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RE-START: THE SECOND OPERATIONAL TEST OF THE STRING THERMIONIC ASSEMBLY RESEARCH TESTBED

CONF-980103--

Francis J. Wyant
Sandia National Laboratories
MS 0744
P.O. Box 5800
Albuquerque, NM 87185-0744
(505) 846-8889

David Luchau
TEAM Specialty Services, Incorporated
11030 Cochiti SE
Albuquerque, NM 87123
(505) 291-0182

T. D. McCarson
New Mexico Engineering Research Institute
901 University Blvd. SE
Albuquerque, NM 87106
(505) 272-7403

Abstract

The second operational test of the String Thermionic Assembly Research Testbed—Re-START—was carried out from June 9 to June 14, 1997. This test series was designed to help qualify and validate the designs and test methods proposed for the Integrated Solar Upper Stage (ISUS) power converters for use during critical evaluations of the complete ISUS bimodal system during the Engine Ground Demonstration (EGD). The test article consisted of eight ISUS prototype thermionic converter diodes electrically connected in series. Results demonstrated the high-temperature structural performance of the reengineered diode mounting assembly, measurable degradation in electrical performance of seven of the test diodes, and the susceptibility of the diode array to load conditions during fast heatup ramps.

INTRODUCTION

An initial test of the prototype Integrated Solar Upper Stage (ISUS) diode array was conducted from March 10 through March 29, 1997 (Boonstra 1997). The intent of this test, "START," was to measure the performance and conversion efficiency of the 8-diode array thermally coupled to an electrically heated graphite block (receiver), simulate the sun-eclipse cycle and monitor the array's electrical performance during the "shadowed" periods, and characterize the electrode and plasma properties of the individual diodes under nominal operating conditions. Insofar as multiple problems, principally electrical shorting to ground and between adjacent diodes, plagued the performance of START, limited value was placed on its outcome. The problems uncovered did, however, lead to the redesign of the diode support structure and several recommendations regarding other changes to the test setup.

Driven by the need to evaluate the effectiveness of the new diode support structure prior to the system-level Engine Ground Demonstration (EGD) test, Phillips Laboratory and the Defense Special Weapons Agency jointly decided to perform a second test on the ISUS bimodal system prototype diode array. The objectives of this second test, called "Re-START," were to evaluate the structural integrity of the reengineered diode mounting assembly at high temperatures, measure the output power and current-voltage (I-V) response of the diodes under a variety of thermal and electrical transient conditions, and provide an operational database for use in the development of the ISUS power management and distribution (PMAD) system (Baez 1997).

Both the START and Re-START tests took place at the Baikal test stand located at the New Mexico Engineering Research Institute (NMERI) OTV Laboratory in Albuquerque, New Mexico (Wold 1993).

TEST ARTICLE

The Re-START test article consisted of seven prototype diodes (James 1997) previously tested during the START test and one diode provided by Lockheed Martin Electro-Optical Systems (LM EOS) to replace the eighth diode, which had failed during START. The replacement diode was one that had previously undergone ~1200 hours of life testing at LM EOS. The array was electrically connected in the same order as was employed during the START test (i.e., the number 1 diode for START was the number 1 diode for Re-START). The eight-diode

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array was tied to ground between the fourth and fifth diodes, thus limiting the difference in potential above and below the structure at the output electrodes to that generated by four diodes in series.

Changes made to conduct Re-START were:

1. The graphite receiver assembly was not used; instead the array diode emitters were heated by direct radiation from the electric heater (this is the operational configuration for START test run 3).
2. A new diode mounting assembly was installed. This structural member was reengineered to prevent movement of the diodes at operational temperatures.
3. The zirconium-oxide felt insulation material was replaced with hard-fired ceramic insulators.
4. The array diode thermocouples were replaced by sheathed, ungrounded thermocouple probes as previously recommended, and additional thermocouples were installed to measure temperatures at three locations on the new diode mounting assembly.
5. Diode electrical interconnections were routed external to the Baikal stand vacuum chamber for ease in reconfiguring the diode array circuit. In this way, vacuum chamber integrity did not need to be compromised in order to bypass one or more of the diodes in the array.
6. A different diode of the same design was employed as a replacement for No. 8 in the original START array.

The new diode mounting assembly (Fig. 1) consists of eight saddle blocks mounted on a single mounting ring segment. One saddle block supports one diode with alumina insulator segments (four per diode) arranged within the grooves machined in the saddle support and the clamp block upper section. The insulator segments fit within the grooved segment around the diode collector-heat pipe interface flange. Additional alumina insulating material was inserted between the diodes and multifoil insulation to prevent shorting to ground. Alumina ceramic insulation was also inserted between adjacent diode hot shoes to prevent interdiode shorting during operation.

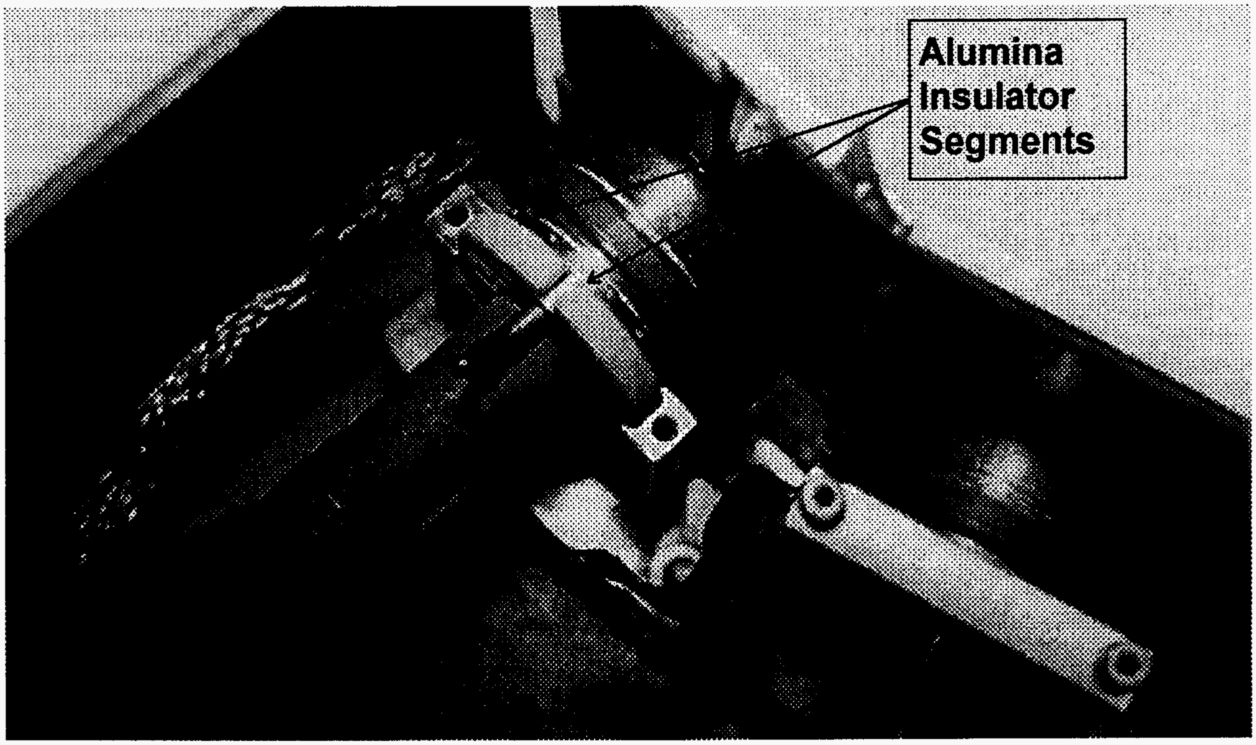

FIGURE 1. Diode Mounting Assembly Ceramic Insulator Segments.

TEST APPROACH

The START diode array was tested on the basis of average emitter temperature of the array. The overall Re-START test emitter temperature profile is shown in Fig. 2. As indicated in the figure, the test was divided into four phases. Each phase was defined primarily by the rate at which the average emitter temperature of the array was changed.

Diode operating temperatures ranged between 1600 and 2100 K during the course of the test. Thermal transients included heatup rates of 100, 300, and 500 K/h. Cooldown rates included minus 300, minus 500, and minus 2000 K/h. Electrical transients were induced by the changing thermal conditions and by manual adjustments of the external resistive load on the array. Dynamic I-V sweep measurements were made on the array and individual diodes at each temperature plateau.

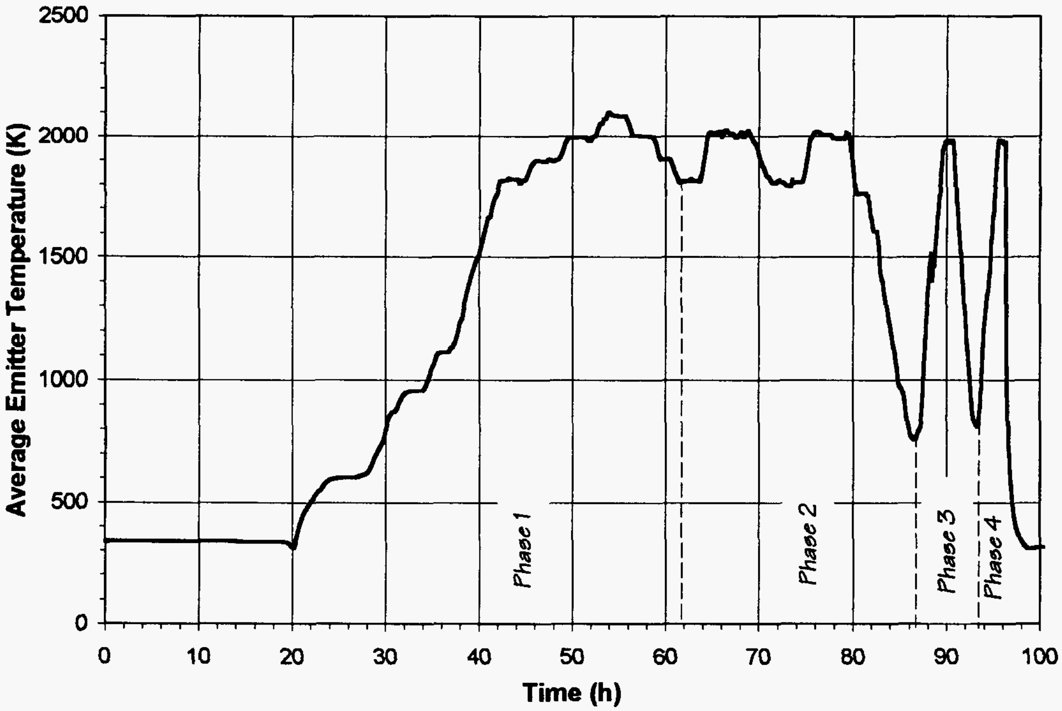

FIGURE 2. Re-START Test Profile.

Phase 1: Initial Heatup and Baseline Data

The nominal average emitter temperature transients of the array occurred at ~100 K/h. Beginning at 1800 K, the emitter temperatures were progressively increased in 100-K steps from 1800 to 2100 K, and back down to 1800 K, with a hold plateau at each step. At each plateau, a dynamic I-V sweep was conducted and the peak array power level was found and maintained during the remainder of the hold time by adjusting the external load resistance.

Phase 2: Thermal and Electrical Transient Data

The nominal average emitter temperature transients of the array occurred at 300 K/h during Phase 2 operations. A number of emitter temperature cycles were run to obtain data on the array's response to thermal transients within the limited operating range of the diodes (18002000 K). Current-voltage sweeps and load bank transients were conducted at each of the steady-state plateaus in this phase, and the peak array power level was reached and maintained during the remainder of the hold time by adjusting the load resistance. At the end of the Phase 2 cycles, the load bank resistance was set to its minimum value (~44 mΩ), and the average emitter temperature of the array was decreased to 800 K at a nominal rate of minus 300 K/h.

Phase 3: Fast Heatup with Minimum Load

The initial conditions at the beginning of Phase 3 were that the average emitter temperature was ~800 K and the load bank was set to 44 mΩ (minimum value). The initial nominal heatup rate was slightly greater than 500 K/h. Power to the electric heater was manually decreased when diode 4 indicated a low-voltage condition (less than minus 2 V) at about 1500 K average emitter temperature (T_B). Heater power was decreased until the problem cleared; diode 4 was electrically bypassed and the heatup ramp continued. At T_B ~1600 K, the bypass shunt was removed from diode 4 and at T_B ~2000 K the heatup transient was completed. Another series of I-V sweeps was completed at the high-temperature plateau and the peak array power level was set and maintained during the remainder of the hold time by adjusting the load resistance accordingly. The load was again set at 44 mΩ prior to the start of the Phase 3 cooldown ramp.

Phase 4: Fast Heatup with Maximum Load

Phase 4 operations were very similar to those described for Phase 3, with the exception of setting the load to its maximum value (~900 mΩ) prior to initiating the 500-K/h heatup ramp and prior to the final rapid cooldown. No alarms were activated during the Phase 4 heatup transient. However, the voltage of diode 4 did go as low as minus 1.5 V at one point during the rampup. In addition, I-V sweeps and peak array power settings were accomplished at the temperature plateau, as usual. The final cooldown ramp was initiated by reducing power to the electric heater as quickly as possible. The resulting cooldown rate on the diodes approached minus 2000 K/h over the range 2000500 K.

RESULTS

A post-test evaluation of the structural performance of the redesigned diode support structure was performed, and the operational data were analyzed to assess the electrical performance of the START array and individual diodes.

Support Structure Performance

Overall, the redesigned diode mounting assembly performed very well throughout the Re-START test: All of the thermocouples attached to the diode mounting assembly structure stayed within specification (i.e., less than 1000°C) and no discernible distortion of any of the mounting hardware was found during post-test disassembly and inspection. Upon disassembly, the top of the diode mounting ring was found to be discolored between adjacent saddle blocks. The additional alumina pieces placed between the emitter flange and the multifoil insulation were also found to be discolored in the area near where the insulator was compressed between the diode emitter flange and multifoil insulation. The blue/black discoloration was on the side facing the multifoil insulation.

The alumina ceramic located between adjacent hot shoes, and the alumina tube insulators placed between the hot shoe multilayer insulation and the multifoil thermal insulation did not show any discoloration. All discoloration of the mounting assembly components and insulators was on the heat pipe side of the multifoil thermal barriers. It was also found that all 32 of the alumina insulator segments in the diode mounting assembly survived the test intact and without any discernible damage. No breaks, cracks, or chipping of these pieces were noted.

Diode Electrical Performance

In summary, the peak electrical performance of the START array was about half of its design value: 113 W measured during Re-START versus 250 W. Seven of the eight diodes in the string were determined to be degraded. Figures 3 and 4 show the dc I-V characteristics of the diodes at T_B ~1820 K and 2000 K, respectively. The reduction of electrical performance for three of the diodes (2, 3, and 4) appears to be due to a loss in the dielectric strength of the interelectrode insulators. The degraded performance of three other diodes (1, 6, and 7) is due to the interelectrode gap being too small (ionization rate in the interelectrode gap being small). The last diode that degraded (5) has indications that its loss of output is due to a decrease in dielectric strength and to a leakage of oxygen into the interelectrode gap. Finally, even though diode 8 does not show signs of degradation in its electrical output, it has indications that its dielectric strength decreases as T_E is increased. This decrease is possibly due to the extended length of operation of this diode. Therefore, there may be a lifetime issue in the dielectric strength of these diodes.

CONCLUSIONS

The results indicate that the diode mounting assembly maintained its structural integrity over the test temperature range. No indications of thermal stress or distortions were found upon disassembly and inspection following the test. Seven of the eight diodes in the array exhibited some degree of operational degradation in electrical performance, possibly due to internal shorting pathways between the emitter and collector. The eighth diode was one received from Lockheed Martin Electro-Optical Systems just prior to installing the array in the test chamber. Its output exceeded all of the other diodes by a significant amount, yet it also showed some degradation in dielectric strength as T_E increased.

Additional ceramic insulators placed between the grounded structure and the diode electrode components eliminated the electrical shorting problems encountered during the original START test. Use of sheathed ungrounded thermocouples also eliminated many of the diagnostic problems that plagued the START test; however, at least three of the new tungstenrhenium high-temperature thermocouples failed during Re-START.

The transient electrical response of one of the ISUS prototype diodes indicates that they may be susceptible to load conditions during fast heatups. Consequently, it is recommended that a resistive load commensurate with an output current of 1 - 5 A at design temperature be placed across the array prior to startup. It is also recommended that hot shoe heatup and cooldown rates be limited to no more than 300 K/h.

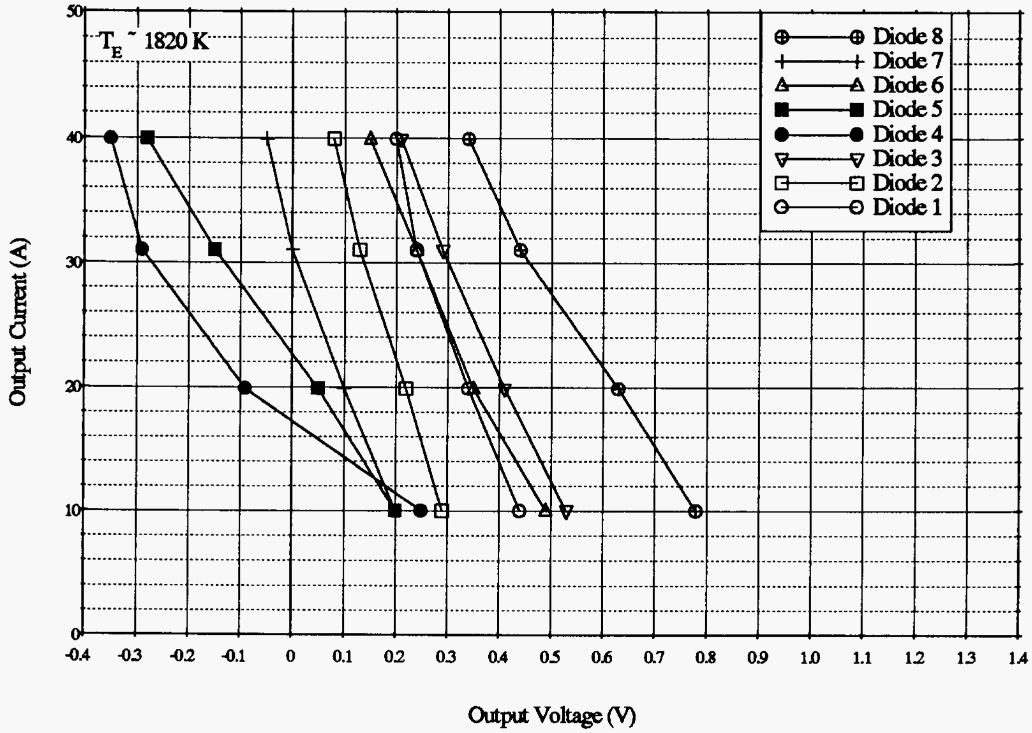

FIGURE 3. Direct Current I-V Characteristics of the Diodes in the Array at T_E ~1820 K.

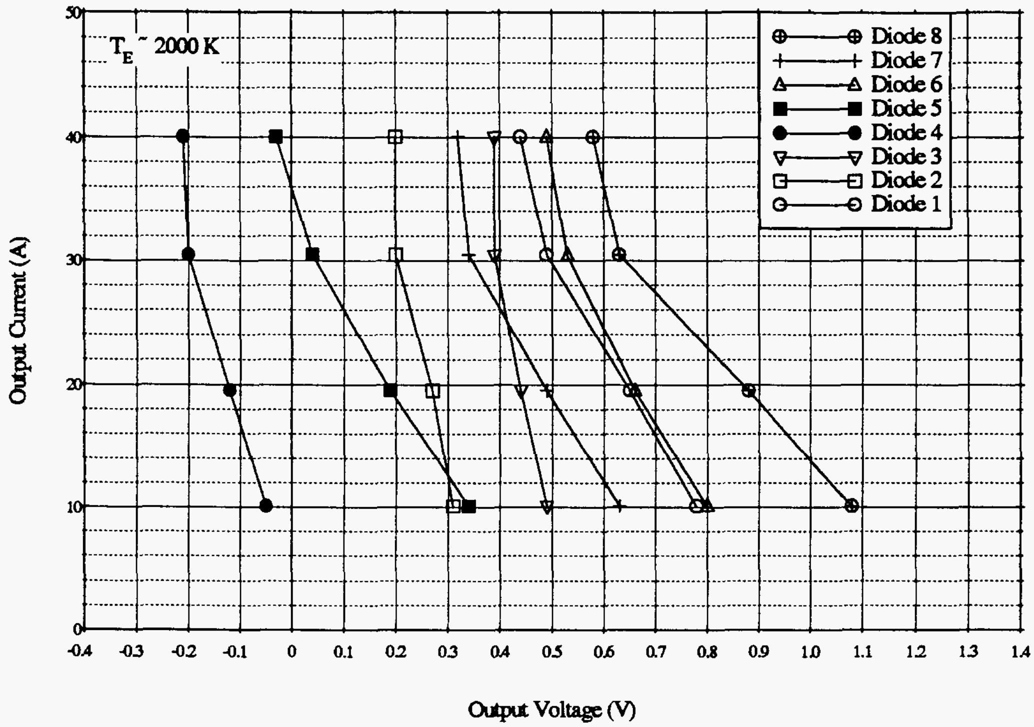

FIGURE 4. Direct Current I-V Characteristics of the Diodes in the Array at T_E ~2000 K.

Acknowledgments

The work presented in this paper was conducted under the joint sponsorship of the U.S. Air Force Phillips Laboratory and the U.S. Defense Special Weapons Agency. The authors would like to thank Dr. Bernard Wernsman, formerly with the New Mexico Engineering Research Institute, for his analysis of diode performance.

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M98002590

Report Number (14) SAND--98-0240C
CONF-980103--

Publ. Date (11) 199801
Sponsor Code (18) DOE/CR, XF
UC Category (19) UC-900, DOE/ER

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