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DESIGN AND TRANSIENT OPERATION

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ABSTRACT
An electrically heated thermionic converter has been designed, built and successfully tested in air (Horner et al., 1995). One of the unique features of this converter was an integral cesium reservoir thermally coupled to the emitter. The reservoir consisted of fifteen cesiated graphite pins located in pockets situated in the emitter lead with thermal coupling to the emitter, collector and the emitter terminal; there were no auxiliary electric heaters on the reservoir. Test results are described for conditions in which the input thermal power to the converter was ramped up and down between 50% and 100% of full power in times as short as 50 sec, with data acquisition occurring every 12 sec. During the ramps the emitter and collector temperature profiles, the reservoir temperature and the electric output into a fixed load resistor are reported. The converter responded promptly to the power ramps with no excessive overshoot and with no tendency to develop instabilities. This is the first demonstration of the performance of a cesium-graphite integral reservoir in a fast transient.

INTRODUCTION
During the Thermionic Fuel Element Verification Program (TFEVP), reservoirs employing Cs-graphite were built and tested for long periods in radiation environments (General Atomics, 1994). Commercially available POCO CZR-2 graphite, loaded with as much as 800 milligrams of cesium per gram of graphite, has been shown to be stable to neutron irradiations as high as $3 \times 10^{22}$ nvt. A number of TFE's equipped with Cs-graphite reservoirs were tested in the TRIGA reactor for times ranging up to 14,000 hours without problems. These reservoirs were equipped with electric heaters for temperature control. In the present converter there are no auxiliary electric heaters and the reservoir temperature is determined by the heat flow between the reservoir and the emitter, collector and the emitter terminal, with a second-order heat flow directly from the main heater leads within the emitter lead cavity. Thus, the reservoir in this converter is a true integral reservoir, unlike those employed in the TFEVP. An area of major concern was whether or not an integral reservoir made of Cs-graphite would respond rapidly enough to avoid developing cesium-pressure related instabilities during transient operation (Schock, 1968). To address this concern, a series of input power ramps between 50% and 100% of full thermal power in times of 500, 200, 100 and 50 sec. There was no indication of instability in the converter output during these tests, validating the design and materials of the integral reservoir.

EXPERIMENTAL SET-UP
Figure 1 is a schematic cross-section of the cylindrical converter which shows the location of the reservoir relative to the emitter and collector. The cylindrical tungsten filament that is located within the emitter cavity is also indicated in the figure. The thermal input to the inner wall of the emitter is provided by a combination of radiation and electron bombardment from this filament. Four emitter thermocouples are located within axial holes drilled into the emitter wall. The axial locations of the thermocouples are indicated by (A,B,C,D). Thermocouples in the collector wall are located at the same elevation as the emitter thermocouples (A,D). The azimuthal locations of both sets of thermocouples are shown in Figure 1. There are thermocouples at two azimuthal locations in the reservoir block and one in the emitter terminal. The input power to the filament is regulated by a power controller that responds to the sum of the power radiated to the emitter and the power delivered to it by electron bombardment. This controller is programmable and is the one that operates the system during scheduled power ramps. Figure 2 is an equivalent circuit of the heat flow paths within the converter that affect the reservoir temperature. The values of thermal resistance shown are only approximate, since the heat flow from the emitter to the reservoir and from the reservoir to the collector depend on the power passing across the interelectrode gap from the emitter to the collector. Radiation from the emitter to the collector was calculated using an emissivity of 0.18; the electron cooling and cesium conduction were calculated independently.
allowing the thermal resistances shown in Figure 2 to be calculated from the measured heat fluxes and temperatures.

Prior to performing the power ramps, the graphite reservoir was charged with cesium from a liquid reservoir for two hours at a pressure of 5.6 torr and a graphite reservoir temperature of 1000 K, which, from previous data, results in a loading near 800 mg Cs/g C. The valve to the liquid reservoir was closed before testing began. During the power-ramp tests the output of the converter was connected to a 1.6 mΩ load resistor. A forty-channel data acquisition system was scanned every 12 sec during the power ramps; these data were archived and are retrievable for analysis. In addition to the 11 thermocouples shown or indicated in Figure 1, there are 20 others located elsewhere on the converter, as well as several voltage and current measuring probes.

RESULTS

Figure 3 plots the input power (radiation plus bombardment), and electric power output during a 50 sec power-down and a 50 sec power-up between 50% and 100% of full input power. At the higher power level, 80% of the total input is electron bombardment while at the lower power level only 56% of the total is electron bombardment; the radiated power level is actually slightly lower at the higher power level. There is an overshoot in the output in both cases, but a steady state value is reached within 12 sec after the end of the input ramp. Figure 4 plots the emitter temperatures during the same two ramps shown in Figure 3 and overshoots in temperature are seen in the two top thermocouples, B and C. At full power the top of the emitter is normally cooler than the bottom, but for a short (12 sec) time after ramp-up its temperature rises to nearly that of the bottom of the emitter until heat transfer down the emitter stem cools it off. The inverse effect occurs during the ramp-down in input power. Figure 5 plots the collector temperatures and the temperature of one of the reservoir thermocouples. The temperature at the bottom of the collector (No. 2) lags considerably behind the others, and behind the power ramp as well, whereas the upper-most thermocouple (No. 4) responds rapidly. This is a consequence of the spike in the heat input to the top of the collector from the upper portion of the emitter that is produced by the emitter temperature spike. The reservoir temperature shows no unusual behavior. Previous studies (Ref. 2) have shown that the sensitivity of cesium-graphite compounds in the present range of cesium loading is close to 20 deg C per torr, which would indicate that the cesium pressure changes by about 3.5 torr during the ramps indicated in Figure 5.

DISCUSSION

At the beginning of a power ramp-up, the controller increases the input power to the filament and as a consequence of the heating of the filament, the (temperature limited) electron emission increases with a time lag of about 30 sec. There is a slight (30 watt) overshoot in the bombardment power after the filament power has been reduced. The bombardment power maximum corresponds very closely (in time) with the peak in the temperature of the upper part of the emitter and also in the electric output. Excursions in temperature and power are not observed in the 500 sec and 200 sec ramps, but are noticeable in the 100 sec ramp.

A finite element thermal analysis of the converter was performed during the design phase of the program. In addition to determining the steady-state temperatures and power flows, the performance of the converter during transient power ramps was calculated. For a ramp from 46% to 100% thermal input power occurring in 54 sec, it was found that the reservoir temperature leveled out about 100 sec after the end of the input ramp. This previous computational result is consistent with the present experimental result, however the latter also show that the converter output is stable during this time.

CONCLUSIONS

This converter with a truly integral reservoir, i.e. a reservoir with only passive heating from the emitter, consisting of cesiated POCO CZR-2 graphite, performs well during high-speed ramps of the input power. No tendency to become unstable was observed. These tests taken in conjunction with earlier component tests in the TF EVP show that Cs-graphite integral reservoirs are viable as a stable, long-term source of cesium in thermionic converters. This conclusion also applies to planar converter designs as well as in-core converters (e.g. TFEs).

REFERENCES


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FIGURE 1. SCHEMATIC LAYOUT OF THE CONVERTER SHOWING THERMOCOUPLE LOCATIONS.

FIGURE 2. LUMPED PARAMETER THERMAL CIRCUIT OF THE CESIUM RESERVOIR
50 sec Ramp Tests

FIGURE 3. POWER INPUT AND POWER OUTPUT DURING RAMPS
50 Sec. Power Ramp Tests

FIGURE 4. EMITTER THERMOCOUPLES DURING POWER RAMP
50 Sec. Power Ramp Tests

FIGURE 5. COLLECTOR AND RESERVOIR THERMOCOUPLES DURING POWER RAMPS
An electrically heated thermionic converter has been designed, built, and successfully tested in air (Homer et al., 1995). One of the unique features of this converter was the integral cesium reservoir thermally coupled to the emitter. The reservoir consisted of fifteen cesiated graphite pins located in pockets situated in the emitter lead with thermal coupling to the emitter, collector, and the emitter terminal; there were no auxiliary electric heaters on the reservoir. Test results are described for conditions in which the input thermal power to the converter was ramped up and down between 50% and 100% of full power in times as short as 50 sec, with data acquisition occurring every 12 sec. During the ramps, the emitter and collector temperature profiles, the reservoir temperature, and the electric output into a fixed load resistor are reported. The converter responded promptly to the power ramps without excessive overshoot and with no tendency to develop instabilities. This is the first demonstration of the performance of a cesium-graphite integral reservoir in a fast transient.