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**FABRICATION AND TESTING OF FULL-LENGTH,
SINGLE-CELL, EXTERNALLY FUELED
CONVERTERS FOR THERMIONIC REACTORS**

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ABSTRACT

The preceding paper described designs and analyses of thermionic reactors employing full-core-length single-cell converters with their heated emitters located on the outside of their internally cooled collectors, and it presented results of detailed parametric analyses which illustrate the benefits of this unconventional design. The present paper describes the fabrication and testing of full-length prototypical converters, both unfueled and fueled, and presents parametric results of electrically heated tests. The unfueled converter tests demonstrated the practicality of operating such long converters without shorting across a 0.3-mm interelectrode gap. They produced a measured peak output of 751 watts(c) from a single diode and a peak efficiency of 15.4%. The fueled converter tests measured the parametric performance of prototypic UO_2 -fueled converters designed for subsequent in-pile testing. They employed revolver-shaped tungsten elements with a central emitter hole surrounded by six fuel chambers. The full-length converters were heated by a water-cooled RF-induction coil inside an ion-pumped vacuum chamber. This required development of high-vacuum coaxial RF feedthroughs. In-pile test rules required multiple containment of the UO_2 -fuel, which complicated the fabrication of the test article and required successful development of techniques for welding tungsten and other refractory components. The tests measured a peak power output of 530 watts(c) or 7.1 watts/cm² at an efficiency of 11.5 %.

INTRODUCTION

After design analyses¹ had shown the potential high performance of thermionic reactor designs based on full-core-length (single-cell) externally fueled diodes, tests were initiated to confirm the feasibility of such devices. Two sets of tests were performed:

unfueled and fueled. Both sets of test employed full-scale diodes having lengths, diameters, and electrode gaps prototypic of previously analyzed reactor designs. The purpose of the initial, unfueled converter tests was to demonstrate the feasibility of repeatedly thermal cycling such full-length converters to typical operating temperatures without inter-electrode shorts, and to measure their power output and efficiency. The purpose of the subsequent fueled converter tests was to demonstrate the design and fabrication of full-length converters with high UO_2 volume fraction, to measure their power output and efficiency in electrically heated tests, and to provide them with triple fuel containment for subsequent in-pile tests.

UNFUELED CONVERTER TESTS

The unfueled converters were double-ended devices having a tungsten emitter with an internal diameter of 1.27 cm and an active length of 20 cm. The emitter was separated from the molybdenum collector by a 0.3-mm cesium gap. The collector was cooled by a fluted water-cooled tube, with its three flutes tangent to the inside of the collector. The space between the fluted tube and the collector was filled with inert gas. The collector temperature could be very effectively controlled by varying the composition or pressure of the inert gas.

Figure 1 shows a cross-sectional view through the emitter lead, the collector, and the fluted cooling tube. The collector shown consists of three layers, with a middle layer of copper for enhanced electrical conductance to minimize ohmic losses. The copper layer was electrically insulated from the inner layer. Also shown are six equispaced sapphire balls embedded in the collector. These serve to center the collector within the emitter.

Fig.1 Diode Cross-Section

In addition to these centering guides at each end of the diode, there is an anti-shorting device at its center. As shown in Figure 2, it consisted of a split alumina ring embedded in the collector, with its two halves held together by a tungsten-rhenium snap ring. With this arrangement, which avoids direct contact between the ceramic insulator and the high-temperature emitter, no shorting was ever experienced during repeated thermal cycling to 1800°C.

Fig.2 Anti-Shorting Device

The full-length converter was heated by RF-induction. The converter in these initial tests was contained in a cylindrical quartz tube, which was surrounded by a coaxial pyrex tube. The space between the two transparent tubes was water-cooled. A helical RF-induction coil was located on the outside of the pyrex tube.

Figure 3 shows a photograph of a full-scale diode under test. As can be seen, the RF-coil had fewer turns at its center so as to produce a uniform emitter temperature. The emitter temperature was measured both pyrometrically and by means of thermocouples (W-3Re/W-25Re). It should be emphasized that these diodes were rather sturdy devices and no special precautions were taken to avoid rough treatment during fabrication, processing or testing. In fact, some of the diodes successfully withstood extremely violent thermal cycles due to unplanned incidents.

Fig.3 RF Heating Arrangement

During testing, current-voltage characteristics were recorded on an XY-oscilloscope using a 60-cps sweep of adjustable amplitude and bias. The diode current was determined by measuring the voltage drop across a 0.001-ohm precision resistor designed for high-current operation. A multipoint strip chart recorder continuously monitored temperatures at all strategic diode locations, as well as the water temperature rise.

After all temperatures had stabilized with the circuit open, current-voltage measurements were made by momentarily closing the test circuit by means of a foot-switch operated relay and photographically recording the I-V trace on the oscilloscope. Because noise from the RF-generator affects the oscilloscope trace, the generator was also momentarily interrupted during measurements. Since the interruptions lasted

only a fraction of a second before the trace was recorded, the effect on the diode temperature is considered negligible, particularly in view of the high heat capacity of the simulated fuel element.

Later tests employed a modified procedure designed to display the effect of varying cesium pressure on the diode's current-voltage characteristics, and to permit determination by inspection of the envelope of these characteristics. After setting both the emitter and collector temperature, the cesium reservoir was first heated above its optimum temperature. The heater was then shut-off and the reservoir allowed to cool slowly. As it cooled, multiple exposure photographs of the diode's current-voltage characteristics were recorded, thereby yielding a family of curves with a clear envelope.

These multiple-exposure I-V traces and their optimized envelopes for emitter temperatures of 1400, 1500, and 1600°C are displayed in Figure 4. The figure also shows the maximum power output and maximum efficiency for each emitter temperature. Both the gross efficiency (before lead losses) and net efficiency (after lead losses) are shown for each case. The externally fueled converter is well suited to efficiency measurements, since it virtually acts as its own calorimeter. Its heat rejection rate is readily computed from the coolant's mass flow rate, specific heat, and temperature rise.

Fig.5 Measured Efficiency Versus Voltage

Fig.4 Measured I-V Characteristics at Various Cesium Pressures

Figure 5 shows plots of gross and net efficiency versus voltage for a 1500°C emitter temperature, and Figure 6 shows corresponding trade-off plots of power versus efficiency. They illustrate the large difference between gross and net performance resulting from unavoidable lead losses.

Fig.6 Power-vs-Efficiency Trade-off

Finally, Table 1 summarizes the measured gross and net performances of the full-length converter at its maximum power point and at its maximum efficiency point, for emitter temperatures ranging from 1400 to 1800°C. As shown, very high power outputs and efficiencies were obtained.

Table 1. Measured Performance Summary

	T_E °C	I amp	V volt	P watt	P^* w/cm ²	η_{gross} %	V_{net} volt	V_w volt	P_{net} watt	P^* w/cm ²	η_{net} %
Maximum Power Point	1400	820	0.40	328	4.8	11.7	0.34	0.06	279	4.0	8.6
	1500	1000	0.56	560	8.1	15.2	0.49	0.07	490	7.1	11.8
	1600	1200	0.60	720	10.5	16.8	0.53	0.07	636	9.2	12.0
	1700	1100	0.67	740	10.7	15.0	0.59	0.08	649	9.4	11.7
	1800	1295	0.66	855	12.4	14.4	0.58	0.08	751	10.9	11.2
Maximum Efficiency Point	1400	560	0.50	280	4.1	13.2	0.44	0.06	246	3.6	10.2
	1500	500	0.80	400	5.8	17.6	0.72	0.08	360	5.2	14.5
	1600	430	1.00	430	6.2	17.3	0.92	0.08	396	5.7	14.7
	1700	632	0.99	623	9.0	18.0	0.90	0.09	569	8.3	15.4
	1800	690	1.00	690	10.0	17.6	0.91	0.09	628	9.1	14.9

FUELED CONVERTER TESTS

The fueled converters had the same basic configuration and size as the previously tested unfueled converters. A major difference was the emitter body, which was a tungsten "revolver" with six fuel chamber holes surrounding the central emitter hole. Another major difference was the multiple containment required for in-pile testing, which greatly complicated the converter fabrication procedure. Like the unfueled units, collectors of the fueled converters were cooled by a central water tube via an inert gas gap, and their emitter bodies were heated by RF-induction during the out-of-pile tests. A major difference was that the RF-induction coil was located inside instead of outside the vacuum chamber.

The fueled in-pile converter design is illustrated by the isometric cutaway view shown in Figure 7 and by

the cross-sectional view of Figure 8. (In the following discussion superscript numerals refer to figure callouts.)

Fuel-Emitter Assembly

The tungsten emitter body had an outer diameter of 3.8 cm, and a 20-cm active length. The 1.27-cm central emitter hole² was surrounded by six 1-cm fuel holes³. The revolver¹ had minimum web thicknesses of 0.15 cm between emitter and fuel, 0.10 cm between fuel and the outside, and 0.28 cm between neighboring fuel holes.

With these dimensions, the fuel chambers occupied 42.8% of the converter cross-section. Assuming a reactor core made up of such elements separated by 0.15-cm vacuum gaps, the fuel chambers would occupy 36% of the core volume. However, the outer boundary of the converter can be hexagonalized, to permit closer packing and higher fuel volume fractions. For example, with the same thicknesses of webs and vacuum gaps as above, and with the emitter and fuel hole diameters increased to 1.68 cm and 1.30 cm, respectively, the fuel chambers would occupy 45% of the core volume.

The converters were loaded with annular cylindrical fuel pellets⁴ of 1.01-cm O.D., 0.51-cm I. D., and 1.30-cm length. The fuel was UO₂ of 92% theoretical density and 9% enrichment. The fuel enrichment was based on the results of a mock-up test in the Battelle Research Reactor, where the in-pile test was to be conducted. The design loading per converter was 58 gm of U₂₃₅.

The emitter body contained six thermocouple wells, not shown in these figures, located at various points of the fuel element periphery. Each well was a slanted hole of 0.1 cm diameter, penetrating to a depth of 0.5 cm into the web between fuel chambers⁸. The external-fuel design lends itself to detailed monitoring of the emitter body temperature distribution. For example, during the in-pile test the converter was to be located not at the center of the core, but nearer to one of its corners. Thus, the use of diametrically opposed thermocouples on the emitter body can show how much transverse temperature gradient is produced by the existing flux gradient. Another interesting point is that the presence of thermocouples at the top, middle, and bottom of the revolver makes it possible to observe the effect of UO₂ redistribution within the fuel chamber on the axial temperature profile of the emitter.

Fig.7 Isometric View of Fueled Converter

To aid in venting the released fission gases during the in-pile test, there was a tungsten snorkel tube⁵ at the center of each fuel chamber, extending over the full length of the fuel element; it had 0.1-cm perforations at 1.27-cm intervals, and was welded to a tungsten cover disk⁹ at its upper end. All fuel holes were connect to a common fission gas plenum at the top of the emitter body.

The ends of the emitter body were joined to W-25Re end caps¹⁰. These sealed the fuel chambers, except for a single W-25Re vent tube¹¹ of 0.15-cm O.D. and 0.1-cm I.D., which was connected to the upper end cap. Integral with each end cap was a 1.27-cm long emitter lead¹² of 0.12-cm wall thickness. The resultant emitter lead resistance was close to the optimum for this diode.

Each emitter lead was connected to a metal-ceramic seal¹³ and to a high-conductance power take-off flange¹⁴. During in-pile testing, these flanges also serve as part of the secondary containment chamber, together with a 0.05-cm thick cylindrical tungsten sleeve¹⁵ connecting them. To permit RF-induction heating of the emitter body during out-of-pile testing, the secondary containment sleeve¹⁵ was not emplaced until after the completion of that test.

Collector Assembly

The columbium collector⁶, which was separated from the emitter by a 0.025-cm cesium gap², had a wall thickness of 0.34-cm. To avoid the complexity of operating a liquid metal loop in the test chamber, the collector was water-cooled across a 0.008-cm wide helium gap (cold), and its temperature was varied by adjusting the helium pressure in the sub-atmospheric range.

The ends of the columbium collector¹⁶, beyond the active length of the diode, were expanded to a 2-cm outer diameter, to reduce ohmic losses. To center the collector within the emitter hole, each end of the collector was positioned by eight sapphire balls¹⁷ of 0.1-cm diameter, which were seated in hemispherical cavities in the collector at 45° intervals. These sapphire balls were in contact with the cool end of each emitter lead.

In addition, there were three anti-shortening spacers¹⁸ within the active region of the diode: one at the center, and the others 2.5 cm from each end. These spacers, which are not shown in Figure 7, consisted of split and grooved alumina rings inserted into corresponding collector grooves, where they were retained by W-25Re wire snap-rings. The W-25Re wires extended 0.13-cm beyond the radius of the collector, and did not touch the emitter when the collector was properly centered.

The collector was joined to a metal-ceramic seal at the upper end of the converter. At the lower end, a columbium bellows¹⁹ was interposed between collector and seal, to allow for the differential thermal expansion of the emitter and collector assemblies. The columbium bellows had a nested configuration and contained fourteen convolutions of 3.5-cm O.D., 2.3-cm I.D., and 0.013-cm wall thickness.

The bottom end of the collector was joined to the cesium reservoir²⁰ by a 2-cm long cesium leg²¹ of 0.40-cm O.D., both of columbium. Heat conduction to

the reservoir through the cesium leg was less than 7 watts, but during in-pile testing the reservoir receives an additional input of 40 watts from gamma heating. The reservoir was water-cooled via a split cooling clamp, not shown. Fine temperature control of the cesium reservoir was effected by means of electrical heaters²²; two independent heaters were provided, for redundancy. The floor of the reservoir was connected to a columbium tube²³ for diode outgassing, cesium charging, and final pinch-off.

Cooling and Electrical Arrangement

The collector cooling water flowed through a 0.39-cm I.D. by 0.52-cm O.D. stainless steel tube⁷. Circular ridges projecting from this stainless steel tube at 1.27-cm intervals provided centering within the collector, to maintain a uniform 0.008-cm cold helium gap. Beyond the active length of the diode the helium gap was increased to at least 0.06 cm, to reduce heat transfer and prevent over-cooling the collector ends.

The upper end of the coolant tube⁷ was joined to a small, hydroformed, stainless steel bellows²⁴, to permit thermal expansion of the collector relative to the coolant tube. These bellows were joined to a stainless steel top cap²⁵ which sealed the helium space, except for a helium port²⁶ to allow adjustment of the gas pressure during diode operation.

Since this was a double-ended diode, there were four converter terminals. These terminals were considered to be the upper and lower emitter power take-off flanges and the upper and lower collector hubs²⁷. Thus, the diode terminal voltage, power output, and efficiency reported later were the values obtained after the electrical and thermal losses in the optimized emitter leads. Any losses beyond these terminals were considered to be merely part of the experimental arrangement, rather than an inherent characteristic of the converter.

The collector cooling water flowed through the collector coolant tube⁷ in an upward direction. A typical flow rate was 31 cc/s and 2.5 m/s. The water inlet and outlet tubes²⁸, which were made of copper, simultaneously served as the high-current collector leads. To avoid overcooling the collector hubs²⁷ below the cesium reservoir temperature, these hubs were connected to the water-cooled copper tubes²⁸ by thermal chokes²⁹.

Fig.8 Fueled Converter Cross-Section

Similarly, water-cooled copper tubes³⁰ served to conduct the upper and lower emitter currents. Again, thermal chokes³¹ had to be employed to avoid overcooling the W-Re emitter power take-off flanges¹⁴. Each of these thermal chokes consisted of a molybdenum skirt with a rectangular cooling channel³² at its outer end, with each cooling channel connected to water inlet and outlet tubes³⁰ at 180°

intervals. The thermal resistance of the emitter heat chokes³¹ was sized so as to maintain the temperature of the power take-off flanges¹⁴ at 600 to 800°C during normal diode operation. Thus, the ceramic seals¹³ and the columbium bellows¹⁹ were lifetested at a temperature which realistically simulated their operating condition in a thermionic reactor.

In addition to their thermal and electrical functions, the molybdenum skirts³¹ also served two other purposes: they were used for mechanical support³² of the converter during testing, and they made it possible to maintain the tungsten and tungsten-alloy components of the converter above their ductile-brittle transition temperature during reactor shut-down, by means of an electrical heater³³ brazed to the inner surface of each Mo skirt.

Containment

Nuclear safety rules at the test reactor required that the fuel be triply contained. In addition to the integrity of the sealed fuel chamber, the emitter power take-off flanges¹⁴ and the connecting tungsten sleeve¹⁵ formed part of the secondary container; and the 7-cm diameter outer wall of the test capsule³⁴, made of 0.14-cm thick stainless steel, served as the tertiary container.

The secondary containment volume was sealed under vacuum after completion of the out-of-pile testing. The tertiary containment volume, which contained the thermal radiation shielding³⁵ consisting of 50 layers of thorium-coated tungsten foil, was evacuated. During the in-pile test it was pumped by a pair of 350-liter/sec ion pumps, a 7500-liter/sec titanium sublimation pump for intermittent duty, and a liquid-nitrogen cold trap.

As illustrated, there were four 0.32-cm O.D. columbium tubes³⁶ joined to the upper emitter power take-off flange¹⁴. These tubes form part of the secondary containment enclosure. Three of the four were cover tubes for the six emitter thermocouples. The W-25Re and W-3Re thermocouples employed multi-strand wire, and had bare junctions that were knotted rather than spot-welded, to avoid embrittlement. The thermocouple leads were beryllia-insulated in the vicinity of the hot emitter body¹, and were sheathed in four-hole alumina insulators within the columbium cover tubes³⁶. During in-pile testing, the thermocouple cover tubes extend for approximately 2.1 m above the top of the reactor core, in order to move the required insulating vacuum feedthroughs to a region of lower neutron flux.

CONVERTER FABRICATION

The converter consisted of five major subassemblies three of which are illustrated in Figure 9: the emitter assembly, the collector assembly, and the coolant assembly. The fourth subassembly, consisting of the

secondary containment sleeve and the thermal radiation shielding, and the fifth, the fission gas collection system, were added after completion of the out-of-pile testing. The columbium components of the collector assembly and the stainless steel parts of the coolant assembly and of the fission gas collection system were all prepared by standard machining techniques. Only the more unusual components of the emitter assembly warrant a more detailed discussion.

Emitter Body

The first step in making the revolver-shaped emitter body was to EDM (electric-discharge-machine) the central emitter hole in the cylindrical tungsten billet. Brass electrodes and copper-impregnated tungsten electrodes have both been successfully employed in the EDM process. To minimize the danger of radial drift, the 20-cm long hole was machined in two parts half way from each end of the tungsten billet. Tubular electrodes were employed, and the central tungsten core dropped out when the two holes met in the middle. If desired, the EDM process would lend itself well to machining blind holes as well as non-circular holes.

After machining, the surface of the emitter hole was honed. The honing process removed a layer of ~ 0.005 cm, which was important because it is this layer which is most likely to contain surface microcracks as the result of the electric discharge machining processes.

After finishing the emitter hole, the ends of the tungsten billet were ground to provide the inner and outer lips required to join it to the end caps. The six peripheral fuel holes were then electric-discharge-machined and honed, in the same manner as the central emitter hole. Finally, the outer surface of the revolver was ground to size, and the six slanted thermocouple walls were introduced by the EDM technique; two of the six are faintly visible in the emitter photograph in Figure 9. The last step was to electropolish the outer surface and end faces of the emitter body. Wherever possible, this process was used as the final step on all tungsten components, due to its sensitivity in revealing any surface defects.

A total of six tungsten revolvers were prepared by the above technique, and it was demonstrated that tool drift can be sufficiently well-controlled so that hole alignment and web thicknesses can be maintained within satisfactory tolerance limits.

Fig.9 Converter Components and Assembly

The first three emitter bodies had been prepared from sintered and forged powder-metallurgy tungsten billets. Although two of the resultant revolver bodies appeared to be leaktight after machining, subsequent electropolishing of their outer surface revealed the existence of microcracks, possibly the result of improper fixturing, which precluded their use in diodes. However, one of these tungsten revolvers was employed for the nuclear mock-up test in the Battelle Research Reactor, which was needed to determine the required fuel enrichment.

The other two emitter bodies were prepared from arc-cast and hot-extruded tungsten billets. Both were leaktight and showed no surface defects after electropolishing. However, one of the units developed two leaks (not near the weld joints) during subsequent thermal processing. The cause of these defects has not been identified. The second of the arc-cast emitter bodies was successfully fabricated into the first of the two diodes built and tested under this program.

Finally, the sixth emitter body was prepared from a thoriated tungsten billet formed by powder-metallurgy techniques and extrusion. The material used contained 2 wt% thoria. The resultant emitter body, which was machined without difficulty by the same techniques as the all-tungsten revolvers, was then used to fabricate the second diode built and tested under this program.

Emitter Assembly

The 9%-enriched UO_2 fuel pellets were cold-pressed to 70% theoretical density, hydrogen-sintered to 92% density, and finish-ground to the desired dimensions. The oxygen-to-uranium ratio was 2.005, and the impurity content was below the measurable limits for all species tested. The tungsten snorkel tubes were prepared by chemical vapor deposition from WF_6 , and the perforations required for venting the fission gases were introduced by electric-discharge machining.

The rest of the emitter assembly consisted of an upper and lower subassembly. As illustrated in Figure 9, each of these subassemblies contained an end cap, a graded metal-ceramic seal, a power take-off flange, and a thermal choke with water coolant connections. In addition, the upper subassembly contained a vent tube and four cover tubes, and the lower assembly included the columbium bellows.

The end caps and the power take-off flanges were prepared from powder-metallurgy tungsten-25% rhenium stock. They were roughed out by electric-discharge-machining, and finished by grinding and electro-polishing, with intermediate annealing steps. The 0.1-cm I.D. vent tube, which was joined to the upper end cap, was made by chemical vapor deposition of W-25Re.

The metal-ceramic seals were prepared by autoclaving graded layers of columbium and alumina powders encapsulated in a Cb-1Zr jacket. At the central plane of each assembly was a 0.15 cm thick alumina (Lucalox) wafer. On each side of this wafer were several layers of mixed powders, with compositions gradating from ceramic-rich to metal-rich. The assembly was consolidated by hot isostatic compaction at approximately 1650°C and 10,000 psi. After autoclaving, the seals were finished by machining, ultrasonic drilling, and diamond grinding. Before use in a diode, each seal was acceptance-tested by leak checking after 25 thermal cycles to 1000°C.

The emitter heat chokes, which are identified as "emitter-terminals" in Figure 9, were made of molybdenum, with water inlet and outlet ports of columbium. The photograph also shows the previously mentioned electrical heaters brazed to their inner surface. Nichrome heaters with magnesia insulation and inconel sheathing were used.

Finally, the emitter expansion bellows consisted of fourteen nested convolutions, joined by EB (electron-beam) welding. Each convolution consisted of two diaphragm rings, which were stamped and shaped from 0.013-cm columbium foil. Individual convolutions were first prepared by EB-welding pairs of diaphragm rings along their inner edges, while their outer edges were separated by a sacrificial molybdenum spacer ring. These convolutions were then joined by EB-welding along their outer edges, after which the molybdenum spacers were chemically removed by dissolution in a mixture of concentrated nitric and sulfuric acids.

Joints

All emitter assembly components were joined by electron-beam welding. The most difficult joints to work out were those between tungsten and tungsten-rhenium components. These included joining the W-Re end caps to the W emitter body, to the W-Re power take-off flanges, and to the W-Re vent tube.

Our welding experience with these joints was described in detail in a separate paper.² As explained there, when the arc-cast tungsten revolver was first welded to the W-Re end cap, it developed leaks; not at the weld joints but about 0.63-cm away, at a region where the tungsten revolver had been preheated by a defocused electron beam. However, once satisfactory methods of pre-heating and post-heating these components by means of a radiant furnace within the welding chamber had been worked out, it was found that joints between W and W-Re could be EB-welded with high reliability. After welding, each of these joints was stress-relieved by vacuum-annealing for one hour at 1300°C.

To salvage the defective revolver mentioned above, a 1.27-cm long section containing the leaky region was cut off, and the cut end remachined. This shortened revolver was then incorporated in Converter No. 1, using a specially machined W-Re end cap transition. As a result, the active length of this diode was only 18.7 cm instead of the 20-cm design value.

Contrary to expectations, pre-heating was also found to be necessary in joining the end caps to the power take-off flange and to the vent tube, joints in which both components consisted of nominally ductile W-Re alloys.

Another class of joints was that between tungsten-rhenium and columbium. In making these joints, which included the end-cap-to-seal and the top-flange-to-cover-tubes, it was found that weld joints which depended on the formation of an alloy between W-Re and Cb tended to be unreliable. However, by shifting the electron beam to the columbium side of the joint, to avoid melting the W-Re, leaktight joints could be made with good reliability, provided pre- and post-heating was applied. Such joints are not really EB-welds; they should more accurately be called "electron-beam selfbrazes", since in effect the melted part of the columbium acts as a braze alloy for the unmelted part of the component.

The joints between the W-Re power-take-off flanges and the Mo heat chokes were EB-welded without difficulty. However, these joints need not be leaktight, since they only serve mechanical and conductive functions.

All joints in the converter between columbium and columbium were made by electron-beam welding, with good reliability. Thus, all joints in the cesium envelope are EB-welded, except the metal-ceramic seals which are pressure-bonded. After EB-welding the power take-off flanges to the end caps (emitter leads), backbrazes of a palladium-nickel-silver alloy (1052°C) were added to these joints, for enhanced thermal and electrical conductance.

Finally, all joints between stainless steel components were also made by EB-welding. Brazing was only used for joining dissimilar metals, such as columbium to stainless steel, and stainless steel to copper. Thus, the only brazes in the converter are the joints at the top and bottom of the diode between the collector cooling assembly and the collector heat chokes. These were RF-heated vacuum brazes, again using a palladium-nickel-silver alloy (1052°C).

Assembly Sequence

The converter assembly sequence is illustrated in Figure 9. Individual components were first joined to form the upper and lower emitter subassemblies. Next, the lower subassembly was joined to the emitter body, the inner lips by means of an axial weld, and

the outer lips by a radial weld. The emitter body was then loaded with fuel and snorkels, and the fueled assembly was vacuum-fired at the emitter operating temperature, after which it was sealed by joining it to the upper subassembly. The finished fuel element was leak-checked through the vent tube.

Since the diameter of the collector ends exceeded that of the emitter hole, the collector assembly had to be fabricated in two parts. After insertion of the spacer rings and sapphire balls, the lower part of the collector assembly, which includes the cesium reservoir and the diode pump-down leg, was inserted into the emitter hole, and the collector extension with sapphire balls in place was inserted into the top of the emitter assembly. Union between the two collector halves was effected by means of an axial EB-weld at the upper collector well. Two additional welds sealed the diode.

Finally, the stainless steel coolant assembly was inserted into the top of the collector hole, and the helium space was sealed by means of the two vacuum brazes. The right photograph in Figure 9 shows the completed diode, ready for outgassing and charging with cesium.

PROCESSING AND TEST ARRANGEMENT

Converter outgassing was performed in the same vacuum chamber, and with the same RF-induction heating arrangement, as subsequent out-of-pile testing. In the previously reported³ out-of-pile testing of unfueled diodes, the converter was located inside a water-jacketed quartz vacuum chamber, and the RF-induction coil was located outside the vacuum chamber, as was shown in Figure 3. Such an arrangement is very convenient, because operation of the induction coil in air eliminates the need for RF-vacuum feedthroughs, and also permits easy adjustment of the position and spacing of the heating coil during the course of a test.

However, there were also some serious disadvantages to this mode of operation. Since the ends of the quartz tube were sealed by organic O-rings, the resultant vacuum in the test chamber was relatively poor. Moreover, since the double-ended diode needed high-conductance current leads and instrumentation feedthroughs at both ends of the test chamber, it was a rather cumbersome procedure to install the diode for testing or to open the chamber for any minor adjustments (such as of the thermocouples).

For these reasons, it was decided that the fueled converter tests would employ a more conventional all-metal belljar using a crushable copper gasket, metal-ceramic vacuum feedthroughs, and with the RF-induction coil located within the test chamber. This made possible a much better vacuum, and greatly simplified the test installation.

RF Feedthrough

To achieve these advantages, however, it was first necessary to develop a reliable high-vacuum high-power RF-feedthrough, since the required unit did not appear to be commercially available. As shown in Figure 10, the RF-feedthrough that evolved is a co-axial unit, with a brazed metal-ceramic seal. The unit was sealed to the test chamber baseplate by means of copper-gasketed knife edges. A co-axial rather than parallel feedthrough design was used, to avoid excessive induction heating of the test chamber wall.

In addition to the ceramic seal at the feedthrough's outer end, there was a slip-fitted ceramic spacer at its inner end. This was to provide centering for the high-voltage copper tube, to minimize the danger of breakdown. However, with the spacer design shown in Figure 10, some difficulty was encountered with RF-breakdown at approximately 7 kilovolts, due to surface conduction along the inner end-face of the ceramic spacer. The radial arc resulted in melt-through of the central copper tube at that point, with consequent release of water into the test chamber.

Fig.10 Co-Axial R.F. Vacuum Feedthrough (450 kHz, 75kw)

The problem was corrected by modifying the spacer design to provide a considerably longer conduction path. The coaxial feedthrough with the modified ceramic spacer was then successfully tested to the maximum 12-kilovolt output of the RF-power supply, and has since operated without difficulties for hundreds of hours at about 8 kilovolts and 35 kVA.

Converter Processing

The general arrangement for processing and out-of-pile testing the converter is illustrated in Figures 11, 12, and 13. Figure 11 shows a close-up view. Figure 12 illustrates the diode outgassing and cesium charging procedure, and Figure 13 presents an overview of the test arrangement.

The ends of the converter⁵³ can be seen projecting from the RF-induction coil⁵⁴. The induction coil was connected to the previously shown coaxial feedthrough⁵⁵, whose outer ends were connected to a 75-kw, 450 kHz RF-power supply⁵⁶. Water-cooled copper tubes acted as high-conductance current leads to the diode, two tubes to the collector⁵ and four for the emitter⁵⁵. These tubes entered the test chamber through ceramic feedthroughs⁵⁹. The 46-cm diameter baseplate⁶⁰ and the 76-cm high belljar⁶¹ of the stainless steel test chamber were both water cooled. During diode outgassing and out-of-pile testing the fission gas vent tube was open to the vacuum chamber.

Fig.11 Out-of-Pile Test Station

To reduce confusion, the photographs were taken before the installation of the thermocouples and voltage probes. W-3Re and W-25Re thermocouples were used at the emitter body, and chromel-alumel thermocouples everywhere else, including the emitter power take-off flanges¹⁴, the collector ends²⁷, and the cesium reservoir²⁰.

Figure 11 shows the cesium reservoir⁶² and its heater⁶³ before installation of the reservoir cooling clamp. Emerging from the bottom of the reservoir was an S-shaped copper tube⁶⁴ which passed through a feedthrough at the bottom of the baseplate. This S-tube was used for outgassing the diode and subsequently charging it with cesium. As shown in Figure 12, after this tube⁶⁴ emerged from the vacuum chamber it was connected to a 1.7 cm diameter extension⁶⁵, which contained the glass ampules with the cesium charge. Below this point, the tube was connected to a 15-liter/sec ion pump⁶⁶ used for outgassing the inside of the diode. The test chamber itself was evacuated by a separate 400-liter/sec ion pump⁶⁷.

Fig.12 Converter Processing and Cesium Charging

During outgassing, the emitter body was heated to a maximum of 1900°C, and the S-tube⁶⁴ and cesium ampule container⁶⁵ were resistively heated to 200°C. All parts of the converter were at or above their normal operating temperatures. To ensure this, a 500-ampere alternating current was passed between the upper and lower collector leads²⁸, to duplicate the ohmic heating in the collector heat chokes²⁹ during diode operation.

Heating was continued for several days, to reduce the pressure at the diode ion pump⁶⁶ to 10^{-8} torr, at which point the ampule container⁶⁵ was squeezed to crush the glass ampules. After some additional

pumping to remove any gas released from the cesium ampules, the diode pumpdown leg⁶⁸ was pinched off. The converter was then cooled and removed from the test chamber, and the liquid cesium was decanted into the S-tube, with care taken to avoid transfer of crushed glass particles. After pinching off the ampule container⁶⁵ with the crushed glass, the liquid cesium was transferred from the S-tube⁶⁴ into the diode. Once this transfer was verified by x-ray observation, the diode was sealed by pinching off the columbium tube just below the cesium reservoir.

Out-Of-Pile Installation

After processing, the converter was again installed in the test chamber and instrumented for testing. In addition to the thermocouples used during the outgassing, voltage probes were attached to the upper and lower collector hubs²⁷ and emitter power take-off flanges¹⁴, as well as to the six current leads at the points where these emerge from the test chamber⁷⁰. These six points were also provided with thermometers with a resolution of 0.1°C. This instrumentation was used to measure the temperature rise of the three coolant streams and the ohmic losses in the diode leads within the test chamber, quantities which were needed later to compute the converter's efficiency.

Figure 13 presents an overview of the out-of-pile test arrangement. It shows the test chamber⁶¹ and its ion pump⁶⁷, the 75-kw RF-power supply⁵⁶, the heater controls⁷¹ and coolant flow meters⁷², the helium pressure regulating system⁷³ with its own vacuum pump⁷⁴ for subatmospheric operation, and a balancing potentiometer for thermocouple readout⁷⁵.

Fig. 13 Out-of-Pile Test Arrangement

The temperature of the emitter body could be measured not only by thermocouples but also by a micro-optical pyrometer⁷⁶ through a window⁷⁷ in the vacuum belljar. This window was kept clean by means of a mask, that could be temporarily moved aside by a magnetically coupled actuator⁷⁵. All pyrometric readings were corrected, with corrections based on the emissivity of clean tungsten.

Emitter Temperature

It should be emphasized that the "emitter temperature" measured, whether by pyrometer or thermocouples, is really the temperature at the outside of the emitter body and not at the actual emitter surface. The temperature difference between these points can be quite significant, particularly during the RF-heated out-of-pile test, where most of the heat is generated near the outside of the emitter body.

At a radio frequency of 450 kilohertz, the skin depth or $1/e$ attenuation distance in 1700°C tungsten is approximately 0.066 cm. Figure 14 presents a typical computed temperature distribution in a transverse cross-section of the emitter body, before significant fuel redistribution has taken place. As can be seen, the average emitter temperature is more than 100°C below that measured at outside of the emitter body.

Fig.14 Temperature Distribution of RF-Heated Emitter Body

By contrast, during in-pile testing most of the heat is generated by fissions within the fuel chambers. Under these conditions, the temperature difference between the inside and outside of the revolver is typically only 50°C , as illustrated by the calculated temperature map presented in Figure 15. This calculation took account of gamma heating as well as fissions. In a thermal test reactor, gamma heating of the massive tungsten revolver contributes about 25 percent of the total heat generated in the fueled emitter body. Note that, at most, there is roughly a

70°C temperature drop within the fuel, resulting in a maximum UO_2 temperature of less than 1900°C , far below its melting point.

Fig.15 Temperature Distribution of Nuclear-Heated Emitter Body (Isotherms at 10° Intervals)

The calculation illustrated in Figure 15 had an additional purpose: to estimate the effect of locating the converter near the outside of the reactor, with a consequent transverse flux gradient. A 20% fission density difference between opposite fuel chambers was measured in a mock-up experiment. As can be seen, this difference leads to a transverse temperature difference of 70°C , which would cause only negligible bowing. Moreover, it can be seen that the 20% fission density variation produces a peripheral emitter temperature variation of only 10°C .

OUT-OF-PILE TEST

Test Conditions

All performance measurements were made under steady-state conditions, since sweep measurements - unless made at very slow sweep rates - would tend to be affected by inductive interactions between the high-current diode leads.

During early measurements, there was appreciable imbalance in the current leads between the upper and lower diode terminals and the external power supply. Since this was a double-ended diode, this imbalance resulted in significant differences between the two output voltages and among the four output currents.

Under these conditions, there is some ambiguity as to the correct way of computing the total power output of the converter. The most rigorous method is to subtract the electrical power consumed in overcoming the resistance of the current leads from the power delivered by the external power supply. However, it was found that even with badly unbalanced voltages and currents, the rigorously computed diode power can be matched within a fraction of a percent simply by multiplying the total diode current by the arithmetic average of the two terminal voltages. In any event, the current-lead imbalance mentioned above was later corrected by changing the diameter of some of the copper lead tubes.

Measured Performance

A typical current-voltage characteristic of this converter is shown by the solid curve in Figure 16. This was obtained by stepwise variation of the dc power supply output voltage, while maintaining a constant setting of the RF-power supply. At each step, the collector temperature (helium pressure) and reservoir temperature were reoptimized, and the diode was allowed to equilibrate.

Fig.16 Measured Converter Performance

Figure 16 also shows an illustrative operating point, at an emitter body temperature of 1940°K, a diode current of 735 amperes or 9.8 amp/cm², and a terminal voltage of 0.72 V after the emitter lead losses. This corresponds to a power output of 530 watts, or a power density of 7.1 w/cm² for the 75-cm² emitter.

As indicated earlier, the converter efficiency and the thermal power supplied to the emitter were computed by applying an energy balance to the diode and the current leads within the test chamber. The efficiency quoted included all those losses that are inherent characteristic of the converter, such as ohmic losses within each electrode, electrical and thermal losses in the emitter leads, and thermal losses through the ceramic seals.

Comparison with Predicted Performance

Finally, it is of interest to compare the measured converter performance with that predicted by theoretical calculations. This comparison is presented in Figure 17. Predicted current voltage characteristics (dotted curves) are shown both for constant thermal power and for constant maximum emitter temperature.

Fig.17 Comparison of Measured and Predicted Performance

The method of computing the predicted performance of the converter was described in some detail in an earlier report.³ In essence, each point on the predicted performance curves represents the simultaneous solution of two Laplacian equations, to determine the axial variation of the emitter temperature, inter-electrode potential, current and power densities, and emitter heat flux. The computations employed performance data generated by the SIMCON analysis.⁴ If desired, our converter analysis program can also calculate the location and shape of the isothermal cavity after UO_2 redistribution in the fuel chamber.

Inspection of Figure 17 shows that the slope of the measured performance curve is intermediate between those of the predicted constant-emitter-temperature curves and the constant-thermal-power curves, but closer to the slope of the latter. This is precisely as it should be. Although the measured performance curve was obtained at constant RF-induction power, the emitter heat flux was not exactly constant. At lower current densities there is less electron cooling, the emitter temperature goes up, more heat is lost by radiation from the outer surface, and the emitter heat flux drops. Therefore, with constant thermal input, a converter would be expected to have a steeper I-V characteristic without thermal insulation than with exterior insulation.

Test Experience

During the initial period of this out-of-pile test, the diode experienced numerous startups and shutdowns, primarily because of malfunctions of various peripheral items. We have already mentioned the initial difficulties with the RF-vacuum feedthrough, which were eliminated by modifying the design of the ceramic spacer bushing. Another difficulty encountered was the development of small leaks between the helium line and the vacuum test chamber. These were eliminated by using only brazed connections in the helium line within the test chamber. Compression fittings are satisfactory for water lines, but tend to relax at elevated temperatures.

Other peripheral malfunctions causing occasional test interruptions included failure of the cesium reservoir heater, which was easily replaced, and automatic shutdown of the RF-power supply. The latter tended to occur on humid days, when condensation of atmospheric moisture on the water-cooled lines inside the RF-unit resulted in high-voltage arcing. This problem was eliminated by

cooling the RF-supply with a recirculating water system, operating above the atmospheric dew point. However, the converter itself was still cooled with fresh water at house pressure, because of the possible failure of the recirculating pump. Although such failure would automatically shutdown the RF-power supply, the heat retained in the massive high-temperature emitter body would probably melt the stainless steel cooling assembly if the water flow were stopped.

No difficulties at all were encountered with the nested columbium bellows, which contained thirty EB-welds and were exposed to high-temperature cesium vapor; but, ironically, we did have problems with the standard-production hydroformed stainless steel bellows, which were only exposed to cold water and helium. These problems were probably due to manufacturing defects. After 400 hours of out-of-pile operations, the converter test had to be interrupted because of a very small bellows leak, permitting cooling water to enter the helium space. The defective stainless steel bellows were replaced, and the out-of-pile test continued.

After 1100 hours of operation, and a total energy production of 480 kilowatt-hours, the qualification test was stopped and the converter was removed from the test chamber. The dimensions of the fueled emitter body were unchanged. The arc-cast tungsten appeared very clean, but its typical grain size had grown to approximately 1-to-2 mm during the out-of-pile test, and a grain boundary leak had occurred between one of the fuel chambers and the outside. To avoid this grain growth problem, a second converter was built and tested. It differed primarily in having an emitter body machined from a tungsten-2% thoria billet produced by powder metallurgy, instead of the arc-cast pure-tungsten billet used for the first converter.

As expected, the thoriated tungsten proved to be significantly easier to machine (EDM) than the arc-cast tungsten used earlier. However, some difficulty was encountered in EB-welding the emitter body ends to their respective end caps. Two of the four weld joints had to be rewelded, one repeatedly, before leaktightness was achieved. Except for these delays, fabrication and processing of Diode No. 2 proceeded quite smoothly, without any of the problems initially encountered with Diode No. 1.

The electrically heated qualification test of Converter No. 2 also was carried out without incidents or difficulties. Because of budgetary constraint, the out-of-pile test was stopped after only 300 hours, to prepare the converter for shipment to the in-pile test contractor.

CONCLUSIONS

The work performed under this program led to the following conclusions:

- 1) Fabrication of revolver-shaped tungsten bodies for use as fuel containers in external-fuel thermionic converters is feasible.
- 2) External-fuel revolver fuel elements can be employed as emitter bodies in cylindrical thermionic converters at least as long as 20 cm.
- 3) Vacuum-tight joints between tungsten and/or tungsten-alloy components can be reliably achieved by EB-welding with appropriate pre- and post-heating. Hermetic joints between columbium and tungsten can be made by an EB-self-brazing technique. EB-weld joints between columbium components are easy to achieve and highly reliable.
- 4) Fully-fueled external-fuel diodes can be tested out-of-pile by RF-induction heating. Such testing is valuable in permitting adjustment of the external load and cooling arrangements, based on actual operating parameters.
- 5) While arc-cast tungsten can be successfully machined and welded, subsequent grain growth in high-temperature service makes long-term hermeticity of this material questionable. A converter employing an arc-cast tungsten fuel element exhibited considerable grain growth with two grain boundary leaks in its fuel chamber wall after 1100 hours of operation.
- 6) A thoriated-tungsten fuel-emitter evidenced relatively little grain growth following three hundred hours of out-of-pile testing, and remained leaktight for this period.
- 7) A converter employing a thoriated-tungsten emitter body yielded performance comparable to one using an arc-cast tungsten emitter, at least to 1700°C.
- 8) Converter performance remained stable for the 300-hour test period, despite the presence of 2 wt% thoria in the tungsten emitter. (The thoria may actually serve to enhance the thermionic performance.)
- 9) Twenty-cm long fueled cylindrical diodes with small (0.025 cm) interelectrode gaps can withstand extended high-temperature operation and numerous thermal cycles without shorting. This confirms the experience of earlier non-fueled out-of-pile tests.
- 10) In spite of higher ohmic losses in long converters, overall performance was quite good, yielding typical power densities of 5 to 7 watt/cm² at 1700°C emitter temperatures, and conversion efficiencies of 11 to 12% after the electrical and thermal losses in the emitter leads.
- 11) The high-voltage RF-feedthrough developed in this program permits reliable RF-heating for diode processing and out-of-pile testing in a high-vacuum test chamber. Power transfer of approximately 35 kW was achieved.
- 12) Water-cooling the collector through a gas gap is quite practical, using a single-component (helium) gas with pressure adjustment to control the collector temperature.
- 13) A thin-walled (0.013-cm) large-diameter (3.8-cm O.D.) nested columbium bellows can reliably be made by EB-welding.
- 14) Although the yield of the high-pressure inert gas autoclaving process used for making the graded columbium-alumina seals was relatively poor (30%), the four seals actually used in the converters proved quite reliable.
- 15) A double-ended, full-core-length external-fuel thermionic converter can be fabricated without any braze joints in the cesium envelope.
- 16) In contrast to the multi-cell converter design, the external-fuel configuration makes possible the direct measurement of the temperature of fuel-emitter body via thermocouples. But such measurement leads to considerable complications because of the triple-containment requirement.

- 17) In general, an external-fuel thermionic converter for operation in a test reactor is much more difficult to design and build than a similar converter for use in the actual thermionic reactor. This is so primarily because the former converter requires individual collection of fission gases as well as the double containment of the fuel element, its thermocouple leads, and the fission gas collector.
- 18) In future converters, the need for leaktight tungsten or tungsten-alloy welds should be minimized or eliminated.

In retrospect, many of the complex fabrication procedures could be avoided by employing single-ended half-length converters instead of double-ended full-length converters. A possible configuration for such a converter is depicted in Figure 18. As can be seen, the single-ended design eliminates the need for bellows, and - most important- avoids the need for joints between hard-to-weld tungsten or W-Re components. This comes about because both the primary and secondary containers are made of easily weldable columbium alloys, with their weld joints in a cooler region of the converter. Figure 18 also shows an emitter body with a scalloped periphery. As illustrated in Figure 19, that shape permits a denser packing of the thermionic fuel elements, resulting in a higher fuel volume fraction in the reactor core.

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Fig.19 High Fuel Fraction Converter Nesting Arrangement

Fig.18 Alternative Converter Design for In-Pile Testing