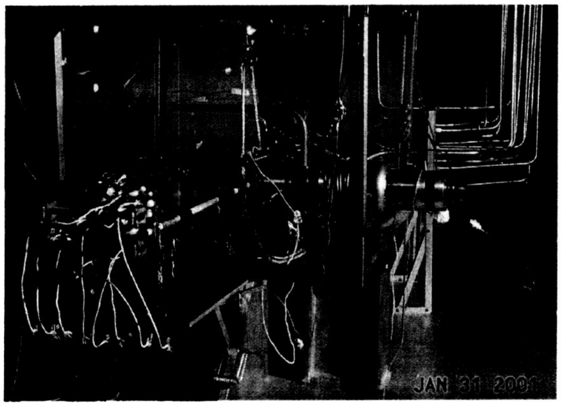

FIGURE 2. Coupled SAFE-30 / Stirling Engine Test.

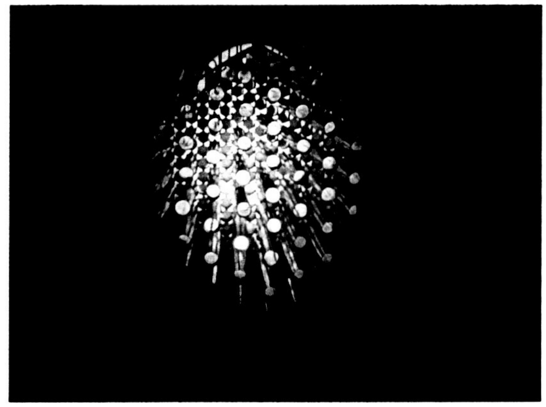

FIGURE 3. SAFE-100 Thermal Simulator Test.

Hardware-Based Technology Assessment of Pumped NaK Cooled Reactors

All space reactors flown to date (US and Former Soviet Union) have been cooled by pumped NaK, and operated at peak NaK temperatures that allow non-refractory vessels and piping. Pumped NaK cooled systems operating at NaK temperatures below 1000 K are significantly different from lithium cooled systems operating at higher temperatures, and would be much easier to develop and utilize. The primary drawback of pumped NaK cooled systems is that their relatively low outlet temperature would likely result in a higher system specific mass relative to systems operating at higher temperatures.

A core concept with fuel pins in annular coolant channels and two-pass coolant flow has been proposed by industry and DOE national laboratories as one option for a testable pumped-NaK system. Figure 4 illustrates the general layout of the core assembly with NaK coolant loops and plenums. The coolant enters the core through an annular inlet plenum (positioned at the top) that directs it into a circumferential flow passage formed between the outer shell and core block. The flow follows this perimeter passage traversing the length of the core and exiting into the lower manifold. This manifold distributes the coolant for a return trip to the top of the core via annular gaps formed between the fuel pin clad and core block. At the top of the core an outlet plenum collects the heated NaK. Figure 5 shows an end view of this same core design layout, illustrating both the perimeter and annular fuel pin flow paths.

The NaK would flow through an appropriate heat exchanger, most likely either a liquid metal to gas heat exchanger (Brayton power conversion) or directly to a Stirling engine heater head. Test instrumentation would consist primarily of temperature and pressure sensors at various locations within the core and heat exchanger. Test objectives would include demonstrating the feasibility of a testable pumped NaK system, benchmarking thermal hydraulic codes used in the design of pumped liquid metal systems, verifying the performance of the flow geometry, and demonstrating the potential for uniform NaK channel outlet temperature.

CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

Programs aimed at developing near-term, affordable space fission systems should have frequent, hardware-based milestones. Component-level demonstrations are necessary, but are not sufficient to ensure that a particular fission system design can actually be developed and utilized. When possible, milestones should be associated with integrated subsystems or systems to ensure that a viable approach is being pursued. Highly realistic non-nuclear testing of candidate nuclear systems appears to be the best way to quickly achieve meaningful hardware-based milestones. At this time, MSFC is negotiating with a commercial customer who will provide detailed drawings of a gas-cooled reactor concept suitable for the three-step testing outlined above. This program will also be pursuing prototypic rotating machinery to couple with this test to enable a near-term, non-nuclear ground testbed to evaluate essential system parameters.

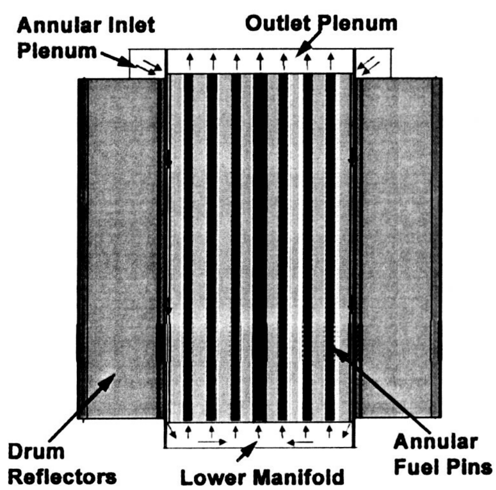

FIGURE 4. General Core NaK Flow Loop.

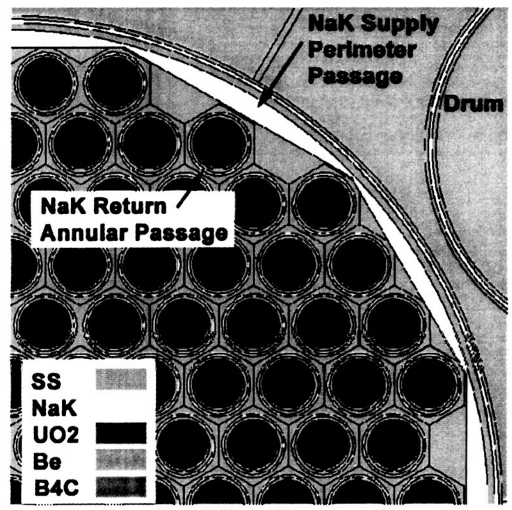

Figure 5. Core End View Showing Flow Passages.

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