DESIGN, FABRICATION, AND TESTING OF A FULL-LENGTH EXTERNAL-FUEL THERMIONIC CONVERTER

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ABSTRACT

The development of a double-ended full-core-length external-fuel converter, a prototypical fuel module for a 200- to 300-ekw thermionic reactor, is described. The converter design is based on a revolver-shaped tungsten emitter body, with six peripheral fuel chambers loaded with enriched UO_2 pellets. The columbium collector is water-cooled through a sub-atmospheric adjustable-pressure helium gap. The converter employs graded metal-ceramic seals, and its double-ended construction is made possible by bellows to compensate for differential axial expansion. Fission gases are vented from the fuel chambers and collected in an accumulator designed for continuous monitoring of the pressure buildup. Component fabrication, assembly sequence, and joining methods are described; also the test procedures, and the converter load control. All tests are performed in vacuum. During in-pile testing, the fuel is triply contained, with thermal insulation between the secondary and tertiary containers. Before insertion in-pile, the fully fueled converter is being qualification-tested by rf-induction heating, using a specially-developed high-vacuum rf-feedthrough. To date, this out-of-pile test has operated for over 1000 hours, producing a total of 480 kilowatt-hours, with a peak output of 530 watts, or 7.1 w/cm², at a conversion efficiency of 11.5%.

INTRODUCTION

This report combines two of the papers^(1,2) presented at the 1970 IEEE Thermionic Conversion Specialists Conference. The first of these described the development of a full-length external-fuel thermionic converter for in-pile testing, and the second paper discussed the test arrangement and the results obtained to date. The development program includes out-of-pile performance testing of the fully fueled-converter, using rf-induction heating, before its installation in the in-pile test capsule.

An external-fuel converter is a cylindrical diode consisting of an outer emitter surrounded by nuclear fuel and of a centrally cooled collector. The term "full-length" denotes that the converter is long enough to extend over the full height of the reactor core. Thus, the converter under development is not a scaled-down test device, but a full-scale element of the thermionic reactor. Potential advantages of this design were discussed in earlier reports^(3,4).

The external-fuel converter concept permits a number of different design options, particularly with respect to the

fuel composition and shape and the collector cooling arrangement. The converter described here is being developed for the Jet Propulsion Laboratory, and is based on their concept for a thermionic reactor with uninsulated collector cooling, as described in an earlier paper⁽⁴⁾. The diode is double-ended, with through-flow cooling, and with ceramic seals and emitter and collector power take-offs at both ends. The design uses a revolver-shaped tungsten emitter body, with the central emitter hole surrounded by six peripheral fuel holes loaded with cylindrical UO_2 pellets.

DESIGN DESCRIPTION

The in-pile converter design is illustrated by the isometric cutaway view shown in Figure 1 and by the cross-sectional views of Figures 2 and 3. The latter figure also shows the fission gas collection system and the lower half of the test capsule. In the following discussion superscript numerals refer to figure callouts; references are designated by numerals in parenthesis.

Fuel-Emitter Assembly

The tungsten emitter body¹ has an outer diameter of 1.5 inches, and an 8-inch active length. The 0.5-inch central emitter hole² is surrounded by six 0.4-inch fuel holes³. The revolver¹ has minimum web thicknesses of 0.060 inch between emitter and fuel, 0.040 inch between fuel and the outside, and 0.110 inch between neighboring fuel holes.

With these dimensions, the fuel chambers occupy 42.8% of the converter cross-section. Assuming a reactor core made up of such elements separated by 0.060-inch vacuum gaps, the fuel chambers would occupy 36.0% 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 0.66 and 0.51 inch, respectively, the fuel chambers would occupy 44.8% of the core volume.

The converters were loaded with annular cylindrical fuel pellets⁴ of 0.396-inch O.D., 0.200-inch I.D., and 0.51-inch length. The fuel was UO_2 of 92% theoretical density and 9% enrichment, which was based on the results of a mock-up test in the Battelle Research Reactor, where the in-pile test is scheduled to be conducted. The design loading per converter is 58 gm of U_{235} .

The emitter body contains six thermocouple wells, not shown in these figures, located at various points of the fuel element periphery. Each well is a slanted hole of 0.040-inch diameter, penetrating to a depth of 0.2 inches into the web between fuel chambers⁵. Thus, the external-fuel design lends itself to detailed monitoring of the emitter body temperature distribution. For example, during the in-pile test the converter will 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 will show how much transverse temperature gradient is produced by the existing flux gradient. Another interesting point is that the presence of

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thermocouples at the top, middle, and bottom of the revolver makes it possible to observe the effect of UO_2 redistribution within the fuel chamber on the axial temperature profile of the emitter.

To aid in venting the released fission gases during the in-pile test, there is a tungsten snorkel tube⁵ at the center of each fuel chamber, extending over the full length of the fuel element; it has 0.040-inch perforations at 0.5-inch intervals, and is welded to a tungsten cover disk⁶ at its upper end. All fuel holes connect to a common fission gas plenum at the top of the emitter body.

The ends of the emitter body are joined to W-25Re end caps¹⁰. These seal the fuel chambers, except for a single W-25Re vent tube¹¹ of 0.060-inch O.D. and 0.040-inch I.D., which is connected to the upper end cap. Integral with each end cap is a half-inch long emitter lead¹² of 0.050-inch wall thickness. The resultant emitter lead resistance is close to the optimum for this diode.

Each emitter lead is 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 0.020-inch thick cylindrical tungsten sleeve¹⁵ connecting them. To permit rf-induction heating of the emitter body during out-of-pile testing, the secondary containment sleeve¹⁵ is not emplaced until after the completion of that test.

Collector Assembly

The columbium collector⁴, which is separated from the emitter by a 0.010-inch cesium gap², has a wall thickness of 0.135-inch. To avoid the complexity of operating a liquid metal loop in the test chamber, the collector is water-cooled⁷ across a 0.003-inch wide helium gap (cold). The system is static, and the collector temperature is varied by adjusting the helium pressure in the sub-atmospheric range.

The ends of the columbium collector¹⁶, beyond the active length of the diode, are expanded to a 0.8-inch outer diameter, to reduce ohmic losses. To center the collector within the emitter hole, each end of the collector is positioned by eight sapphire balls¹⁷ of 0.040-inch diameter, which are seated in hemispherical cavities in the collector at 45° intervals. These sapphire balls are in contact with the cool end of each emitter lead.

In addition, there are three anti-shortening spacers¹⁸ within the active region of the diode: one at the center, and the others one inch from each end. These spacers, which are not shown in Figure 1, consist of split and grooved alumina rings inserted into corresponding collector grooves, where they are retained by W-25Re wire snap-rings. The W-25Re wires extend 0.005-inch beyond the radius of the collector, and do not touch the emitter when the collector is properly centered.

The collector is joined to the metal-ceramic seal at the upper end of the converter. At the lower end, a columbium bellows¹⁹ is interposed between collector and seal, to allow for the differential thermal expansion of the emitter and collector assemblies. The columbium bellows has a nested configuration and contains fourteen convolutions of 1.375-inch O.D., 0.9-inch I.D., and 0.005-inch wall thickness.

The bottom end of the collector is joined to the cesium reservoir²⁰ by a 0.8-inch long cesium leg²¹ of 0.156-inch O.D.; both are of columbium. Heat conduction to the reservoir through the cesium leg is less than 7 watts, but during in-pile testing the reservoir receives an additional input of 40 watts from gamma heating. The reservoir is water-cooled via a split cooling clamp, not shown. Fine

temperature control of the cesium reservoir is effected by means of electrical heaters²²; two independent heaters are provided, for redundancy. The floor of the reservoir is connected to a columbium tube²³ for diode outgassing, cesium charging, and final pinch-off.

Cooling and Electrical Arrangement

The collector cooling water flows through a 0.204-inch O.D. by 0.152-inch I.D. stainless steel tube⁷. Circular ridges projecting from this stainless steel tube at 0.5-inch intervals provide for centering within the collector, to maintain a uniform 0.003-inch cold helium gap. Beyond the active length of the diode the helium gap is increased to at least 0.025-inch, to reduce heat transfer and prevent over-cooling the collector ends¹⁴.

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

Since this is a double-ended diode, there are four converter terminals. These terminals are considered to be the upper and lower emitter power take-off flanges¹⁴ and the upper and lower collector hubs²⁷. Thus, the diode terminal voltage, power output, and efficiency reported later are the values obtained after the electrical and thermal losses in the optimized emitter leads. Any losses beyond these terminals are considered to be merely part of the experimental arrangement, rather than an inherent characteristic of the converter.

The collector cooling water flows through the collector coolant tube⁷ in an upward direction. A typical flow rate is 0.5 gpm and 8.2 ft/sec. The water inlet and outlet tubes²⁸, which are made of copper, simultaneously serve as the high-current collector leads. To avoid overcooling the collector hubs²⁷ below the cesium reservoir temperature, these hubs are connected to the water-cooled copper tubes²⁸ by thermal chokes²⁹.

Similarly, water-cooled copper tubes³⁰ serve to conduct the upper and lower emitter currents. Again, thermal chokes³¹ must be employed to avoid overcooling the W/Re emitter power take-off flanges¹⁴. Each of these thermal chokes consists 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 is 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 are lifetested at a temperature which realistically simulates their operating condition in a thermionic reactor.

In addition to their thermal and electrical functions, the molybdenum skirts³¹ also serve two other purposes; they are used for mechanical support³³ of the converter during out-of-pile and in-pile testing, and they make it possible to maintain the tungsten and tungsten-alloy components of the converter above their ductile-brittle transition temperature during reactor shutdown, by means of an electrical heater³³ (not shown in Figure 1) brazed to the inner surface of each Mo skirt.

Containment

Nuclear safety rules at the test reactor require 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 form part of the secondary container; and the 2.75-inch diameter outer wall of the test capsule³⁴, made of 0.057-inch thick stainless steel, serves as the tertiary container.

The secondary containment volume is sealed under vacuum after completion of the out-of-pile testing. The tertiary containment volume, which contains the thermal radiation shielding³⁵ consisting of 50 layers of thoriated tungsten foil, is an active vacuum. During the in-pile test it is 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 are four 0.125-inch O.D. columbium tubes³⁶ joined to the upper emitter power take-off flange¹⁴. These tubes form part of the primary containment enclosure. Three of the four are cover tubes for the six emitter thermocouples. The W-25Re and W-3Re thermocouples employ multi-strand wire, and have bare junctions that are knotted rather than spot-welded, to avoid embrittlement. The thermocouple leads are beryllia-insulated in the vicinity of the hot emitter body¹, and are sheathed in four-hole alumina insulators within the columbium cover tubes³⁶. During in-pile testing, the thermocouple cover tubes extend for approximately seven feet above the top of the reactor core, in order to move the required insulating vacuum feedthroughs to a region of lower neutron flux.

Fission Gas Collection

The fourth of the above columbium tubes³⁷ serves as the secondary container around the W/Re fission gas vent tube¹¹. As illustrated in Figure 3, the vent tube is joined to a fission gas accumulator³⁸, and the cover tube³⁷ is joined to the secondary containment shell³⁹ which surrounds the accumulator. Both connections are made via bellows⁴⁰ to allow for differences in expansion. The fission gas collection system, which is made of stainless steel, is not joined to the converter assembly until after completion of the out-of-pile test and installation of the secondary container. Note that there are two separate tubes for sequential vacuum pumpdown and pinch-off, one for the accumulator and fuel volume⁴¹ and one for the secondary containment shell⁴².

The fission gas accumulator³⁸ has a 2-inch diameter and 6-inch length. It is sized so as to develop a maximum pressure of 100 torr after 10,000 hours of operation, assuming complete release of xenon and krypton. There are two differential pressure transducers, one⁴³ to measure the pressure difference between the accumulator and the secondary container, and the other⁴⁴ to measure the difference between the secondary and tertiary containers. Thus, the system is designed not only to monitor the extent of fission gas venting from the fuel element, but also to detect the occurrence of leaks from the fuel element or the fission gas collection system into the secondary container.

The two transducers, which are located 3 feet above the top of the reactor core, are radiation-hardened versions of the LVDT (linear variable differential transformer) type. As shown in Figure 3, the two pressures whose difference is to be measured are separated by a 2.375-inch diameter diaphragm⁴⁵. This diaphragm is connected to a rod-shaped magnetic core⁴⁶, whose displacement is measured by a set of coaxial transformer coils⁴⁷. The transducers have a theoretical resolution of 0.5 torr.

In-Pile Test Arrangement

Figure 3 shows the lower end of the in-pile test capsule wall. At the bottom of the capsule is a centering hub⁴⁸ for seating the capsule in the reactor grid plate. Above this hub there are eighteen 1-inch diameter inlet ports⁴⁹ for the forced circulation of the reactor cooling water. Above the reactor core, the 2.75-inch diameter capsule wall³⁴ is expanded to a 6-inch pipe⁵⁰ by means of an eccentric transition section⁵¹.

An overview of the whole test capsule, showing its location in the test reactor, is presented in Figure 15. As can be seen, the top of the previously shown 6-inch diameter pipe is connected to a tee-section, whose top is sealed by a 8.5-inch diameter assembly plate. The converter and the fission gas collection system are suspended from this assembly plate. It contains numerous insulated feedthroughs for the diode and heater leads, water and helium lines, thermocouples and voltage probes. To minimize axial stress, all solid lines are connected via bellows, with flexible high-conductance bypass straps on all current-carrying lines.

Above the assembly plate is an offset 6-inch diameter dry well, through which the various instrumentation and plumbing lines are brought to the top of the reactor pool. The side port of the tee-section is connected via 8-inch plumbing to the previously described vacuum ion pump system at the top of the reactor bridge.

CONVERTER FABRICATION

The converter consists of five major subassemblies three of which are illustrated in Figure 4: 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, are 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 are 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 is 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 8-inch long hole is machined in two parts; i.e., half way from each end of the tungsten billet. Tubular electrodes are employed, and the central tungsten core drops out when the two holes meet 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 is honed. The honing process removes a layer of approximately 0.002-inch, which is important because it is this layer which is most likely to contain defective material as the result of the electric discharge process.

After finishing the emitter hole, the ends of the tungsten billet are ground to provide the inner and outer lips required to join it to the end caps. The six peripheral fuel holes are then electric-discharge-machined and honed, in the same manner as the central emitter hole. Finally, the outer surface of the revolver is ground to size, and the six slanted thermocouple walls are introduced by the EDM technique; two of the six are faintly visible in the emitter photograph in Figure 4. The last step is to electropolish the outer surface and end faces of the emitter body. Wherever possible, this process is used as the final step on all tungsten components, because of its sensitivity in revealing any surface defects.

A total of five 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.

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 defined. The second of the arc-cast emitter bodies was successfully fabricated into the diode described herein.

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 consists of an upper and lower subassembly. As illustrated in Figure 4, each of these subassemblies contains 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 contains the vent tube and four cover tubes, and the lower assembly includes 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 electropolishing, with intermediate annealing steps. The 0.040-inch I.D. vent tube, which is 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 is a 0.060-inch thick alumina (Lucalox) wafer. On each side of this wafer are several layers of mixed powders, with compositions grading from ceramic-rich to metal-rich. The assembly is consolidated by hot isostatic compaction at approximately 1650°C and 10,000 psi. After autoclaving, the seal is finished by machining, ultrasonic drilling, and diamond grinding. Before use in a diode, each seal is acceptance-tested by leakchecking after 25 thermal cycles to 1000°C.

The emitter heat chokes, which are identified as "emitter-terminals" in Figure 4, are 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 consists of four nested convolutions, joined by EB (electron-beam) welding. Each convolution consists of two diaphragm rings, which are stamped and shaped from 0.005-inch columbium foil. Individual convolutions are first prepared by EB-welding pairs of diaphragm rings along their inner edges, while their outer edges are separated by a sacrificial molybdenum spacer ring. These convolutions are then joined by EB-welding along their outer edges, after which

the molybdenum spacers are 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 include 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 is described in detail in another paper⁽⁵⁾ of these proceedings. 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 0.25-inch 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 very 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 discussed above, a half-inch long section containing the leaky region was cut off, and the cut end remachined. This shortened revolver was then incorporated in the converter, using a specially machined W-Re end cap transition. As a result, the active length of this diode is only 7.5 inches, instead of the 8-inch 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 is that between tungsten-rhenium and columbium. In making these joints, which include 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 4. Individual components are first joined to form the upper and lower emitter subassemblies. Next, the lower subassembly is 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 is then loaded with fuel and snorkels, and the fueled assembly is vacuum-fired at the emitter operating temperature, after which it is sealed by joining it to the upper subassembly. The finished fuel element can be leak-checked through the vent tube.

Since the diameter of the collector ends exceeds that of the emitter hole, the collector assembly must 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, is inserted into the emitter hole, and the collector extension with sapphire balls in place is inserted into the top of the emitter assembly. Union between the two collector halves is effected by means of an axial EB-weld at the upper collector well. Two additional welds seal the diode.

Finally, the stainless steel coolant assembly is inserted into the top of the collector hole, and the helium space is sealed by means of the two vacuum brazes. The right photograph in Figure 4 shows the completed diode, ready for outgassing and charging with cesium.

DIODE PROCESSING AND TEST ARRANGEMENT

Converter outgassing takes place in the same vacuum chamber, and with the same rf-induction heating arrangement, as subsequent out-of-pile testing. RF-induction heating had also been employed in previously reported (6) out-of-pile testing of unfueled diodes. In that test program, the converter was located inside a water-jacketed quartz vacuum chamber, and the rf-induction coil was located outside the vacuum chamber, as shown in Figure 5. 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 (e.g., of the thermocouples).

For these reasons, it was decided that the present program would employ a more conventional all-metal bell-jar using a crushable copper gasket, metal-ceramic vacuum feedthroughs, and with the rf-induction coil located within the test chamber. This would make possible a much better vacuum, and greatly simplify 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 does not appear to be commercially available. As shown in Figure 6, the rf-feedthrough that evolved is a co-axial unit, with a brazed metal-ceramic seal. The unit is sealed to the test chamber baseplate by means of copper-gasketed knife edges. A co-axial rather than parallel feedthrough design is used, to

avoid excessive induction heating of the test chamber wall.

In addition to the ceramic seal at the feedthrough's outer end, there is a slip-fitted ceramic spacer at its inner end. This is to provide centering for the high-voltage copper tube, to minimize the danger of breakdown. However, with the spacer design shown in Figure 6, 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.

The problem was corrected by modifying the spacer design to provide a considerably larger 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 7, 8, and 9. Figure 7 shows a close-up view, Figure 8 illustrates the diode outgassing and cesium charging procedure, and Figure 9 presents an overview of the test arrangement.

The ends of the converter³³ can be seen projecting from the rf-induction coil³⁴. The induction coil is connected to the previously shown coaxial feedthrough³⁵, whose outer ends are connected to a 75-kw, 450 kHz rf-power supply³⁶. Water-cooled copper tubes act as high-conductance current leads to the diode, two tubes to the collector³⁷ and four for the emitter³⁸. These tubes enter the test chamber through ceramic feedthroughs³⁹. The 18-inch diameter baseplate⁴⁰ and the 30-inch high belljar⁴¹ of the stainless steel test chamber are both water cooled. During diode outgassing and out-of-pile testing, the fission gas vent tube is open to the vacuum chamber.

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 flanges⁴⁴, the collector ends⁴⁷, and the cesium reservoir²⁰.

Figure 7 shows the cesium reservoir⁴² and its heater⁴³, the reservoir cooling clamp was not yet installed. Emerging from the bottom of the reservoir is an S-shaped copper tube⁴⁴ which passes through a feedthrough at the bottom of the baseplate. This S-tube is used for outgassing the diode and subsequently charging it with cesium. As shown in Figure 8, after this tube⁴⁴ emerges from the vacuum chamber it is connected to a 0.75-inch diameter extension⁴⁵, which contains the glass ampoules with the cesium charge. Below this point, the tube is connected to a 15-liter/sec ion pump⁴⁶ used for outgassing the inside of the diode. The test chamber itself is evacuated by a separate 400-liter/sec ion pump⁴⁷.

During outgassing the emitter body was heated to a maximum of 1900°C, and the S tube⁴⁴ and cesium ampoule container⁴⁵ 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 leads⁴⁸, to duplicate the ohmic heating in the collector heat chokes⁴⁹ during diode operation.

Heating was continued for several days, to reduce the pressure at the diode ion pump⁴⁶ to 10⁻⁸ torr, at which point the ampoule container⁴⁵ was squeezed to crush the glass ampoules. After some additional pumping to remove any gas

released from the cesium ampoules, the diode pumpdown leg⁶⁶ 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 ampoule container⁶⁶ with the crushed glass, the liquid cesium was transferred from the S-tube⁶⁶ 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 hubs⁷⁷ 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 is 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 are needed later to compute the converter's efficiency.

Figure 9 presents an overview of the out-of-pile test arrangement. It shows the test chamber⁶¹ and its ion pump⁶⁷, the 75-kw rf-power supply⁶⁶, 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 readout.⁷⁵

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 actuator⁷⁸. All pyrometric readings were corrected, with corrections based on the emissivity of clean tungsten.

Emitter Temperature

It should be emphasized that the "emitter temperatures" 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 0.026 inch. Figure 10 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.

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 11. 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 UO₂ temperature of less than 1900°C, far below its melting point.

The calculation illustrated in Figure 11 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.

Load Control

Figure 9 also shows the voltage and current meters⁷⁹, an xy-recorder⁸⁰ for tracing the current-voltage characteristics of the diode, and the diode current leads⁸¹.

Early in the program, considerable effort had been devoted to devising a remotely adjustable power load, to be located within the test chamber, directly at the upper and lower ends of the converter. Such an arrangement would be very desirable, because of the very high currents (~ 1000 amperes) generated by this diode. Even with water-cooled high-conductance copper leads, delivering such currents to an externally located adjustable load consumes more power than that generated by the diode. Ohmic losses in the leads are particularly severe in the case of the in-pile test, where the current must be delivered from the core to the top of the reactor pool. To overcome these lead losses requires a high-current dc-power supply, which could be eliminated if a remotely adjustable load were available.

The load design which was investigated is illustrated in Figure 12 for the lower end of the converter. The emitter and collector power take-off flanges⁸² are connected by a flexible molybdenum strap⁸³ in series with a 0.25-inch diameter columbium chamber⁸⁴ partially filled with sodium. This chamber, which acts as a variable-resistance load, is connected to a liquid metal reservoir⁸⁵. The liquid metal level in the load is adjusted by remote control of the inert gas pressure⁸⁶ above the sodium reservoir. To decrease the sensitivity of the liquid level to changes in the inert gas pressure or the sodium vapor pressure, inert gas at a fairly high pressure (~ 1 atm) was trapped above the liquid metal in the load chamber⁸⁷.

Even with that precaution, however, this load control system proved to be inherently unstable. To understand the cause of the instability, suppose the partially filled load chamber under equilibrium operation were to experience, for some reason, a small drop in the liquid level. This would raise the resistance of the load and increase the ohmic heating. The resultant temperature rise expands the trapped inert gas, forcing more of the liquid metal out of the load chamber. This continues until the chamber is completely dry. Conversely, an initial rise in the liquid level would lead to the reverse condition, tending to fill the load chamber. Thus, there was a strong tendency for the load to switch to either its maximum or minimum resistance condition; intermediate levels were very difficult to maintain.

The above stability problem may be solvable by resorting to higher gas pressures, or by more effective cooling of the load tube. The latter remedy, however, is limited because of the need to maintain the desired high temperatures at the collector hubs and the emitter flanges. In any event, it was decided to abandon the remotely adjustable load concept, and bring the diode current out of the vacuum chamber to a more conventional external power supply.

A high-current dc power supply was therefore built. It employs a 5-kw Y-to-Y-connected variable autotransformer, to vary the ac input voltage delivered to a three-phase

full-wave silicon rectifier bank. This rectifier bank is water cooled, to permit a maximum current capability of 1200 amperes.

The positive output side of the full-wave rectifier stack is divided into two parallel branches, which are connected to the two collector ends of the converter. Calibrated shunts are used to measure the individual current. Each side of the rectifier has a single-section-inductance input LC filter, where L is about 3 microhenries and C is 0.46 farads.

At a typical operating point, with the converter producing 800 amperes at 0.6 volt, the power supply delivered 1.8 volts. Thus, a total of 2.4 volts was consumed in overcoming the various lead resistances in out-of-pile testing.

If desired, the in-pile test could be operated without an external power supply, by installing a fixed load resistance (e.g., 0.001-ohm) at each end of the converter. However, such an arrangement was rejected because it would sacrifice the ability of adjusting the load resistance during the in-pile test, to compensate for the possible deviation of the fission density from its predicted value.

OUT-OF-PILE TEST RESULTS

All performance measurements were made under steady-state d.c. condition, 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 is 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 power delivered by the external power supply from the electrical power consumed in overcoming the resistance of the current leads. 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.

A typical current-voltage characteristic of the converter is shown by the solid curve in Figure 13. 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 re-optimized, and the diode was allowed to equilibrate.

Figure 13 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 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.

Heat Balance and Efficiency

As indicated earlier, the converter efficiency and the thermal power supplied to the emitter are computed by applying an energy balance to the diode and the current leads within the test chamber. For example, for the illustrative operating point depicted in Figure 13, the

collector cooling water flowed at a rate of 0.550 gpm and experienced a temperature rise of 25.6°C between the inlet and outlet points at the test chamber feedthroughs. This corresponds to a total heat input of 3717 watts to the collector coolant within the test chamber. From this we must subtract 259 watts, the ohmic heating at the upper collector heat choke and the upper collector lead within the test chamber; and 266 watts, the analogous ohmic loss at the bottom of the collector. Therefore, the true heat loss from collector to coolant, which includes radiation, electron heating, ohmic losses within the collector, and thermal conduction across the cesium gap, is 3192 watts. Note that this value includes diode end losses, i.e., thermal conduction through the ceramic seals.

Similarly, the upper and lower emitter lead coolant streams picked up 636 and 554 watts, respectively, within the test chamber. Subtracting the ohmic heat generation in the emitter heat chokes and the emitter test leads, we obtain heat loss rates of 464 and 369 watts from the upper and lower emitter power take-off flanges. This represents the rate at which heat is transferred, by conduction and radiation, from the ends of the emitter body to the power take-off flanges.

Thus, the emitter heating rate, which is the actual rf-induced heating rate less the radiative heat loss from the uninsulated outer surface of the emitter body, consists of four terms: the 3192 watts lost to the collector, the 464 and 369 watts lost to the upper and lower emitter leads, and the 530 watts transformed into electrical energy, making a total of 4555 watts.

The corresponding conversion efficiency is $530/4555 = 11.6\%$. This does not include the effect of extraneous losses, such as electrical losses in the rf-power supply and induction coil, thermal radiation from the outside of the emitter body, and ohmic losses in passing the diode current through the heat chokes and bringing it to the outside of the vacuum test chamber. These losses are merely the result of the particular test arrangement used, and would not be present in a properly insulated thermionic reactor. The efficiency quoted does include all those losses that are an 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 14. Predicted current voltage characteristics (dotted curves) are shown both for constant thermal power and for constant maximum emitter temperature.

The method of computing the predicted performance of the converter was described in some detail in an earlier report⁽⁶⁾. 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, interelectrode potential, current and power densities, and emitter heat flux. The computations employ performance data generated by the SIMCON analysis⁽⁷⁾. If desired, our converter analysis program can also calculate the location and shape of the isothermal cavity after UO₂ redistribution in the fuel chamber.

Inspection of Figure 14 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.

Comparison of the measured illustrative operating point in Figure 14 with the predicted performance curves reveals two discrepancies: For a 4500-watt heat input, the measured power output is significantly less than predicted, i.e., the conversion efficiency is lower. On the other hand, for the given emitter temperature, the measured output is appreciably above prediction; particularly since the actual emitter temperature may have been as much as 100°C lower than the 1940°K measured on the outside of the emitter body, as illustrated earlier in Figure 10.

The reasons for the second discrepancy are not clear. The first one, the seemingly low conversion efficiency, could be due to a combination of factors: First, the SIMCON⁽⁷⁾ performance analysis may simply be over-optimistic, particularly in estimating the radiative heat loss from emitter to collector. Second, the inferred measurement of the converter heat rejection rate may be overly conservative, since it neglects any radiative heat transfer from the outside of the uninsulated hot emitter body to the three coolant lines which go to the top of the diode. As a result, the net heat input to the converter may be several hundred watts lower than the inferred value of 4555 watts. And, third, thermal end losses may be significantly higher for a water-cooled converter than for liquid-metal-cooled devices, because of radiation, helium conduction and natural convection from the collector extensions to the cold water.

Test Operation

At present the converter is undergoing an extended qualification test before installing it in-pile. 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 feed-through, which were eliminated by modifying the design of the ceramic spacer bushing. Another difficulty encountered was the development of small leaks between the helium and the vacuum test chamber. These have been 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 is 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 is 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 have been experienced to date with the nested columbium bellows, which contain thirty EB-welds and are exposed to high-temperature cesium vapor; but, ironically, we have had problems with the standard-production hydroformed stainless steel bellows, which are 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 have since been replaced, and the out-of-pile test is continuing. At this writing, the converter has operated for over 1000 hours, with a total energy production of 480 kilowatt-hours.

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Fig. 1: ISOMETRIC VIEW OF CONVERTER

Fig. 2: CONVERTER CROSS-SECTION

Fig. 4: CONVERTER COMPONENTS AND ASSEMBLY

Fig. 5: PREVIOUS RF-HEATING
ARRANGEMENT

Fig. 6: CO-AXIAL R.F. VACUUM FEEDTHROUGH (450 kHz, 75 kw)

Fig. 7: OUT-OF-PILE
TEST STATION

Fig. 8: CONVERTER PROCESSING
AND CESIUM CHARGING

Fig. 9: OUT-OF-PILE
TEST ARRANGEMENT

core layout

DIODE

CONTROL ROD

Fig. 11: TEMPERATURE DISTRIBUTION OF NUCLEAR-HEATED EMITTER BODY

Fig. 12: REMOTELY ADJUSTABLE to
LIQUID METAL POWER LOAD **pressure controller**

Fig. 13: MEASURED CONVERTER PERFORMANCE

Fig. 14: COMPARISON OF MEASURED AND PREDICTED PERFORMANCE

Fig. 15: IN-PILE TEST ARRANGEMENT