First Generation Least Expensive Approach to Fission (FiGLEAF) Testing Results

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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. The paper describes the SAFE 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 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. Factors to consider when performing nuclear tests include the following:

1. Time and cost associated with fabricating and handling the test article;
2. Non-flight-prototypic modifications to the test article required to enable ground testing;
3. Required modifications to existing nuclear facilities to enable testing;
4. Time and cost associated with testing the article at a nuclear facility;
5. Time and cost associated with radiological cool down and transfer/shipping to a hot cell;
6. Expense and slow pace of assessing failures in a hot cell environment; and
7. Limited ability to correctly identify failure mechanisms in a hot cell environment.

History provides examples related to the seven concerns listed above. During the highly successful Rover Nuclear Rocket Development Program, it still took nearly four years to move from the Pewee ground nuclear test in 1968 to the follow-on nuclear test, the Nuclear Furnace 1 test in 1972 . The first five full ground nuclear power tests of the program (Kiwi A, Kiwi A', Kiwi A3, Kiwi B1A, Kiwi B1B, total cost >$1B FY00 equivalent) all resulted in massive fuel damage due to thermal hydraulic problems and flow-induced vibrations. These problems were not resolved until non-nuclear cold-flow tests were performed. During the SP-100 program, tens of millions of dollars were spent attempting to modify the Hanford Site 309 Building to allow a full ground nuclear test of an SP-100 system. In addition, the system to be tested (SP-100 Ground Engineering System) was significantly different from the SP-100 Generic Flight System . The Hanford Site 309 Building was selected in 1985 to be the site of the Ground Engineering System test. At the end of the SP-100 program (nearly 10 years later) significant modifications still remained before nuclear tests could be performed in the building. During the Thermionic Fuel Element Verification Program it frequently took more than a year for thermionic fuel elements (TFEs) and TFE components to be removed from the test reactor, shipped, and readied for post-irradiation examination (PIE). When PIE was performed, limited data was obtained due to the expense, time, and limited equipment availability associated with working in a hot cell. Neither the Rover program, nor the SP-100 program, nor the TFEVP led to the flight of a space fission system.

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 established radiation damage and fuel burn up limits. In addition, the system must be designed such that minimal assembly is 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 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. First-generation 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, experience and support gained from the in-space utilization of earlier systems should facilitate their development. In order to address some of the first generation 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.

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 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 (On-The-Way (OTW) 300/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. The main purpose of the testbed was to demonstrate the superiority of hardware-based technology assessment over the never-ending cycle of paper studies often associated with advanced system development. Through a series of realistic non-nuclear testing, thermal hydraulic and other issues associated with space fission system development could be resolved. Specific objectives of the MUTT included demonstration of the module to operate at 1477°C. (1750 K) a heat pipe operating temperature of 1027°C (1300 K), 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 50 to 53 cm long and 1.17-cm diameter to simulate the heat produced by nuclear fuel elements, and were capable of reaching over 2000 K. Temperature readings were obtained with an optical pyrometer and thermocouples. 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 1450 K. The heat pipe was instrumented with 9 type C thermocouples tack welded to the heat pipe on a nickel foil interlayer. Figure 2 shows the position of the heat pipe, the resistance heaters, and the gas entrance.

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 heaters were set at a constant power level and the uninsulated module temperature was recorded using an optical pyrometer. The power level was kept at this constant level until it appeared that module temperature reached a steady state. The terminal voltage across each heater was then increased by 20 V and kept at the constant level until the module again reached steady state. This procedure continued until the maximum available current that could be delivered by the power supply was reached. This corresponded to a maximum power of approximately 7 kW delivered to the heaters and a module maximum temperature of 1663 K. Radiation calculations verified that the heat rejected from the module was approximately equal to that delivered to the module from the heaters. The test was repeated with identical settings and procedures and yielded the same results. These two tests verified that the heaters could be used to realistically simulate heat from fission.

In an effort to increase the power available to the heaters, the power supply was rewired so an increase in current, resulting in an increase in available power, could be delivered to the heaters. The next test showed that at the same power levels, the time-temperature profiles were identical to the first two tests. The maximum power delivered by the heaters for this test was approximately 9.2 kW corresponding to a maximum module temperature of 1754 K. 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 verified the operation of the heat pipe under various operating conditions. Type C thermocouples were installed on both the heat pipe and on the module to record temperatures. The thermocouple on the module served both to verify the optical pyrometer readings from earlier tests and to serve as a frame of reference for the heat pipe thermocouples. The first heat pipe test was to verify heat-pipe operation, instrumentation hook-up, and test procedure. The first test ran for a total of 115 min and showed successful operation of the heat pipe. Since a slow start-up of the pipe was desired, the power supply was initially set to deliver 60 V (0.12 W), and increased at approximately 10 V increments every 10 min. This brought the heat pipe to a maximum operating temperature of 1220 K after 115 min. Figure 3 shows the thermocouples instrumented heat pipe during test and Figure 4 shows the thermocouple profile for the first heat pipe test. In the last MUTT heat pipe test, the heat pipe was brought to isothermal (1448 K corresponding to a heat transfer rate of at least 3 kW) in 55 minutes. These tests showed the operability of a heat pipe under various start-up transients (fast and slow), even when exposed to extreme conditions. This test series also verified the restart capability of the heat pipe.

The final set of tests was to demonstrate the ability of gas to transfer heat from the module. To avoid corona effects (due to the gas used and the voltage of the heaters), the module was raised to an operating temperature of 1200 C. At this temperature, the power was turned off and gas was flowed through the system. 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. Figure 5 shows the temperature at the end of one of the gas holes and the temperature of the tungsten module as a function of time. These tests showed that gas could extract heat from the module (direct thermal thrust), and that the tungsten block could withstand the thermal stresses.

SAFE30

The second test series, SAFE 30, is a full core test capable of producing 30 kW, again 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 (1.0 inch diameter, 47" length) welded together longitudinally to formulate a core similar to that of a fission flight system. Figure 6 shows the core hardware with the resistance heaters and colorimeters. As in an actual fissioning system, heat will be removed from the core via the 12 heat pipes, closely simulating the operation of an actual system. Each heat pipe will have a calorimeter which measures the heat extracted by the heat pipe. Heat can also be removed by passing gas through the interstitials of the core. Gas will enter into a plenum which will distribute the gas to 9 interstitials before exiting the core into an exit plenum. Gas temperatures will be 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 is 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.
- Assess system performance and robustness with heat pipes
- Startup of the heat pipes under rapid heating conditions (room temp to 973K in less than 1 hour);
- Demonstration of the ability to successfully undergo multiple start-ups and shutdowns.
- 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
- Determine heat transfer characteristics of gas flow through the core;
- 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.

The first check out test verifying facility and test article integration is expected to be complete mid-July 2000. Nine sets of tests (each set with multiple tests) will be completed by mid-fall 2000.

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 7 shows a drawing of the entire core / heat pipe / Stirling engine assembly. Since the purpose of this test is to show proof-of-concept with inexpensive off-th-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 [1,2]. 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.

IN-SPACE FUELING

In order to address the ever-increasing public concern on launching a fully fueled core, 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 fully loaded using automation while in-space. The purpose of this research is to design, fabricate, and test a mechanism that will enable (1) complete separation of critical nuclear fuel elements from the reactor core during launch and (2) convenient insertion of these elements into the core immediately prior to reactor startup. The mechanism will eliminate any potential for inadvertent reactor startup during a launch accident. The mechanism will thus enable space fission systems to be 100% safe. In order to characterize the design requirements for an in-space fueling mechanism, an analysis was performed to assess reactor response to a "worst case" scenario. This would be a launch accident where the control drums rotate to the maximum on position and the reactor falls intact into water. The analysis will determine how much of the fuel material must be removed to prevent reactor activation assuming these conditions. These calculations will guide design of the mechanism needed to safely insert the fuel back in the reactor once it is in space and ready for operation. Two methods are under study and prototype.

The first method involves placing the nuclear fuel off axis and external to the fuel. Enough fuel is removed such that it 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 8 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. Figure 9 shows this concept.

Both methods are under study by Advanced Methods and Materials and MSFC. Initial prototype testing is expected to begin summer 2001 at MSFC.

SAFE300/OTW300

After the SAFE30 has been demonstrated, the next core that will be demonstrated will be the SAFE300. This will be a refractory metal core using molybdenum heat pipes and is capable of 300 kW thermal at 1700 K. 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 10). Because the number of resistance heaters needed to simulate the fuel pins is large (~200), testing is also being done to determine how to manufacturer these heaters at MSFC at an order of magnitude less expensive than what can be bought off-the-shelf commercially.

Manufacturing Technique Testing

The manufacturing of an article that would withstand the trials of fission is not a standard course of action. Although brazing is the main technique of choice, several various alternatives to brazing were considered: vacuum plasma sprayed, spot welded, 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 (Figure 11). Initial testing was based on eddy-current. An effort to pinpoint the homogeneity and evenness of the braze was made using this process, however due to the size limitations and time constraints, this course of action was abandoned. The use fiber optics as an apparatus to study the sections was also investigated, but was abandoned since it was deemed that not enough information could be gleamed from this type of test. Destructive testing will be the evaluation method of choice. Each of the approximately 4 inch long bundles was sectioned into ¾" 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 2200 and 2700 degrees F 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 in fall 2000.

Heater Fabrication and Testing

Each resistance heater for the SAFE 300 must capable of providing 1700 deg K, and 1.5 kW or better per heater. Each heater must be approximately 15 inches long with a cold zone of 3 inches. What makes the manufacturing of these heaters so difficult is the close proximity of the electrical connectors due the small diameter requirement of (0.25 – 0.375 inches) 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 heaters capable of 1600 K and 1.3 kW per heater when tested in a ceramic module . Figure 12 shows one of the heater tests conducted at MSFC. The next step in the test series addresses electrical insulation between the element and module.

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 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.

In order to address some of the first generation system issues, MSFC is leading a 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.

References

[1] Brophy, J.R., Pless, L.C., Mueller, J.M., and Anderson, J.R., "Operating Characteristics of a 15-cm dia. Ion Engine for Small Planetary Spacecraft," IEPC-93-110, 23rd International Electric Propulsion Conference, Seattle, WA, Sept. 1993.

[2] Mueller, J.M., Brophy, J.R., Brown, D.K., and Garner, C.E., "Performance Characterization of 15-cm. Carbon-Carbon Composite Grids," AIAA-94-3118, 30th Joint Propulsion Conference, Indianapolis, IN, June 1994.

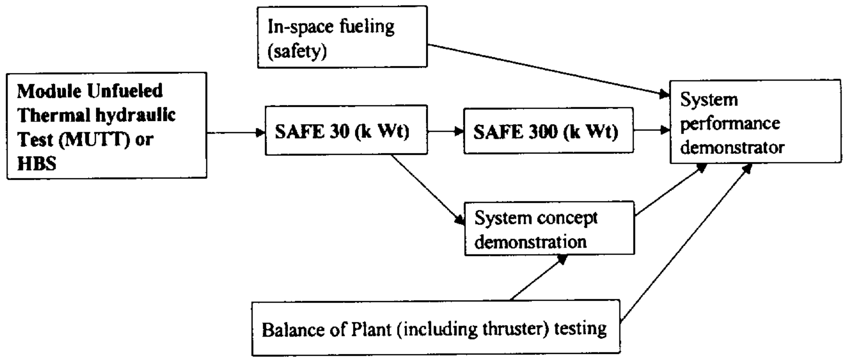

Figure 1. The Safe Affordable Fission Engine (SAFE) Test Program.

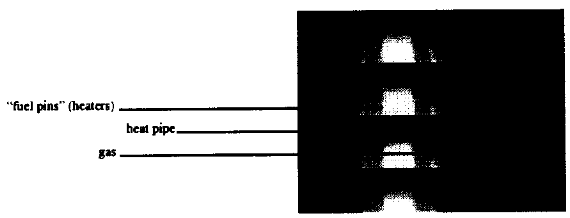

FIGURE 2. Position Of Heat Pipe, Heaters, And Gas Entrance On MUTT.

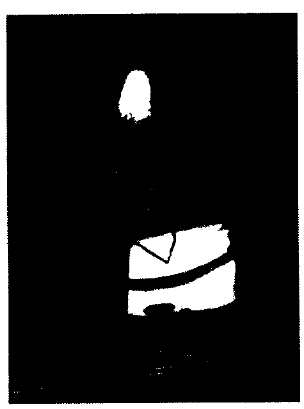

FIGURE 3 Instrumented Molybdenum-Lithium Heat Pipe.

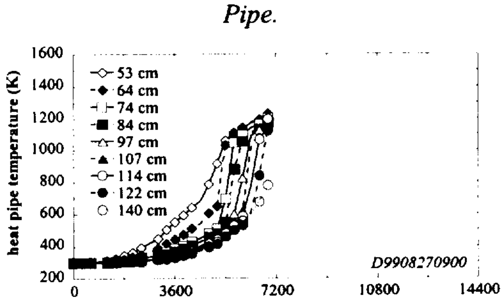

FIGURE 4. Start-Up Time Versus Temperature Profile For The First Heat Pipe Test.

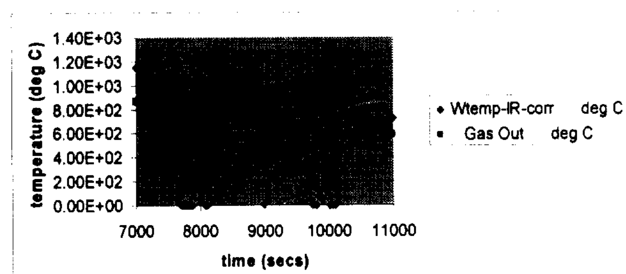

FIGURE 5. Time Versus Temperature Profile For Gas Test.

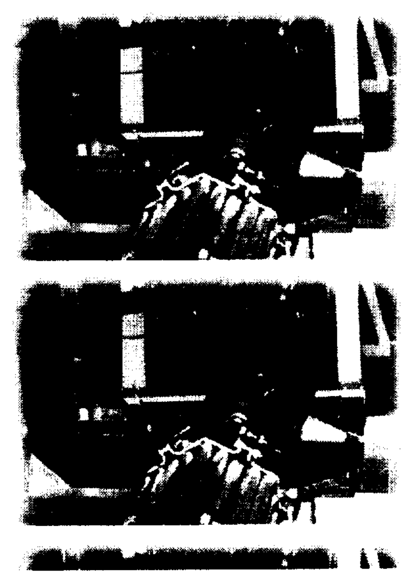

FIGURE 6. SAFE 30 Core With Resistance Heaters, Heat Pipes And Calorimeters.

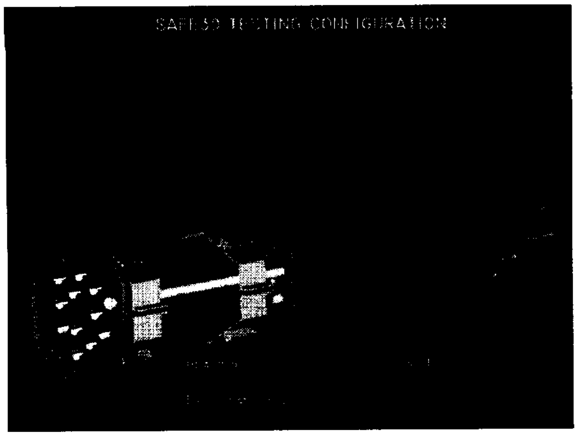

FIGURE 7. End-To-End Demonstartor Concept Of SAFE30. Electric Propulsion Engine Is Not Shown.

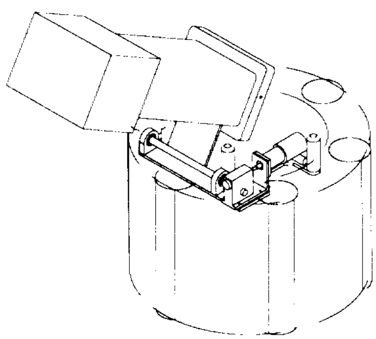

FIGURE 8. In-Space Fueling Concept. First Method Involves Placing The Nuclear Fuel Off Axis And External To The Fuel.

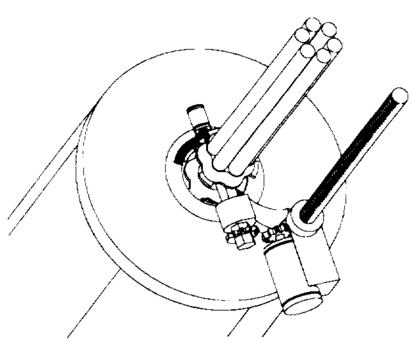

FIGURE 9. In-Space Fueling Concept. The Second Method Involves Removing The Nuclear Fuel And Replacing It With A Neutron Absorbing Material.

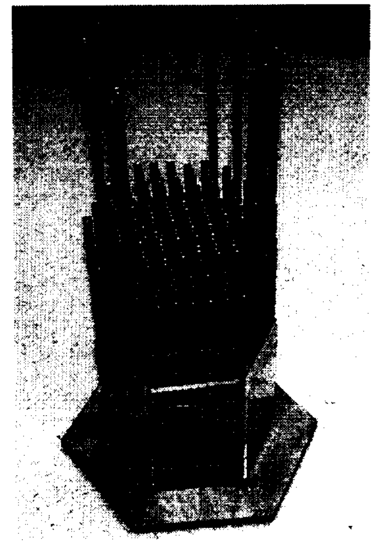

FIGURE 10. SAFE300 Stainless Steel Prototype.

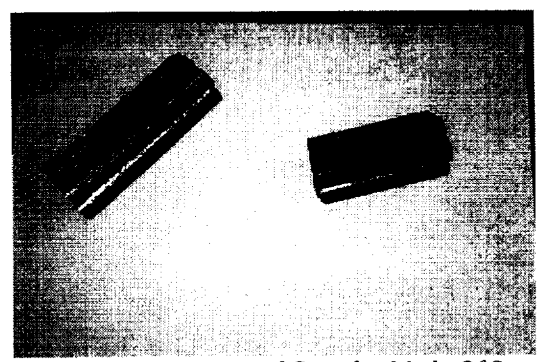

FIGURE 11. Experimental Samples Made Of Seven (7) Tubes Brazed Together With Vanadium.

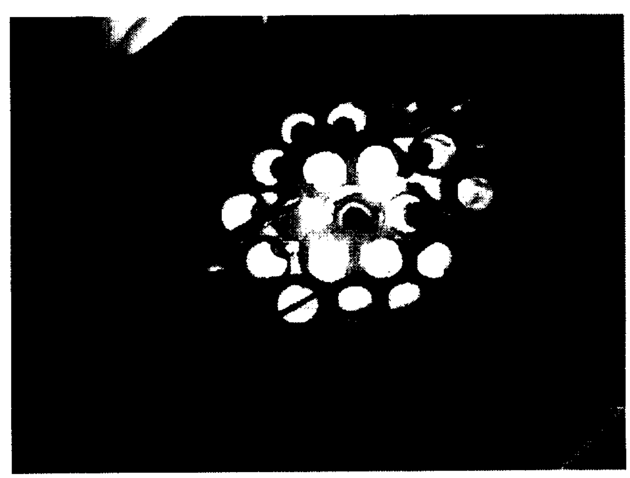

FIGURE 12. Heater Test At MSFC – SAFE300.