SAND98-2255C

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OCT 19 1998

START-3: Operational Evaluations Of The ISUS Engine Ground Demonstration Thermionic Power System

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Abstract. START-3 was a test program conducted in order to demonstrate and characterize the operational performance of the prototype Integrated Solar Upper Stage (ISUS) thermionic power system. The test device consisted of a graphite thermal storage unit, multilayer foil insulation, and sixteen thermionic converters electrically connected in a series array. Several thermal input conditions were achieved during the test, which resulted in measuring converter performance at average converter hot shoe temperatures in the range of 1600 K to 2000 K. Results indicate that the thermionic converters did not perform as well as expected in the array configuration. Follow-on testing of the individual sixteen converters is currently being performed.

INTRODUCTION

An operational demonstration and performance characterization test of sixteen prototype thermionic converters was undertaken in mid-1998 as part of the Air Force Research Laboratory (formerly Phillips Laboratory)-sponsored Integrated Solar Upper Stage (ISUS) development program. The START-3 test took place at the Baikal Test Stand, located at the University of New Mexico's Energy Conversion Research Lab at the New Mexico Engineering Research Institute (NMERI) in Albuquerque, NM. The Defense Special Weapons Agency, as part of their Advanced Thermionics Program, also supported this assessment test. This test was a follow-on test to the Engine Ground Demonstration (EGD) test conducted in 1997 at the National Aeronautics and Space Administration (NASA) Lewis Research Center where the performance capability of the propulsion unit was investigated (Kudija, 1998).

The principal objective of the START-3 test was to demonstrate and characterize the operational performance of the ISUS EGD thermionic power system at several emitter temperatures. The thermionic converter array was tested under vacuum ($\sim 10^{-6}$ torr) and heated using a tungsten electric filament. Voltage-ampere (I-V) sweep measurements provided the basis of performance evaluations for the array and individual converters. A secondary objective of the test was to develop a predictive operational performance model of the ISUS thermionic power system. Other EGD system design features were also evaluated during the course of this test. Data generated from this test are being made available for use by the Solar Orbital Transfer Vehicle space experiment design team.

TEST DEVICE

The START-3 test device consists of a graphite thermal storage receiver/absorber/converter (RAC), a multilayer foil thermal insulation package (MLI), and the EGD thermionic converter array. The RAC is made from machined graphite blocks (POCO grade TM-I) encased in a 1-mm thick rhenium shell. The RAC serves two purposes for the ISUS system: it acts as the primary heat exchanger for the gaseous propellant (H_2) to provide propulsive thrust for

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orbit maneuvering, and it acts as the heat source for the thermionic power conversion system. The MLI package is composed of refractory metal foils (tungsten and molybdenum) that completely surround the graphite thermal storage unit. The purpose of the MLI is to limit the amount of heat loss from the RAC. The MLI has a movable section that serves as a window to radiatively couple the thermionic converter array hot shoes to the thermal mass's outer surface. During the assembly of the converters this movable section was opened fully to the surrounding support structure and remained open throughout the duration of the test.

The thermionic converter array provides electric power by the direct conversion of heat to electricity. The array consists of sixteen thermionic diodes mounted with their hot shoes facing the RAC outer surface and connected in electrical series (to increase the total array voltage output). Each diode is supported and held in position by a support/clamp block assembly.

Thermal power to the test device was accomplished by using an electric heater. The heater is made of tungsten mesh and is approximately 3 inches in diameter and 7 inches high. Room temperature electrical resistance is approximately one milliohm. The heater is powered by 208 Vac, 50 Hz European power from an uninterruptible power supply with a backup diesel generator that is located at the NMERI facility. Power was supplied to the heater through power feedthroughs located on the vacuum chamber.

TEST APPROACH

Test operations began on May 5, 1998. However, the initial operation of the START-3 test device demonstrated that the desired emitter temperatures could not be achieved even though the electric heater was operating at its temperature limit. At nearly the same time, the primary vacuum chamber pressure gauge began to behave erratically, spiking above the set pressure limit, 5×10^{-5} torr, without apparent cause. Also, visual inspection of the test device indicated possible damage occurring to the ceramic insulators located on the heater's electrodes. Consequently, the system was shut down and cooled to investigate these problems. This initial thermal operation of the START-3 test, with the RAC installed, is designated as Run #1.

A detailed inspection of the test device was undertaken and completed within a few days after the vacuum chamber was opened. In general, a coating of black and gray-blue material covered much of the flat, horizontal surfaces of the test device and its support structure. Significant damage to the heater electrodes and the insulators was discovered. The vacuum chamber pressure sensor was disassembled and found contaminated with carbon compounds. Additionally, the RAC was tilted out of vertical alignment because the rhenium pins supporting it at the bottom had bent during the test.

The operational problems encountered during Run #1 and the findings from the inspection activities were presented to project managers, and a decision was made to continue with the START-3 test, but without the RAC installed. This meant the thermionic converter hot shoes would be absorbing heat by direct radiation from the electric heater. Following the completion of necessary modifications, the test device was reassembled and the second thermal operation of the START-3 test was initiated. This second operation of the unit, without the RAC, is designated as Run #2. The priority for the model development effort was increased at this time which changed the purpose of the test to provide the operational data necessary to support the model.

Figure 1 shows the average emitter temperature plot obtained during Run #2. As shown in the figure, this run can be identified as a series of six separate operational stages: (1) Heat Up Ramp, (2) Phase-1 Baseline Operations, (3) Special Data Collection Runs, (4) Phase-2 Long-Term Operations, (5) Comparative Data Collection Runs, and (6) Shutdown Ramp.

At an average emitter temperature of 2000 K, the diode 4 insulator seal temperature (brazed metal-to-ceramic electrical insulator) reached its alarm set-point (1100 K) during the heat up ramp. Power was reduced until the alarm cleared, at an average emitter temperature of 1980 K. Based on this situation, 1980 K was established as the

FIGURE 1. Average emitter temperature versus time obtained during START-3, Run #2.

maximum average emitter temperature allowed for the duration of the test. In addition, an indication of a short to ground required that a bypass jumper be installed from the collector of diode 13 (also the emitter of diode 12) to ground in order to establish a fixed ground at that point in the array. This action effectively took diodes 9 through 12 out of the thermionic power circuit.

The START-3 Phase-1 operations consisted of a series of hold points at discrete average emitter temperatures for the purpose of obtaining baseline diode and array performance data. The first of these hold plateaus was a 12-hour hold at the (newly defined) peak temperature of 1980 K. During this hold, dynamic I-V sweeps of the array and peak output power determinations were performed every four hours. Following the initial hold point, heater power was decreased to lower the average emitter temperature to 1700 K at a 100 K/h rate. A four-hour hold was conducted at this temperature and the same I-V and peak output power measurements were conducted. Additional four-hour hold points occurred at 1800, 1900, 1800, 1900, 1800, and 1700 K, in order. Again, at each plateau, a series of I-V sweeps and peak power determinations were made.

Additions were made to the measurements taken at each hold point for the purpose of collecting the special data requested by the model development team. Specifically, diode voltage-to-ground readings were logged for each emitter and collector, and static I-V sweeps were conducted using a constant current source. This new data gathering continued throughout the remaining time of the START-3 test. Initially, data were gathered at the starting condition of 1980 K average emitter temperature, and again at temperature plateaus of 1900, 1800, 1700, and 1600 K.

The period of the Phase-2 long-term hold covered a little more than six days. It began with the ramp to the average emitter temperature of 1980 K followed by the long-term hold operations. Heater power was not adjusted once the average emitter temperatures had stabilized at 1980 K. The same measurements required for the special data collection stage of the test were conducted once per eight-hour shift during this period. Over the course of this operation, the thermionic converters showed marked degradation in their performance. Eventually, all but diodes 4, 5, 13, and 14 were bypassed, effectively taking them out of the array circuit. The string power decreased by ~25% over the six-day hold.

Following the Phase-2 hold operation, heater power was again reduced to lower the average emitter temperature in 100 K increments and collect the same data at each temperature plateau, as was done during the special data

collection stage. The final shutdown was accomplished by reducing power to the electric heater from 25 kW to zero within 30 seconds. The rate at which the average emitter temperature decreased began at rates in excess of -8000 K/h and, because the RAC was not installed in the test device, the average emitter temperature dropped from 1980 K to near ambient conditions (333 K) in approximately four hours.

RESULTS

The performance of the diodes degraded significantly over the short duration of this test. After nine days, diodes 2, 6, 15, and 16 had ceased to produce power. Diode 1 was only producing power below about 12 A (see Figure 2), and the performance of diodes 7, 8, 3, and 5 had degraded by as much as 72% based on dynamic I-V sweep results. The only diodes that still performed as they did at the beginning were diodes 4, 13, and 14. The output power from the array decreased from 170 W at the beginning of Run #2 to 58 W nine days later (Figure 3). At the end of Run #2, at 394 hours into the test, the peak power from the array at 1980 K was 53 W. At 1900 K, the peak power from the array decreased from 116 W at 70 hours to 30 W at 289 hours.

The basis of this evaluation is the results obtained from the dynamic I-V sweep diagnostics, wherein a continuous sinusoidal wave form is superimposed on the array's dc output and plotted in the form of system output current versus the simultaneous voltage measured across the full array or individual diodes. The open circuit voltage (voltage output at zero current) of a thermionic converter is determined by the difference in the emitter and collector work functions, while the I-V curve strongly depends on the cesium pressure. As the cesium vapor pressure in a thermionic converter decreases, a higher voltage (shown as more negative in the dynamic I-V curves) is required to drive a given current. While the I-V characteristics of the failing diodes become worse over time, the open circuit voltage remains approximately the same. Therefore the cause of the failure of diodes 1, 2, 6, 15, and 16 appears to be loss of cesium pressure. Although there is still some cesium and the diodes can produce power in the unignited mode at low current, at high current the voltage across the failed diodes is negative. Therefore, at a relatively high operating current (above about 10 A), these diodes actually reduce the output power from the array. Jumpering out one failed diode increased the total output power from 58.6 W to 69.7 W, an increase of 19 %.

FIGURE 2. Comparison of I-V sweep results for diode 1 at 70 and 289 hours into Run #2.

FIGURE 3. Comparison of array output power measured at 70 and 289 hours into Run #2.

Another result of the START-3 test was the development of a predictive model to determine the effect of jumpering out bad diodes. A commercial circuit analysis code called PSpice™ was used. The model includes the interconnect straps between the diodes and any jumpers that may be present. The model was able to correctly calculate the increased output from the array as a result of jumpering out a bad diode. The test case for the model was diode 16, which had failed, and was modeled as either being in the circuit or jumpered out. The model calculation is shown in Figure 4 compared to the experimental data.

FIGURE 4. Comparison of model results to measured data.

CONCLUSIONS

The START-3 performance evaluation test of the prototype ISUS thermionic power system afforded the opportunity to assess its true capability under operating conditions closely approximating the design conditions of the ISUS flight system. In addition, an ISUS thermionic converter power system model was developed based on the data collected during test operations.

The measured performance of the sixteen-converter thermionic array was far below expectations—170 watts versus the 230 watts expected at 1980 K—and continued to decrease as the test progressed. It appears that loss of cesium from several of the diodes was the main contributing factor in this result. The reasons for the loss of cesium vapor from the affected converters is not understood at this time, since the peak operating point was limited to 1980 K in order to keep the insulator seal temperatures below the 1100 K seal braze flow temperature. Diode 6 exhibited very large negative voltages virtually from the beginning of the test operations. Other diodes, 10, 2, 16, 15, and 1, in order, also required bypassing during the course of the test.

Follow-on tests of the individual thermionic converters is presently under way. These individual diode tests are being performed to provide a comparison of each converter's performance to their pretest characteristic data set.

ACKNOWLEDGMENTS

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

The work presented in this paper was conducted under the joint sponsorship of the U.S. Air Force Research Laboratory and the U.S. Defense Special Weapons Agency. The authors would like to thank the members of the ISUS team at Lockheed Martin Electro-Optical Systems, in Pomona, CA; NASA Lewis Research Center, in Cleveland, OH; and the ISUS Program Office at Kirtland Air Force Base, Albuquerque, NM for the exceptional support they provided during this test.

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