Results of a First Generation Propellant Energy Source Module Testing: Non-Nuclear Testing of a Fission System

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Abstract The use of resistance heaters to simulate heat from fission allows extensive development of fission systems to be performed in non-nuclear test facilities, saving time and money. Resistance heated tests on the Module Unfueled Thermal-hydraulic Test (MUTT) article has been performed at the Marshall Space Flight Center. This paper discusses the results of these experiments to date, and describes the additional testing that will be performed. Recommendations related to the design of testable space fission power and propulsion systems are made.

INTRODUCTION

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 cooldown 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 (1968) to the follow-on nuclear test, the Nuclear Furnace 1 test in 1972 (Koenig, 1986). 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 a SP-100 system (Carlson, 1993). In addition, the system to be tested (SP-100 Ground Engineering System) was significantly different from the SP-100 Generic Flight System (Fallas, 1991). The Hanford Site 309 Building was selected in 1985 to be the site of the Ground Engineering System test (Baxter, 1991). 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 (Ranken, 1994). 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 burnup 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 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. 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.

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 burnup 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. Testing of the MUTT at the Marshall Space Flight Center is a first step towards the testing of nuclear systems in a non-nuclear test facility. The MUTT is the first test in a series of tests for the First Generation Least Expensive Approach to Fission (FiGLEAF) program proposed by the Propulsion Research Center (PRC) at NASA/MSFC.

The MUTT test series has four top-level goals:

1. Demonstrate that realistic non-nuclear testing can be used to resolve thermal hydraulic and other issues associated with space fission system development.
2. Demonstrate that the eventual user of space fission systems (in this case NASA) can be heavily involved in all aspects of space fission system development.
3. Demonstrate the desirability of a modular core design that allows issues to be resolved on a module level prior to fabrication and test of a full core.
4. Demonstrate the superiority of hardware-based technology assessment over the never-ending cycle of paper studies often associated with advanced system development.

Specific technical goals of MUTT test series include the following:

1. Gain experience using resistance heaters to realistically simulate heat from fission. Test module to thermal design limits by demonstrating capability of module to operate at 1477 ^{O} C. (1750 ^{O} K).
2. Demonstrate energy transfer capability of heat pipe Test heat pipe to thermal design limits by demonstrating an operating temperature of 1027 ^{O} C (1300 ^{O} K).
3. Demonstrate heat pipe operation at extreme transients (fast start followed by instantaneous shutdown).
4. Demonstrate direct thermal propulsion by introduction of cold gas (ambient conditions) and extraction of hot gas (900 ^{O} C) from the chamber.
5. Development instrumentation techniques for flow, temperature, and other measurements in a simulated fission system.
6. Experience gained from the MUTT test series will be directly applicable to full-core tests slated to begin later in FY00.

EXPERIMENTAL APPARATUS

This MUTT is a 2 inch diameter, 17.75 inch long pure tungsten "block", which represents a module with 6 "fuel" pins surrounding a central Molybdenum-Lithium heatpipe. It is supported at each end by stainless steel endcaps that are insulated with a molybdenum foil to prevent reaction with the block, see Figure 1. A support member, mounted to an extension elbow, holds the two endcaps. Fingers from the elbow capture the internal diameter of two opposing viewports to hold the MUTT in place. The block is insulated with graphfoil insulation (not shown).

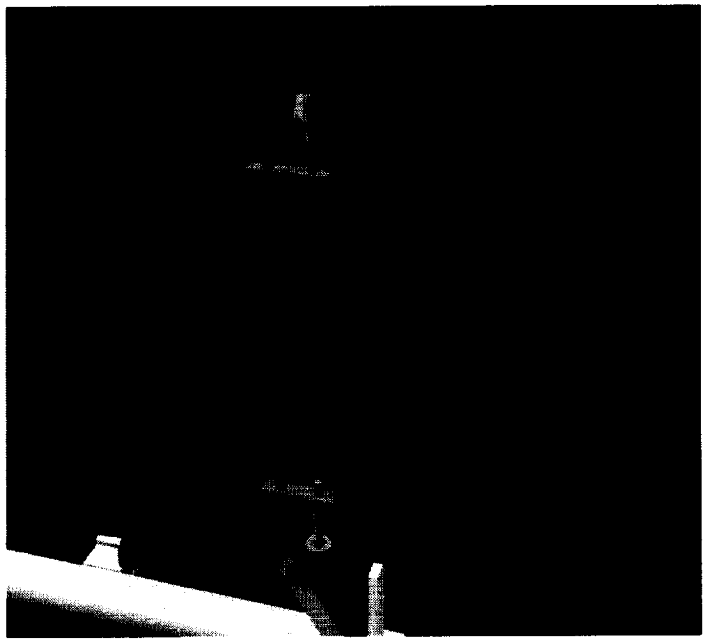

FIGURE 1. Module Unfueled Thermal-hydraulic Test Article in PEST.

The tungsten block is heated with 6 resistance heaters (simulating "fuel" pins) 19.75 to 21 inches long and 0.46 inch diameter to simulate the heat produced by nuclear fuel elements. The high temperature boron nitride heaters, capable of reaching over 2000 ^{O} K, were designed and produced by Advanced Ceramics Inc., of Lakewood, OH. They are connected in two heater pairs, which are connected in parallel to an electrical feed through in the chamber. Fourteen gauge copper is connected the heaters to the feedthrough. This provides MUTT with a maximum available power of 3 kilowatts to each heater (operating temperature limit, not power available limitation). Digital output multimeters deliver total heater current and voltage information to the data acquisition system. Temperature readings are 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 simulates direct heating.

A Molybdenum-Lithium heatpipe, manufactured by Los Alamos National Laboratories, is inserted in the center hole of the tungsten block and supported at the far end by a stainless steel support bar. The heat pipe is 64.86 inches in length, 0.5-inch outer diameter, and has a crescent-annular wick structure consisting of 7 layers of 400 mesh sintered molybdenum screen. Prior to delivery at MSFC, the pipe was tested at Los Alamos National Labs where it was capable of radiating approximately 3.2 kilowatts at 1500 ^{O} K The heat pipe is instrumented with 9 type C thermocouples tack welded using nickel foil. The distance between the first 8 thermocouples is approximately four inches with the first thermocouple installed 2.5 inches from the end of the block. The distance between the last two thermocouples (8 and 9) is approximately 8.5 inches. One thermocouple was attached to the tungsten block between the block and one thermocouple was attached to the chamber wall of PEST. An optical pyrometer is used to verify the accuracy of the thermocouple data. The thermocouple temperature data was directed to the data acquisition system.

The Helium is injected through a gas feedthrough to a manifold that distributes the gas into six feeds that connect to the inlet side endcap of the tungsten block. The gas is then heated by the block and vented into the chamber where it is pumped out. The exhaust endcap is outfitted with thermocouples positioned over the gas exhaust holes to record change in temperature. Inlet temperature of the gas is measured prior to injection into the chamber. Flow rate is monitored and controlled by an MKS flow control unit

Pressure in the chamber was monitored using multiple vacuum TC gauges for pressures above 1 x 10^{-3} Torr. For pressures below the TC gauge capability, a Cold Cathode and Baypert-Albert ion gauge were used. A stand-alone "Varian Vacuum Multi-Guage Controller" and LabView gathered both real-time pressure data.

LabView software and correspondingly National Instruments hardware was selected as the data acquisition and control (DAC) software due to its high level of industry implementation and high level of versatility. LabView is highly modular and has been customized to perform most all the routine operations standard to PEST. The data acquisition and control hardware consisted of a SCXI chassis outfitted with cards specific to MUTT needs. The chassis contained a Thermocouple card, a control card for operation of valves and switches, and card to handle the pressure information. Interface with the SCXI chassis was by computer running LabView software. LabView collected and assembled the data as well as monitored most aspects of the experiment. All electronic controls and data acquisition devices were located on a rack next to the chamber.

RESULTS OF EXPERIMENT

The first test determined the ability of the heaters to heat the module (neither gas flow or heat pipe were included in this test). 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 power level was then increased by 20 volts 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 kilowatts delivered to the heaters and a module maximum temperature of 1663 ^{O} K. Figure 2 shows the time-temperature profile for this test. Although the curve shape is similar for each power level, at higher power levels (temperatures), the module temperature had a larger slope and reached steady state fairly quickly. Figure 3 shows the module at approximately 7.2 kilowatts at 4000 seconds.

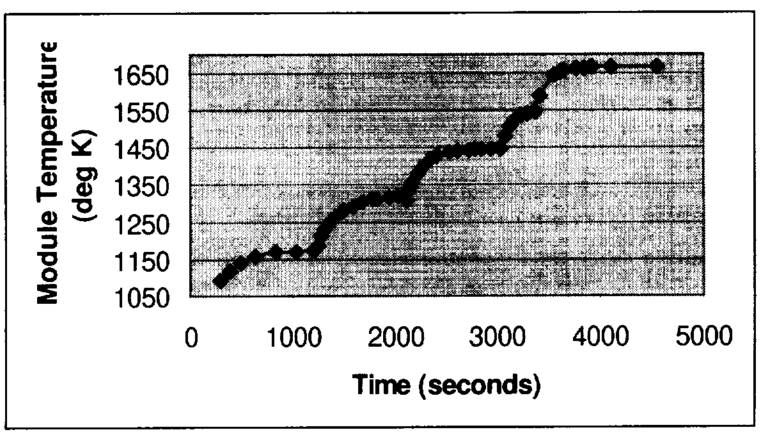

FIGURE 2. Time Temperature Profile for First Run of Uninsulated Module.

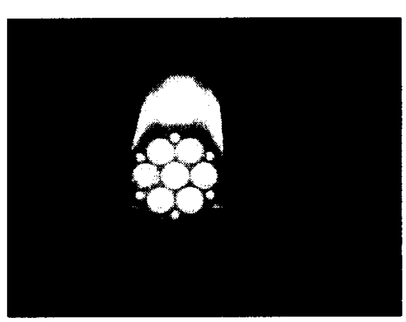

FIGURE 3. Uninsulated Module at 7.2 kilowatts at 4000 seconds.

Radiation calculations verified that the heat rejected from the module was approximately equal to that delivered to the module from the heaters. A second test, carried out with the identical settings and procedures as the first test, yielded the same results as the first test. This 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 third 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 the third test was approximately 9.2 kilowatts corresponding to a maximum module temperature of 1754 K. This temperature is higher than what a stainless steel or super alloy core would experience for a potential first flight demonstrator.

The next series of tests were to verify the heat pipe's ability to operate under desired 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 heatpipe test was to verify heat-pipe operation, instrumentation hook-up, and test procedure. The first test ran for a total of 115 minutes and showed successful operation of the heat pipe. Since a slow start-up of the pipe was desired, the power supply was set to deliver 60 volts (0.12 W), increasing approximately 10 volts every 10 minutes. This brought the heatpipe to a maximum operating temperature of 1220 K after 115 minutes. Figure 4 shows the thermocouples instrumented heatpipe. Figure 5 shows the thermocouple data over the period of the test.

Insert Picture of instrumented heat pipe here

FIGURE 4. Instrumented Heatpipe.

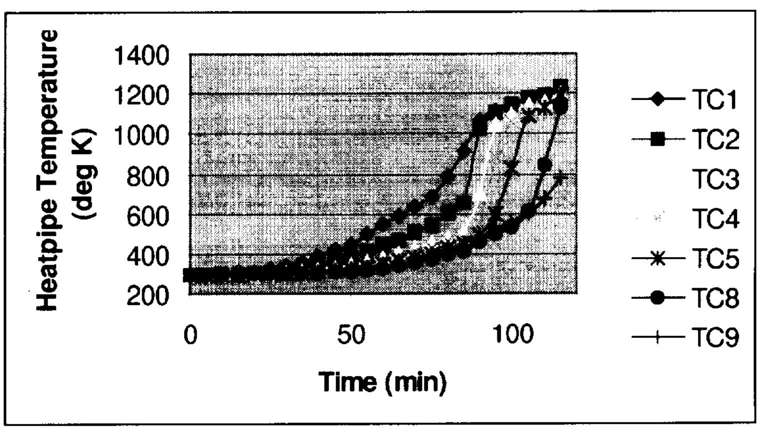

FIGURE 5. Time -Temperature Profile of Heatpipe Test #1.

At the end of the first test, a defective sight glass allowed air to inadvertently leak into the chamber. The chamber was flooded with gaseous helium and kept at 1 torr until the module and heat pipe were allowed to cool to ambient conditions. The module was hydrogen cleaned and a second heat pipe test was conducted again to determine the operational capability of the heat pipe and to verify that no damage had occurred. Since a slow start-up of the pipe was desired, the power supply was set to deliver 60 volts (0.154 W), increasing approximately 15 volts every 10 minutes. This brought the heatpipe to a maximum operating temperature of 1395 K after 245 minutes. Figure 6 shows the thermocouple data over the period of the test. The data showed successful heat pipe operation with the entire heat pipe at an operating temperature greater than that of the first test (>1220 K). At the end of the 245 minutes, the pipe was isothermal and the test terminated. This demonstrated that the heat pipe was able to operate successfully, even when exposed to worst case conditions. Both an optical pyrometer and a thermocouple were used for measuring the temperature of the thermocouple on the heatpipe that was closest to the module (TC1). The difference between both methods varied by only a maximum of 1.5 %, verifying the "goodness" of the data from the first three tests which used only the optical pyrometer. .

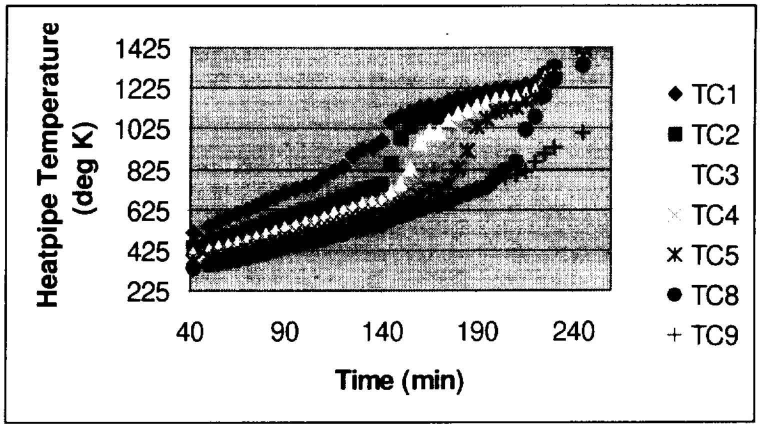

Figure 5. Time -Temperature Profile of Heatpipe Test #2

Additional MUTT Tests Planned

Several more test series are scheduled for the MUTT and should be completed by early 2000. Specifically the following areas to be addressed are:

- Insulation of module to reduce radiation losses to chamber;
- testing to thermal design limits (i.e. capability for extremely high temperature (>2000 K))
- Testing of direct thermal propulsion, including introduction of cold gas and extraction of hot gas from the chamber;
- Testing of a fission system that allows simultaneous testing of thermal propulsion and heat pipe operation; and
- Investigation of the feasibility of using laser diagnostics to determine temperatures;

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.

The MUTT was successful at demonstrating the use of resistance heaters to realistically simulate heat from fission. The MUTT demonstrated the ability to use several different instrumentation techniques for measuring temperature and pressure in a simulated fission (thermal hydraulic) environment. Finally, the MUTT was able to demonstrate the energy transfer capability and operation of a heat pipe under worst case operating conditions.

Additional testing will be completed shortly which should demonstrate the capability to test direct thermal propulsion and heat pipe operation simultaneously.

RECOMMENDATIONS

This test series demonstrated that some aspects of the fission systems could be simulated using non-nuclear test facilities. Any future fission program, whose goal is a flight system, should investigate the use of non-nuclear testing where appropriate to decrease programmatic costs by orders of magnitude. Data gained from such tests may be more thorough (i.e. failure testing and margin testing) since a great deal of the safety issues associated specifically with nuclear testing, such as hot cells, will not have to be addressed.

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