

Early Flight Fission Test Facilities (EFF-TF) and Concepts That Support 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. If the system is designed to operate within established radiation damage and fuel burn up limits while simultaneously being designed to allow close simulation of heat from fission using resistance heaters, high confidence in fission system performance and lifetime can be attained through non-nuclear testing. Through demonstration of systems concepts (designed by DOE National Laboratories) in relevant environments, this philosophy has been demonstrated through hardware testing in the Early Flight Fission Test Facilities (EFF-TF) at the Marshall Space Flight Center. The EFF-TF is designed to enable very realistic non-nuclear testing of space fission systems. Ongoing research at the EFF-TF is geared towards facilitating research, development, system integration, and system utilization via cooperative efforts with DOE labs, industry, universities, and other NASA centers.*

I. INTRODUCTION AND BACKGROUND

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.

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. If nuclear technology developed by previous programs is used, then 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. 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 Interagency Nuclear Safety Review Panel (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 are obtained from a full-power ground nuclear test, and that the only potential benefit from that test is to gather data related to system reliability. The cost effectiveness of several full-power ground nuclear tests 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.

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.

To allow early use, system designs must be relatively simple, easy to fabricate, and easy to test using non-nuclear heaters to closely mimic heat from fission. This combination of attributes will allow pre-prototypic systems to be designed, fabricated, and tested quickly and affordably. The ability to build and test units is key to the success of a nuclear program, especially if an early flight is desired. This approach may help avoid the need for a series of expensive and time-consuming full power ground nuclear tests. Required data would be obtained from a combination of full-power non-nuclear heated tests, zero-power criticals, and in-pile testing of components or modules. Even if it is still determined that a full power ground nuclear test is needed, the ability to perform very realistic non-nuclear testing prior to that test would increase the success probability of the full power ground nuclear test.

The focus of the hardware based effort within NASA Marshall Space Flight Center's Propulsion Research Center is on enabling early utilization of

space fission systems. The result of this focus has been the development of fabrication and test capabilities necessary for rapidly building and testing potential near-term space fission systems. This capability includes advanced thermal simulators, an extremely versatile test chamber, high purity alkali metal handling capability, and advanced manufacturing (e.g. e-beam welding, high temperature braze).

Through hardware based design and testing, the EFF-TF investigates fission power and propulsion component, subsystems, and integrated system design and performance. Previous non-nuclear tests in the EFF-TF have proven to be a highly effective method (from both cost and performance standpoint) to identify and resolve integration issues. For example, in designing the test plenums for a heat pipe reactor heat exchanger concept and for the Testable Direct Gas Cooled Reactor flow channels concept, several stress and heat transfer issues were identified resulting in a redesign of the proposed heat exchanger for the heat pipe reactor and of the gas entrance plenum for the gas cooled reactor. Because both of the involved DOE laboratories (Los Alamos and Sandia) are testing specific parts of their designs, DOE modified their reactor/heat exchanger designs used in the current DOE systems trade studies.

All of the current Early Flight Fission (EFF) hardware work supports a systems integration testbed that allows prototypic testing of the systems under investigation. Each year, the testbed provides prototypic products that feed into the current systems integration trade studies/design. The testbed is built such that when new components become available, they can readily be incorporated into the system without having to build new facilities and train people. By working in conjunction with the DOE labs, both sets of expertise (e.g. LANL/Sandia for nuclear design and MSFC for testing) can be utilized. As of the end of FY02, the EFF Test Facilities will have demonstrated the capability to test heat pipe cooled reactors and direct gas cooled reactors, two leading options for use on an early flight. Preliminary work will also be completed on designing and testing a stainless steel based pumped NaK system, which is a third potential option for an early flight.

II. THE TEST FACILITIES

The EFFTF describes the facilities at MSFC that are used to demonstrate very realistic non-nuclear testing of space fission systems. This includes, but is not limited to, a 9ft diameter and a 2 ft diameter vacuum chamber, and various other manufacturing facilities. Ongoing research at the EFF-TF is geared towards facilitating research, development, system integration, and system utilization via cooperative efforts with DOE labs, industry, universities, and other NASA centers.

Full scale testing is performed in the 9 ft diameter (18 ft barrel length with elliptical domes) vacuum facility (Figure 1). This facility, driven by 4 diffusion pumps (32,000 l/s each) and 3 roughing pumps (34,000 l/s each), is capable of vacuum levels of 10^{-6} torr or better. Power is provided to the test article via an automated 32-zone power and control system. The zones allow very accurate matching of the predicted core radial nuclear power profile. The zones operate at low voltage (150 V maximum) to allow testing to occur in vacuum or with any desired gas mixture and pressure. Although the control system is capable of delivering 480 kW, more power is available and can be tapped from the 1.5MW switchboard by adding extra power supplies to the system. A closed loop gas conditioning system exists that can be utilized for any test article. Although the system is designed for a He/Ar mix, it can accommodate other gases as well. Currently the system is designed for .09 to 0.2 kg/sec flowrate, 600 to 900 K inlet temperature (to test article), 850 to 975 K out (from test article), and a gas pressure between 1.0 to 2.5 Mpa.

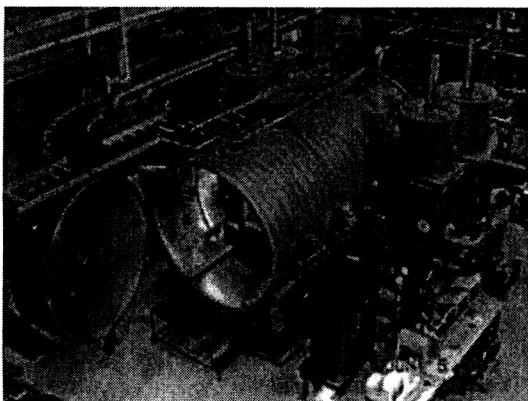


FIGURE 1. 9 ft Vacuum Chamber.

Experimental verification of heat transfer and stress issues is best performed if non-nuclear thermal simulators can be used to very closely mimic heat from fission. To accomplish this, the thermal simulators must be able to fit within the nuclear fuel pin cladding, must be able to match the predicted axial nuclear power profile of the fuel pin, and must be able to match the effective radial conductivity of the fuel pin. To meet these criteria, two types of thermal simulators are being developed at NASA MSFC. One is an alumina sleeved graphite heater with a minimum outer diameter of 0.365". The baseline heater is designed to operate at 1300 W, with a peak temperature capability >1700 K. The design allows for axial power profiling and radial conductivity matching. The other type of thermal simulator is an alumina sleeved spiral wound refractory alloy wire design. Potential advantages of this approach include smaller minimum outside diameter (<0.30 "") and ease of attaining smooth axial power profiling. This design also allows for axial power profiling and radial conductivity matching. Figure 2 is a picture of this thermal simulator test. Because of the uniqueness of the thermal simulators, MSFC has patents pending on both the heating elements and the power lead assemblies.

A smaller vacuum chamber whose primary focus of testing is modular level problem solving, small-scale concept demonstration, and heater research is located in an adjacent laboratory. This vacuum chamber is a 24" diameter, 6 foot long, cylindrical water jacket cooled stainless steel vacuum chamber capable of operating at pressures below 1.0×10^{-7} Torr.

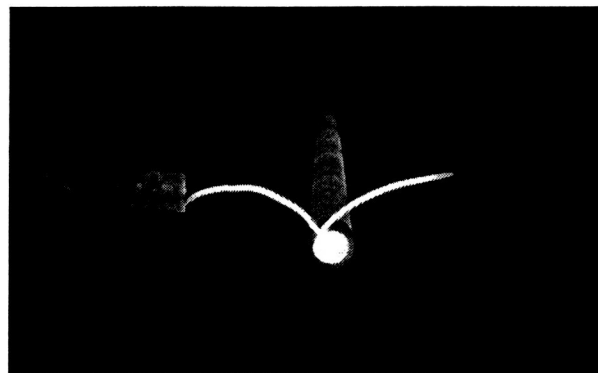


FIGURE 2. Thermal Simulator.

A plethora of manufacturing facilities are available for the fabrication of special test equipment,

facilities support equipment and for posttest analysis. These facilities include, but are not limited to : a high purity liquid metal handling machine, vacuum induction melt furnaces, roll mill, hammer forge, various heat-treat and brazing furnaces, Hot Isostatic Press (HIP) machines, tensile testers, hardness testers, scanning transmission electron microscope (STEM), field emission scanning electron microscope (FESEM), electron spectroscopy for chemical analysis (ESCA), plating facilities , welding/machining facilities, vacuum plasma spray facilities, rapid prototyping facilities, and EB welders.

III. 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. The next sections describe the test stays of each of these three concepts in the EFF-TF.

III.A. 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.

The first step in this program is to test a 37-channel design 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.



FIGURE 3. Potential 37-Channel Gas Cooled Reactor Test Article.

III.B. 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. The test demonstrated operation at full rated power, restart capability, and the soundness of the modular approach (Houts, 1997 and 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.

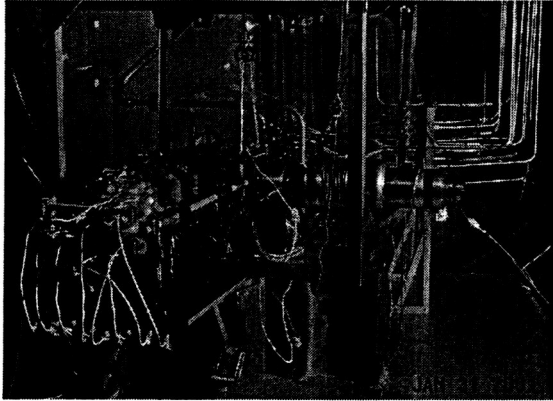


FIGURE 4. Coupled SAFE-30 / Stirling Engine Test.

III.C. 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. While 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, no testing has been performed at this time due to the complexity of the system coupled with funding constraints.

IV. SUMMARY

The focus of non-nuclear research and development testing within NASA Marshall Space Flight Center's Propulsion Research Center is on enabling early utilization of space fission systems. The result of this focus has been the development of fabrication and test capabilities necessary for rapidly testing potential near-term space fission systems. This capability includes advanced thermal simulators, extremely versatile test chambers, high purity alkali metal handling capability, and advanced manufacturing (e.g. e-beam welding, high temperature braze).

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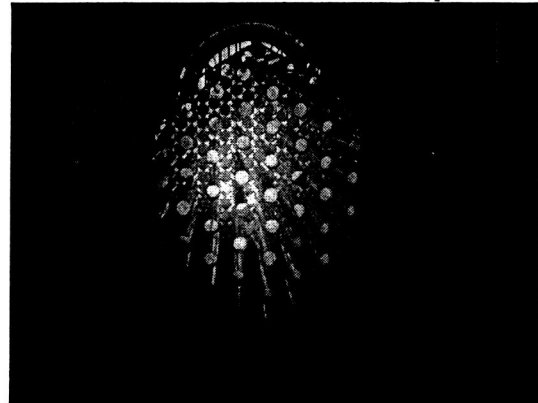


FIGURE 5. SAFE-100 Thermal Simulator Test.

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