Phase 1 Space Fission Propulsion System Testing and Development Progress

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Abstract. Successful development of space fission systems will require an extensive program of affordable and realistic testing. In addition to tests related to design/development of the fission system, realistic testing of the actual flight unit must also be performed. Testing can be divided into two categories, non-nuclear tests and nuclear tests. Full power nuclear tests of space fission systems are expensive, time consuming, and of limited use, even in the best of programmatic environments. 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 a series of non-nuclear tests. Non-nuclear tests are affordable and timely, and the cause of component and system failures can be quickly and accurately identified. MSFC is leading a Safe Affordable Fission Engine (SAFE) test series whose ultimate goal is the demonstration of a 300 kW flight configuration system using non-nuclear testing. This test series is carried out in collaboration with other NASA centers, other government agencies, industry, and universities. If SAFE-related nuclear tests are desired, they will have a high probability of success and can be performed at existing nuclear facilities. The paper describes the SAFE non-nuclear test series, which includes test article descriptions, test results and conclusions, and future test plans.

INTRODUCTION AND BACKGROUND

Successful development of space fission systems will require an extensive program of affordable and realistic testing. In addition to tests related to the design/development of the fission system, realistic testing of the actual flight unit must also be completed. Because heat from fission cannot be used for full-power testing of flight units (due to radiological activation), space fission systems must be designed such that heat from fission can be very closely mimicked by some other means. While some nuclear testing will be required, the system will ideally be optimized to allow maximum benefit from non-nuclear testing during the development phase.

Non-nuclear tests are affordable and timely, and the cause of component and system failures can be quickly and accurately identified. The primary concern with non-nuclear tests is that nuclear effects are obviously not taken into account. To be most relevant, the system undergoing non-nuclear tests must thus be designed to operate well within demonstrated radiation damage and fuel burn up capabilities. In addition, the system must be designed such that minimal operations are required to move from non-nuclear testing mode to a fueled system operating on heat from fission. 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 a series of non-nuclear tests. Any subsequent operation of the system using heat from fission instead of resistance heaters would then be viewed much more as a demonstration than a test - i.e. the probability of system failure from nuclear effects would be very low.

NON-NUCLEAR TESTING

All future space fission system development programs could benefit from optimizing the use of realistic non-nuclear tests. Phase 1 fission systems will benefit the most, as they are most likely to operate within established radiation damage and fuel burn up limits. Although advanced fission systems will require extensive nuclear testing, select non-nuclear tests will still be of real benefit. In addition, experience and support gained from the in-space utilization of Phase 1 space fission systems should facilitate the development of more advanced systems. In order to address some of the Phase 1 space fission system issues, MSFC is leading a Safe Affordable Fission Engine (SAFE) test series. This test series is carried out in collaboration with other NASA centers, other government agencies, industry, and universities. Figure 1 shows the SAFE series of non-nuclear test programs that ultimately leads to the (non-nuclear) demonstration of a 300 kW flight configuration system. Five out of the seven test series have either been completed or are currently in test at MSFC.

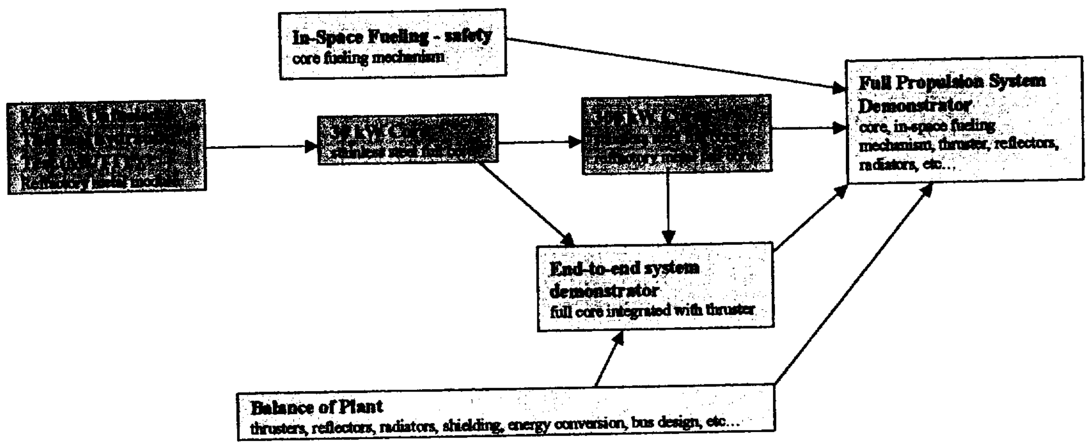

FIGURE 1. The Safe Affordable Fission Engine (SAFE) Test Program.

The purpose of the first test series (MUTT) was to verify that the heat from fission could realistically be demonstrated with resistance heaters. The heat from "fission" was utilized by transport through a heat pipe, or through GHe that was passed through the module. The second test series (SAFE-30) is a full core test capable of producing 30 kW, again using resistance heating, which contains 48 "fuel pins" or heaters and 12 stainless steel / sodium heat pipes. Heat can be carried out from the core either from the heat pipes, or from the gas that flows through the interstitials. The third test series (System Concept Demonstration) uses the SAFE-30 core in combination with a Stirling engine and an electric propulsion engine to perform a full NEP system demonstration, the first of its kind in the U.S. The fourth test series (In-space fueling) addresses the design and demonstration of an in-space fueling mechanism whose purpose is to show that a partially fueled core could be launched and fully loaded using automation while in-space. A fifth test series, SAFE 300, is similar to the SAFE 30 test series; however, this series uses a refractory metal core with more fuel pins and heat pipes. Additionally, the core and balance of plant components are more representative of a flight-like configuration.

MODULE UNFUELED THERMAL-HYDRAULIC TESTS (MUTT)

The MUTT test series was performed in 1998 and 1999 at MSFC. Specific objectives of the MUTT included demonstration of the module to operate at 1477 °C, a heat pipe operating temperature of 1027 °C, heat pipe operation at extreme transients (fast start followed by instantaneous shutdown), energy transfer capability of the heat pipe greater than 1 kW, and introduction of cold gas (ambient conditions) and extraction of hot gas (~900°C) from the chamber.

The MUTT (figure 2) was a 5.08-cm diameter, 45-cm long pure tungsten "block", which represents a module with 6 "fuel" pins surrounding a central molybdenum-lithium heat pipe. The tungsten block was heated with 6 resistance heaters to simulate the heat produced by nuclear fuel elements, and was capable of reaching over 1726 °C. Representative interstitial holes run parallel to the "fuel pins" for direct thermal heating of gases. Gaseous helium passing through module simulated direct heating. A molybdenum-lithium heat pipe, developed at Los Alamos National Laboratory, was inserted in the center hole of the tungsten block and supported at the far end by a stainless steel support bar. The heat pipe was 145-cm long, 1.27-cm outer diameter, and has a crescent-annular wick structure consisting of 7 layers of 400 mesh sintered molybdenum screen. Before delivery to MSFC, the heat pipe was tested at Los Alamos where it demonstrated radiation-coupled operation to the environment of 1 kW at 1176 °C. Figure 2 shows the heat pipe, the resistance heaters, and the gas entrance.

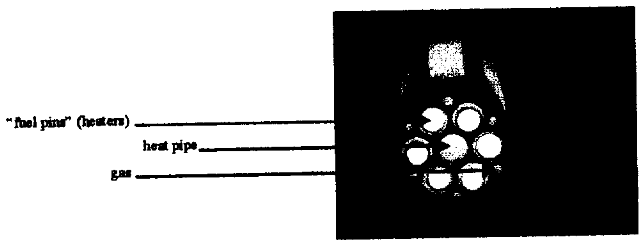

FIGURE 2. Position Of Heat Pipe, Heaters, And Gas Entrance On MUTT.

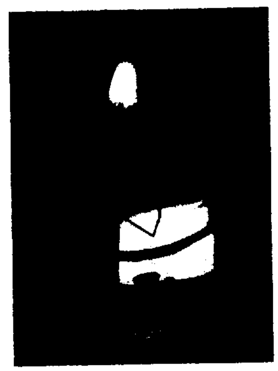

FIGURE 3. Instrumented Molybdenum-Lithium Heat Pipe.

The first set of tests verified the test set-up and verified the ability of the heaters to heat the module (neither gas flow or heat pipe were included in these tests). The maximum power delivered by the heaters was approximately 9.2 kW corresponding to a maximum module temperature of 1490 °C. Radiation calculations verified that the heat rejected from the module was approximately equal to that delivered to the module from the heaters. These tests provided time temperature profiles that served as a baseline for determining performance capability of the heat pipe, as well as demonstrated high temperature test capability.

The next set of tests showed the operability of a heat pipe under various start-up transients (fast and slow), even when exposed to extreme conditions. In the slow start-up, the heat pipe was brought to a maximum operating temperature of 946 °C after 115 min. Figure 3 shows the thermocouples instrumented heat pipe during test. The fast start-up test brought the heat pipe to isothermal at 1174 °C, corresponding to a heat transfer rate of at least 3 kW, in 55 minutes.

The final set of tests was to demonstrate the ability of gas to transfer heat from the module. These tests showed that gas could extract heat from the module (direct thermal thrust), and that the tungsten block could withstand the thermal stresses. Although the gas did not reach the desired 900 °C, the gas and module temperatures were the same during gas flow indicating that the gas did extract heat from the module tracking the module temperature exactly.

SAFE30

The SAFE 30 test series is a full core test capable of producing 30 kW using resistance heating to simulate the heat of fission. The 30 kW core consists of 48 stainless steel tubes and 12 stainless steel/sodium heat pipes (2.54 cm diameter, 119 cm length) welded together longitudinally to formulate a core similar to that of a fission flight system. Figure 4 shows the core hardware with the resistance heaters and colorimeters. As in an actual fissioning system, heat is removed from the core via the 12 heat pipes, closely simulating the operation of an actual system. Each heat pipe has a calorimeter which measures the heat extracted by the heat pipe. Heat was also be removed by passing gas through the interstitials of the core. Gas enter into a plenum which distributes the gas to 9 interstitials before exiting the core into an exit plenum. Gas temperatures are measured at the core exit before entering into the gas exit plenum. The core and heat pipes are donated by the Los Alamos National Laboratory. Los Alamos has also performed extensive neutronic analyses using the Monte Carlo neutral particle transport code "MCNP".

The primary objective of the SAFE30 was to obtain experimental data demonstrating the robust operation of the simulated nuclear core and heat pipe system. The information gained will be used for validation of existing computational models. Specifically, the tests are designed to accomplish the following:

- Simulation of nuclear core environment (thermally) through non-nuclear resistance heaters.
- Demonstration of the ability of the core to efficiency transfer heat from the fuel elements to a point external to the core, both by heat pipe and by direct thermal heating.
- Margin testing
  - Assess system performance and robustness with heat pipes
  - Demonstration of the ability to successfully undergo multiple start-ups and shut downs.
  - Demonstration of system performance with simulated heat pipe failure.
  - Heat transfer characteristics and efficiency of the heat pipes (temperature and power)
  - Determine performance of core heat pipe system operating in Mars type environment
- Verification of theoretical analysis regarding the performance of the core
- Assess system performance in an end-to-end demonstration where thermal energy is transferred to an energy conversion cycle and electric propulsion engine

The first test of the SAFE 30 (Figure 5) demonstrated the ability of the core to operate under extreme conditions. Three dummy heat pipes, used to simulate heat pipe failure, were placed in the center of the core. The heat pipes successfully reached an operating temperature of 700 °C with no performance degradation of the remaining heat pipes. This testing series is still on going at the time of this paper submission and several more tests are planned.

FIGURE 4. SAFE 30 Core With Resistance Heaters, Heat Pipes And Calorimeters

FIGURE 5. Operational SAFE 30 Core – Heat pipes at ~600 °C.

SYSTEM CONCEPT DEMONSTRATION

After completion of the SAFE30 test series, a heat exchanger and an off-the-shelf Stirling engine from the Stirling Engine Corporation will be attached to the heat pipes of the SAFE 30 in order to test an en-to-end concept. This will be the first time in the U.S. that a hardware ground based system of an entire concept (core, energy conversion and an electric propulsion engine) will be demonstrated. Figure 6 shows the core / heat pipe / Stirling engine assembly. Since the purpose of this test is to show proof-of-concept with inexpensive off-the-shelf materials, the system will not be optimized for performance. The Stirling engine will provide 350 W of power that will feed into an electric propulsion engine supplied by the Jet Propulsion Laboratory (JPL). After an initial system's checkout checkout of the core, heat exchanger, and Stirling engine assembly are completed at MSFC, the assembly will be shipped to JPL for attachment of the electric propulsion engine and final end-to-end testing. In an initial end-to-end demonstration of a nuclear electric propulsion system, the SAFE-30 power system will be tested with a 15-cm diameter ion engine at the Jet Propulsion Laboratory (JPL). This small, laboratory model engine was developed at JPL and incorporates several advanced ion engine technologies such as carbon-carbon ion optics (Brophy, 1993 and Mueller, 1994). The resistively heated reactor, Stirling engine, power conversion equipment and ion engine will be mounted in a 2.5-m diameter by 5-m long vacuum chamber. The 100 V output from the Stirling engine will be converted to 1000 V and used to accelerate the xenon ion beam. For these preliminary tests, the ion engine discharge and neutralizer cathode will be run with laboratory power supplies. The engine will be operated at beam power levels up to 350 W.

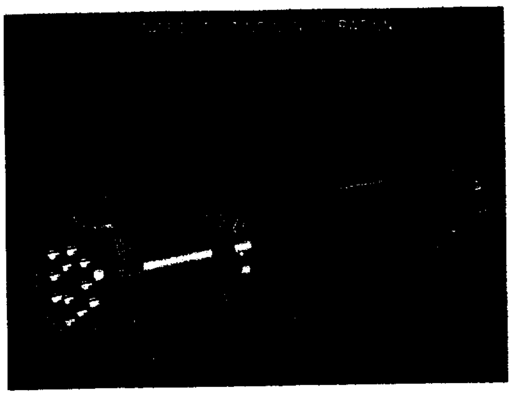

FIGURE 6. End-To-End Demonstartor Concept Of SAFE30. Electric Propulsion Engine Is Not Shown.

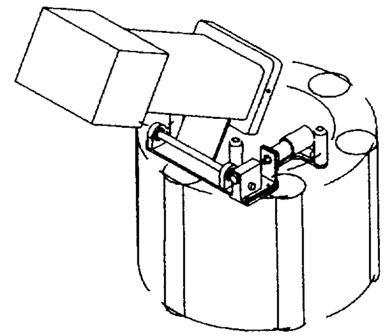

FIGURE 7. In-Space Fueling Concept. First Method Involves Placing The Nuclear Fuel Off Axis And External To The Fuel.

IN-SPACE FUELING

In order to address technical and programmatic concerns with launching fission systems, AMM and MSFC are working on the design and demonstration of an in-space fueling mechanism whose purpose is to show that a partially fueled core could be launched and then automatically fueled in space. Launching the core with a significant portion of the fuel removed eliminates the potential for inadvertent startup during a launch accident. The purpose of this research is to design, fabricate, and test a mechanism that will enable (1) complete separation of several nuclear fuel elements from the reactor core during launch and (2) convenient insertion of these elements into the core immediately prior to reactor startup (once the reactor reaches the desired orbit or location).

Two methods are under study. The first method involves placing the nuclear fuel off axis and external to the fuel. Enough fuel is removed such that the reactor cannot turn on even when submersed in water. This method leaves a void in the reactor until the fuel is inserted and is attractive because the fuel is physically external with no chance for 'accidental' insertion. Figure 7 shows this concept. The second method involves removing the nuclear fuel and replacing it with a neutron absorbing material. Once in space this neutron absorbing material is removed and replaced with the nuclear fuel. The benefit of this method is that less nuclear fuel needs to be removed and there is no void in the reactor during launch. Initial prototype testing is expected to begin during FY 2001 at MSFC.

SAFE300

After SAFE-30 primary heat transport performance has been evaluated, the next core that will be evaluated will be the SAFE-300. This will be a refractory metal core using molybdenum heat pipes capable of delivering 300 kW thermal at 1126 °C even following multiple heat pipe failures. The initial core design has been completed by LANL and small prototype modules have been fabricated to investigate manufacturing techniques. A stainless steel core has been made with the exact geometry of the initial design (Figure 8). Because the number of resistance heaters needed to simulate the fuel pins is large (~200), testing is also being done to determine how to manufacture these heaters at MSFC at an order of magnitude less expense than what can be bought off-the-shelf commercially.

Manufacturing Technique Testing

The desired option for the SAFE 300 core will result in a core with good neutronic characteristics and adequate resistance to thermal stresses generated within the core. Although brazing is the technique of choice, several alternatives to brazing were considered: vacuum plasma spray, spot welding, wire bundling, e-beam welding and plating. The final decision was made that brazed tubes would be the manufacturing practice of choice. A testing matrix was established to study the effectiveness of the process. Four (4) experimental samples made of seven (7) tubes brazed together with vanadium were made for the study. Each of the approximately 10 cm long bundles was sectioned into 1.9 cm pieces. The study will first look at half of the articles in the as-brazed condition. The samples are to be tested for shear strength. They will be visually and microscopically inspected for braze adherence and uniformity. The remaining pieces will be cycled in a vacuum furnace at between 1204 °C and 1482 °C for twelve hours (heat up and cool down is about 16 hours) in an effort to simulate the foreseeable thermal environment. These are also to be tested and examined in the same fashion as the as-brazed specimens. These tests will determine braze material compatibility and strengths, as well as provide insight into the structural stability of the unit. Fabrication of the test specimens has been completed and testing is expected to be completed early in FY 2001.

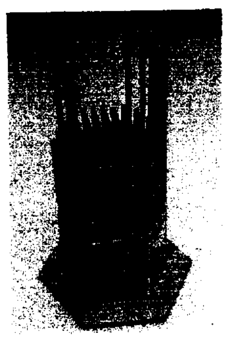

FIGURE 8. SAFE300 Stainless Steel Prototype.

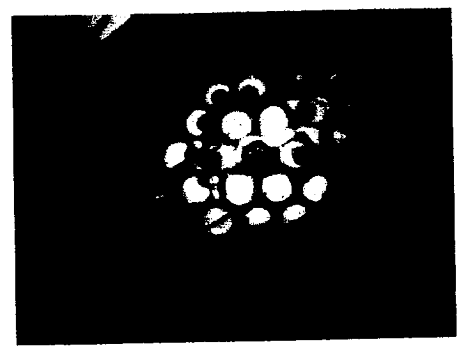

FIGURE 9. Heater Test At MSFC – SAFE300

Heater Fabrication and Testing

Each resistance heater for the SAFE-300 must capable of providing 1450 °C and 1.5 kW or better per heater. Manufacturing of these heaters is made even more difficult by the close proximity of the electrical connectors due the small diameter requirement of (0.95 – 1.27 cm) of the heater. Several configurations have been investigated including the use of graphite elements with boron nitride and alumina coatings. To date, MSFC has been successful in producing electrically isolated heaters capable of 1326 °C and 1.3 kW per heater when tested in a ceramic module. Figure 9 shows one of the heater tests conducted at MSFC.

CONCLUSIONS

Full power nuclear tests of space fission systems are expensive, time consuming, and of limited use, even in the best of programmatic environments. Non-nuclear tests are affordable and timely, and the cause of component and system failures can be quickly and accurately identified. If the system is designed to operate within established radiation damage and fuel burnup limits while simultaneously being designed to allow heat from fission to be closely mimicked using other methods, high confidence in fission system performance and lifetime can be attained through a series of non-nuclear tests. In addition, realistic testing of actual space fission system flight units can be performed.

In order to address some of the first generation system issues, MSFC is leading the SAFE test series. This test series is carried out in collaboration with other NASA centers, other government agencies, industry, and universities. Programs either tested, or currently undergoing testing, include refractory metal modules, heat pipes, high temperature heaters, stainless steel cores, end-to-end demonstrators and in-space fueling.

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