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QUANTIFYING THE HEAT SWITCHING CAPABILITY OF A THERMIONIC DIODE

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ABSTRACT

The Integrated Solar Upper Stage (ISUS) Advanced Technology Demonstrator (ATD) program, recently initiated by the U. S. Air Force Phillips Laboratory (USAF PL), will demonstrate the feasibility of a combined solar power and propulsion upper stage. The solar bimodal design approach will use thermal energy storage to reduce engine mass and concentrator area. However, in order to store enough energy over an orbit period there must be minimal heat lost with a system that is designed to remove heat for energy conversion. A unique feature of thermionics is their ability to reduce heat flow by reducing or eliminating the electron cooling. However, demonstration and quantification of this capability is needed.

This paper presents the results to date of the Receiver Diode Integration Test, one of two critical experiments of the ISUS ATD program being performed by the Idaho National Engineering Laboratory (INEL). Results of the demonstration testing of thermionic heat pipe modules (THPMs) to operate as heat switches in conjunction with the solar receiver cavity are presented as are the performance limits and operational constraints of a combined receiver/diode subsystem.

INTRODUCTION

A series of high temperature, high vacuum experiments, hereafter termed the Receiver/Diode Integration Test (RDIT), are being performed by the INEL in support of the ISUS ATD Program. Early in the ISUS ATD Program, two critical missing pieces of information were identified that would provide significant credence to the combined solar power and propulsion upper stage concept. The missing pieces are: 1) the effect a thermal storage device would have on the operability and performance of a THPM (e.g. heat losses, heat flow, inlet/outlet gas temperatures), and 2) the response of the thermal storage device to thermal cycling (e.g. changes to mechanical and chemical properties). Hence, the RDIT Program is aimed at addressing the integration of the thermal storage (i.e. "receiver") and the energy converter (i.e. "diode") components and performing tests and evaluation of these two components to demonstrate subsystem feasibility. In addition, the RDIT Program will address several component and subsystem fabrication issues and evaluate performance issues that are necessary in order to develop the ISUS as a viable means of space based power and propulsion. The RDIT experimental program involves several separate tests in which characteristic thermal conditions are imposed upon the receiver/diode subsystem.

RDIT PROGRAM OBJECTIVES

The primary objective of the RDIT program is to evaluate the performance limits and operational constraints of a combined receiver/diode subsystem to be used by the ISUS concept. However, several technical issues have to be resolved before the feasibility of the receiver/diode subsystem can be determined, including the following:

1) The electrical power generation capabilities of the THPM,

2) The fabrication of a rhenium-coated graphite thermal storage component,
3) The thermal behavior of a rhenium-coated graphite thermal storage component,
4) The performance of an integrated THPM and thermal storage component (e.g. THPM electrical load versus heat transfer from the thermal storage component), and
5) The operational capability of the subsystem (i.e. the combined components).

Technical issue 1) was evaluated at the INEL using internal R&D funds. The results of that evaluation are presented in this paper since it forms the baseline data for the performance of a THPM without the presence of a thermal storage media.. Technical issues 2) through 5) will be addressed by activities encompassed by the RDIT Program. The following paragraphs detail the results of each activity aimed at resolving these five technical issues. (Note that Issue 2 is discussed last.).

SETUP OF THE RDIT EXPERIMENT

The experimental setup for the RDIT Program was made up of the following major components:

1) THPM 1127-C (i.e. the "diode"),
2) The Hot Hydrogen Test Facility (HHTF) vacuum vessel,
3) The HHTF hot zone assembly,
4) The HHTF vacuum system and controllers,
5) The RDIT graphite sleeve (i.e. the "receiver"),
6) Various instrumentation for subsystem control and signal measurement, and
7) Data acquisition system.

The following paragraphs describe the major components listed above.

THPM 1127-C

THPM 1127-C is a half length (25-cm) thermionic heat pipe designed and fabricated by Thermacore, Inc. (Lancaster PA) for the USAF (see Figure 1). This particular THPM was extensively tested by Thermacore after its fabrication; hence a significant amount of performance data was available to the test engineers prior to the testing at the INEL. However, this THPM had been in storage at the USAF's Phillips Laboratory in Albuquerque NM for nearly two years so it was important to verify its operability.

The THPM has an annular solid tungsten sheath serving as the emitter and a cylindrical molybdenum-sodium heat pipe operating as the collector. A total of 24 power takeoff leads are connected to the two seal flanges with an equal number dedicated to each of the emitter and collector sides of the converter. A metal-to-ceramic seal using a kovar cup is employed on the power takeoff flange using a single crystal sapphire and a tungsten metalizing surface. To protect this seal, the temperature of the emitter flange must not exceed 1123 K. Nominal operating temperature of the emitter will be 1925 K with the collector heat pipe operating at about 1000 K.

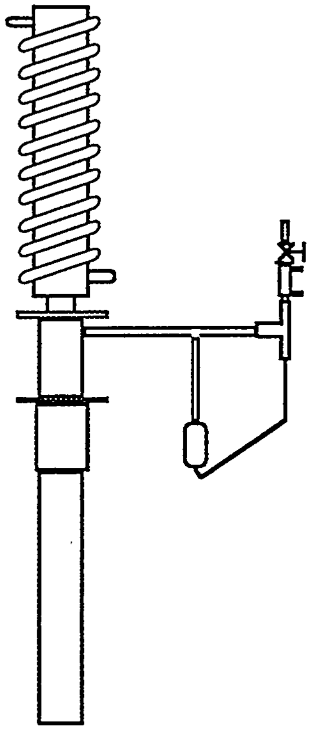

Figure 1. THPM 1127-C.

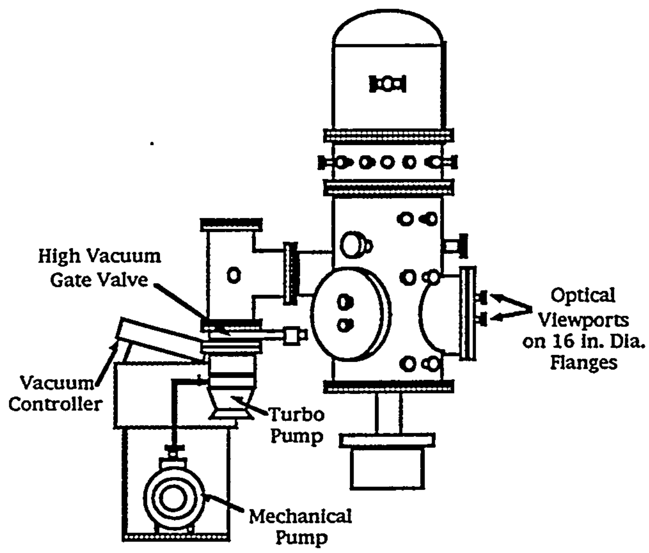

Figure 2. HHTF vacuum vessel.

HHTF Vacuum Vessel

Figure 2 shows the HHTF vacuum vessel (referred to as simply the "vessel") is a double walled, water cooled cylinder of three separate pieces; a main vessel chamber, a "bell-jar" collar, and an upper hemispherical dome. Together, they provide an overall vessel length of 1.60 m and an internal diameter of 0.46 m.

The main vessel chamber provides the primary test space and is designed to provide site specific access to key test equipment such as the main heater power feedthroughs, THPM power take-off feedthroughs, clamshell and calorimeter cooling water feedthroughs, etc. Three large ports provide the main access into the vessel proper. Mounted on the flange blanks that attach to these ports are two optical view ports with quartz windows and mechanical shutter assemblies. These shutters allow the quartz windows to be shielded from direct shine from the hot zone when the window is not in use. The location of the view ports differ on each flange so that a wide range of axial positions can be accessed. Further, the flanges can be rotated to allow additional variations in viewport locations. In all, a total of 22 access ports are accommodated on the main vessel chamber itself besides the 8-inch diameter vacuum pump connection port and tee assembly. The bell-jar collar provides added instrumentation and diagnostic capability by providing 12 generic instrumentation access ports.

The upper hemispherical dome is a 0.56-m high dome added specifically to accommodate testing of the full length THPMs. This dome has only a single penetration which supports a multiport "tee" assembly for housing both a low vacuum thermocouple (TC) gauge and a high vacuum nude ion gauge. If necessary, it can also accommodate one or two temperature sensor probes for monitoring the condenser region of the full length test article.

HHTF Hot Zone Assembly

The HHTF hot zone (see Figure 3) consists of the THPM thermionic diode and the heat pipe evaporator for the THPM and integral test phases, the graphite sleeve for the graphite and integral phases, the tungsten mesh heater elements, the heat shields, the insulated support, and the clamshell. The hot zone is designed to simulate the high temperature (2000 K) environment that the THPM is expected to experience under normal operation while transferring energy to the test article.

The heater element consists of three strips of tungsten wire mesh each of which is attached to individual tungsten ring segments at the top that serves as the electrical input lead. The three tungsten mesh strips form a segmented cylinder with each strip attached to a single solid tungsten ring at the bottom. The geometry of the heater element is equivalent to a balanced 3-phase (3ϕ) "wye" electrical circuit. A heat shield package consisting of several concentric cylinders of 4 mil tungsten foil provides insulation against radiant heat loss from the hot zone. Additional shielding is provided by top and bottom shield assemblies that consist of several layers of tungsten foil stacked one atop another and separated by thin tungsten strips. The heater element and cylindrical shield assembly sit inside a water cooled copper clamshell which serves to reduce vessel wall heat loads and provide a platform for mounting and securing instrumentation such as thermocouples and fiber optic temperature sensors.

The heater element is powered by a 60 KVA, 3ϕ AC power supply. The power supply is feedback controlled on power using a digital PID controller. Diagnostics for the tungsten heater include a current sensing transformer on each leg of the 3ϕ circuit, three current transducers, and a 3ϕ watt meter which provides a 0-10 VDC signal proportional to the true three-phase power in the circuit. This signal is supplied to the PID controller which maintains power at a desired set point.

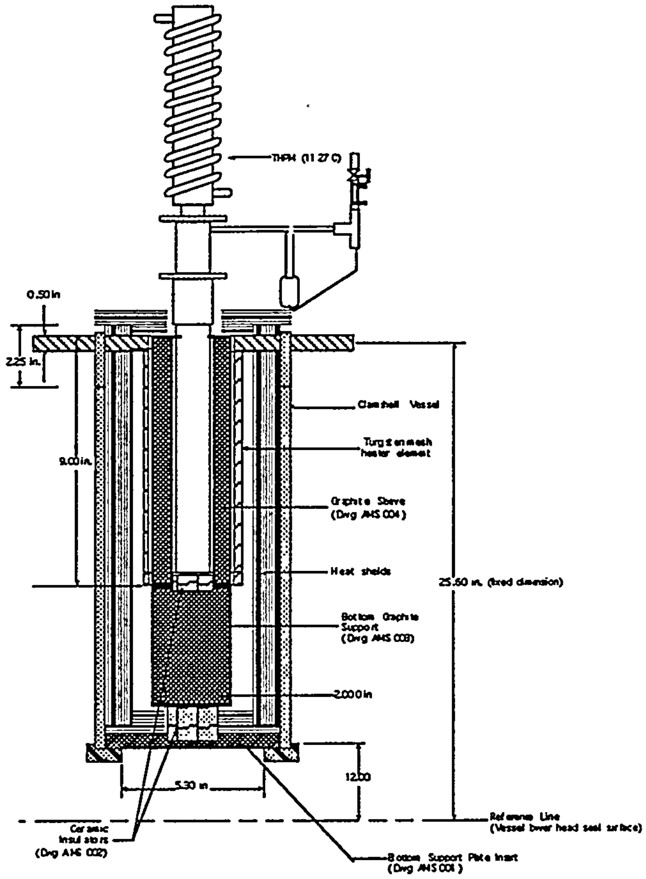

Figure 3. HHTF hot zone assembly.

Vacuum System and Controllers

The vessel is brought to a high vacuum (10^{-6} torr) using a 1000 liter/s turbo molecular pump backed by a double stage mechanical roughing pump. The turbo-pump is operated through a controller that automatically handles startup and shutdown sequences and steady operation of the fore-pump, vent valve, and turbo-pump. Automatic fault detection and shutdown are accommodated for several conditions such as overpower and over-temperature of the pump. In addition to the turbo-pump controller, a vacuum gauge controller is used to control two high vacuum ion gauges and up to four thermocouple gauges. The gauge controller has also been equipped with a remote I/O board to allow for remote operation of the gauge controller via an RS-232 interface.

RDIT Graphite Sleeve

A graphite sleeve, coated with rhenium metal to eliminate carbon vaporization which would contaminate the test apparatus (e.g. heaters), was placed over the THPM and provided thermal mass to the system in order to investigate the "performance" of a receiver/diode subsystem. Special features were incorporated into the sleeve design to act as standoffs to ensure that the sleeve did not come in contact with either the THPM or the heaters. The sleeve was be fabricated from Grade AFX-5Q graphite in two segments to facilitate coating of the sleeve's inside surface with rhenium powder (see Figure 4).

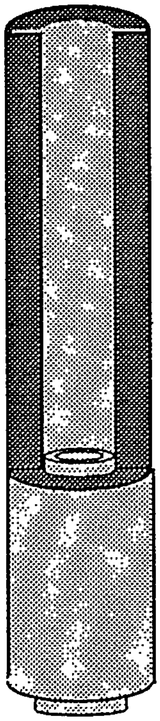

Figure 4.

The graphite sleeve was instrumented with thermocouples to provide the temperature profile data for the test program. In addition, a holes were drilled through the graphite substrate to allow access to the THPM for optical pyrometry and temperature measurements with TCs.

Instrumentation and Control Equipment

The instrumentation and control of the experiment was incorporated into the overall design of the test platform and utilized many of the components and equipment already described. Control of the main heater was via a PID controller mounted on a control panel with total power serving as the control point. The design and use of the control panel allowed for remote operation of the test apparatus thereby reducing the risk to project.

The THPM emitter and the heater element temperatures were measured with optical pyrometers and were controlled by adjusting the power to the heater. The graphite sleeve temperature was measured with embedded thermocouples.

The water-cooled clamshell provided a calorimetric measurement of the heat losses from the hot zone.

The THPM condenser was surrounded by a gas gap and a water-cooled jacket. The condenser temperature was measured by a light pipe optical pyrometer and this temperature was fed to a helium/argon gas mixture controller to control the temperature of the condenser. The water-cooled jacket provided a calorimetric measurement of the power transferred out of the condenser.

The emitter-to-collector interelectrode gap cesium vapor pressure was controlled by the temperature of the cesium reservoir. The temperatures of the reservoir and the tubing from the reservoir to the THPM were controlled with temperature controlled electric heaters. The temperature of the tubing above the junction of the reservoir and the THPM was controlled by water cooling and an electrical heater. The cooling condensed the cesium vapor and the liquid flowed back to the reservoir.

The THPM electrical power was determined by measuring the emitter-to-collector voltage across the THPM and the current to an active load. The active load was a high current, low voltage power supply and the loop current was controlled by adjusting the power supply voltage.

Several interlock circuits were incorporated into the design of the test assembly. The main heater power supplies are interlocked on selected water flows including flow to the water cooled clamshell, the heat exchanger, and the THPM calorimeter. Should a loss of flow occur to any of these systems, power was shut off and the system was brought to a safe state. Additional interlocks existed for protection from such things as over-temperature or over-power conditions on the heaters or power supplies, and over pressure on the vessel or vacuum pump. As a final option, power to the heaters and test article could be manually shut down using a large red panic button located on the control panel.

Temperature measurements were taken using a variety of low and high temperature sensors representing both direct contact and non-intrusive methods. For all low temperature measurements, Type-K (chromel/alumel) thermocouples were used. Where electrical insulation and/or RF noise reduction was necessary, ungrounded, sheathed Type-K TCs were used. Similarly, measurements inside the hot zone, where operating temperatures reached 2500 K, were made using ungrounded sheathed thermocouples (tungsten/rhenium Type-C thermocouples sheathed in molybdenum or tungsten with either a hafnium oxide, HfO, or beryllium oxide, BeO, insulator).

Three different optical sensors were used to obtain both direct-contact and remote temperature measurements; i.e. blackbody, lightpipe, and optical pyrometry sensors. The three optical pyrometers all had a two-foot focal length and were therefore placed outside of the vessel.

Acquisition System Data

The data acquisition system at the HHTF includes three major components: the fiber optic temperature measurement system (described above), a data acquisition and control unit (Hewlett-Packard 3852A), and a system controller computer system (Apple Macintosh Quadra 700). These components are linked via an IEEE-488 bus. Data acquisition and analysis was implemented using *Labview* software. This software provides an object-oriented programming environment in which customized data acquisition and analysis "virtual instruments" can be created as needed.

The HP 3852A data acquisition and control unit is modular and can accommodate up to eight boards. Presently it is configured with four 20-channel multiplexer boards, two digital voltmeters, and two analog signal output boards. This configuration allows for up to eighty input channels representing signals from the various thermocouples, pressure transducers, flow meters and other diagnostic devices. The analog output boards provide the capability for remote control from the computer of any device that accepts a 0-10 VDC or a 4-20 mA control signal.

EXPERIMENTAL RESULTS

The first step in quantifying the heat switching capability of a thermionic diode was to establish the performance of the diode (i.e. THPM) without a thermal storage component (i.e. graphite sleeve). To accomplish this, an extensive THPM performance mapping test program was undertaken to determine the thermal response of the THPM emitter and collector heat pipe (shown in Figure 1) as well as the electrical response of the converter. The emitter is designed to present as nearly as possible an isothermal surface to the collector during normal operations when the device is producing electricity. Overall efficiency is degraded if the collector surface "sees" an emitter surface with a non-uniform temperature profile. Under normal operations, the emitter experiences a relatively small thermal gradient over the length of the core, i.e. 100-200 K.

Testing was initially performed under conditions of vacuum to examine the thermionic converter performance under varying thermal load conditions. The temperature and electrical measurements of the THPM and associated hardware were monitored as were the applied heater power and thermal energy removal by the clamshell calorimeter, the emitter calorimeter and in-vessel cooling systems to determine overall energy throughput of the system. Characteristic current density versus voltage (J-V) curves of the converter were generated at several cesium vapor pressures while maintaining constant emitter and collector temperatures. Once a baseline performance map was established at nominal emitter and collector temperatures, similar maps were generated for alternate combinations of emitter and collector temperatures. The following range of parameters was investigated for this test phase:

Emitter Temperature	1825-2025 K
Collector Temperature	900-1100 K,
Cesium Reservoir Temperature	550-630 K.

Once the THPM's maximum power had been determined and established, the heater power was turned off and the resulting power decay of the THPM was recorded. Finally, the THPM was electrically shutdown at power (i.e. "an open circuit") and the resulting energy balance compared to the maximum power of the THPM. These two latter conditions allowed the direct comparison with the data that was gathered in the second phase of the RDIT Program. Sample results from the THPM performance mapping activity are shown in Figures 5 and 6.

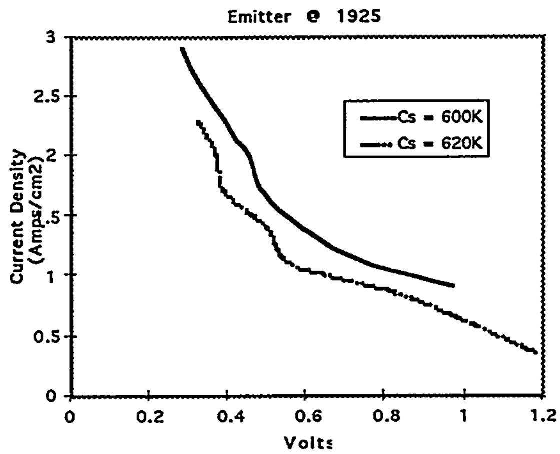

Figure 5

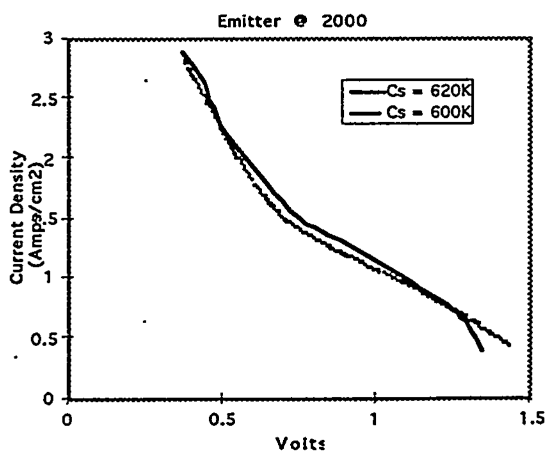

Figure 6.

RDIT Program

Upon completion of the THPM performance mapping, the receiver diode integration testing will begin. The RDIT Program itself is divided into two distinct phases. Following removal of THPM 1127-C, the graphite sleeve (coated with rhenium) will be placed in the HHTF vacuum vessel and heated to approximately 2000 K. The heater power will be turned off and the cooldown characteristics of the graphite recorded. This thermal cycling will be repeated several times. Following this thermal cycling the sleeve will be removed from the vessel and visually inspected for damage to the rhenium coating and/or graphite substrate.

The second phase of the test program entails evaluation of the response of a THPM (i.e. diode) in the presence of the graphite sleeve (i.e. receiver). In this phase, after installation of the THPM inside the graphite sleeve, the systems will again be heated to an equilibrium temperature of approximately 2000 K. The heater power will be turned off and the performance of the THPM in the presence of the graphite sleeve recorded and evaluated. Then, the THPM will be electrically shutdown at power and the resulting energy balance compared to the maximum power of the THPM, this time in the presence of high thermal mass. Power (of the converter) versus temperature (of the graphite) curves will be generated at several conditions to determine the transient behavior of thermal storage as a function of energy throughput in the THPM. Once a baseline performance map has been established at nominal cesium vapor pressure and emitter and collector temperatures, similar maps will be generated for alternate combinations of cesium vapor pressure and emitter and collector temperatures. The proposed range of test parameters are identical to those specified for the THPM performance mapping.

SUMMARY

Several tests of the electrical capabilities of the THPM have been completed. Initial review of the test data indicates the electrical power generation is close to the design criteria for the THPM. In addition, the results appear to track well with the calculated ability to "switch" off the heat transfer by open circuiting the THPM. This capability will be quantified further as additional tests are performed. The next step is to perform intergrated testing of the THPM and a thermal storage component. A graphite sleeve, designed to fit around the emitter of the THPM has been fabricated. This sleeve will be coated with rhenium prior to undergoing thermal testing and performance testing with the THPM. It is expected the performance of the THPM will not be effected by the presence of the thermal storage component. Also, the heat switching capability should not experience any significant effects with the integration of the diode and receiver components. Based upon the results to date, the integrated testing will begin in late May and conclude by mid June.

ACKNOWLEDGMENTS

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REFERENCES

Kennedy, F. and Jacox, M., 1995, "The Integrated Solar Upper Stage (ISUS) Program," AIAA 95-3628 to be published in 1995 AIAA Space Programs and Exhibits.

Miller, B. and Rochow, R., 1995 "Design and Fabrication of a High Temperature Solar Receiver Cavity," 95-AT0398 to be published in the 1995 IECEC.