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**Development of Techniques for
Joining Fuel Rod Simulators
to Test Assemblies**

A. J. Moorhead
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DEVELOPMENT OF TECHNIQUES FOR JOINING FUEL ROD SIMULATORS TO TEST ASSEMBLIES

A. J. Moorhead and R. W. Reed

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DEVELOPMENT OF TECHNIQUES FOR JOINING FUEL ROD
SIMULATORS TO TEST ASSEMBLIES

A. J. Moorhead and R. W. Reed

ABSTRACT

We have developed a unique tubular electrode carrier for gas tungsten-arc welding small-diameter nuclear fuel rod simulators to the tubesheet of a test assembly. Both the close-packed geometry of the array of simulators and the extension of coaxial electrical conductors from each simulator hindered access to the weld joint. Consequently, a conventional gas tungsten-arc torch could not be used. Two seven-rod assemblies that were mockups of the simulator-to-tubesheet joint area were welded and successfully tested. Testing consisted of thermal cycling 500 times from 370°C (698°F) down to 100°C (212°F) with an internal pressure of 11.72 MPa (1700 psi). No leakage was detected by helium mass spectrometry, either before or after testing.

We have also developed modified versions of the electrode carrier for brazing electrical leads to the upper ends of the fuel pin simulators. Satisfactory brazes have been made on both single-rod mockups and an array of 25 simulators by using the modified electrode carrier and a filler metal with a composition of 71.5 Ag-28 Cu-0.5 Ni.

INTRODUCTION

Every nuclear reactor program has the need for in-depth understanding of reactor core thermal-hydraulic phenomena and for detailed investigations of safety-related occurrences. Although some of the necessary research and development can be conducted only in an actual reactor, many of the studies on thermomechanical performance of steady-state and transient operating conditions are conducted on test assemblies that simulate segments of the core of the reactor. These test assemblies or bundles use high-performance electrically heated fuel rod simulators (FRS) in place of radioactive fuel rods. The FRS have the same external diameter and function (to produce a high heat flux) as

the fuel rods in a nuclear reactor but accomplish this through resistance heating of a spirally wound metallic ribbon, rather than by radioactive fission. However, because the simulators have a somewhat lower heat capacity than an actual fuel rod, the FRS do not easily simulate the transient test conditions of a fuel rod.

The Core Flow Test Loop (CFTL), a part of the Gas-Cooled Fast Breeder Reactor (GCFR) Program at Oak Ridge National Laboratory (ORNL) will be built to conduct experiments using these test assemblies. The CFTL will be a high-pressure, high-temperature, helium-circulating system that will permit detailed study of simulated segments of core assemblies for a GCFR Demonstration Plant envisioned by the General Atomic Company.¹ The normal operating pressure for the CFTL will be 2.0 MPa (1500 psi) and the nominal inlet and outlet temperatures will be 350°C (660°F) and 593°C (1100°F), respectively.

The FRS are highly complex devices that thoroughly test the skills of designers and fabricators alike. A comprehensive review of some of the aspects of the design and fabrication of fuel rod simulators has been written by Saucum et al.² Although that report is concerned with a heater designed specifically for Liquid-Metal Fast Breeder Reactor (LMFBR) out-of-reactor tests, many of the problems and the developed solutions for the LMFBR simulator also apply to the FRS for the Core Flow Test Loop. Grindell and Huntley have written a description of the system design for the CFTL,³ and Moorhead et al.⁴ have published a report on the development of joining techniques for fabrication of the fuel rod simulators for this test system.

Both pulsed ruby laser welding⁵ and electron beam welding (EBW) have⁶ previously been investigated for welding fuel rod simulators to a tubesheet to form a test assembly. The EBW process was superior, and eight bundles of rods have been fabricated with this process. These assemblies have operated collectively for over 26,000 h to date in high-temperature sodium with no failures in the fuel rod simulator-to-tubesheet joints.⁶

Although the EBW process has proven capable and reliable in this application and is the reference process for attaching the CFTL simulators to the tubesheets, it does have the drawback that the test bundle

must be placed in a vacuum for welding. An electron beam welder with adequate chamber size (other than in a production facility) for welding of the 1.3-m-long (51-in.) FRS for the above-mentioned Thermal-Hydraulic Out-of-Reactor Safety (THORS) Facility was not available at ORNL. Consequently, the THORS program shipped its test bundles to a job shop in California for welding. This caused significant problems in handling and transportation. But even when the simulator lengths were increased to 1.6 m (64 in.), the THORS program managed to use the California facility by adding an extension to the top of the chamber.

The simulators for the CFTL are approximately 2.5 m (98 in.) long so that only electron beam welders with very large vacuum chambers could be used for these simulator-to-tubesheet welds. Although we have located a company with a machine that apparently can accommodate these very long bundles, the packing and shipping problems remain. Consequently, we have undertaken a program to develop an alternate technique for making these welds. We have selected the gas tungsten-arc process, and our equipment and procedural developments will be discussed below. We will also describe our work developing a technique for brazing the electrical conductors to the coaxial leads that protrude from the top of the FRS.

GEOMETRY OF FUEL ROD SIMULATOR

The present design (although subject to change) of the simulator for the CFTL is shown in Fig. 1. The outside diameter of the type 316 stainless steel sheath or cladding is 7.47 mm (0.294 in.), and as mentioned previously the overall length is about 2.5 m (98 in.). This simulator differs from some others of its kind in that both power leads enter at one end, rather than at opposite ends.

In other simulators, such as those for the LMFBR Program, the electrical circuit is completed by grounding one end of the element to the end of the rod, thus completing the circuit through the coolant. The reentrant design of the CFTL simulators complicates the attachment of the electrical cables, as will be seen below. There are four 0.51-mm-diam (0.020-in.) sheath type thermocouples installed internally

Fig. 1 — The GCFR-Core Flow Test Loop Fuel Rod Simulator.

in the FRS during fabrication, and these must be protected from damage when the simulator-to-tubesheet welds are made. The thermocouples are temporarily stored in a spiral wrap around the copper power leads, and this increases the diameter of the projection from 4.06 mm (0.160 in.) to 5.08 mm (0.200 in.). Thus, the already limited available space for welding is decreased even more.

Although the 7.47-mm-diam (0.294-in.) FRS is the present reference design, we are considering a modified version with the sheath flared out to 9.52 mm (0.375 in.) in diameter in the weld area. We have simultaneously developed equipment and techniques to accommodate each size. The flared design has the advantages of minimizing contact of the boron nitride preforms with the stainless steel sheath during simulator fabrication (thereby reducing the chances for subsequent weld problems) and of enhancing bundle assembly by reducing the area of close fit between the FRS and the tubesheet to the weld joint only. Since we have not determined the length that the conductors will extend beyond the sheath, we have worked with lead extensions (i.e., the copper rod and tubular conductors) from 26.9 mm (1.06 in.) up to 190.5 mm (7.50 in.).

The plan of a portion of a 91-rod bundle of simulators (Fig. 2) for CFTL shows that the rods will be tightly packed in the assembly with each FRS at a distance of only 11.20 mm (0.441 in.) from each of its nearest neighbors. This distance will be the same whether the diameter of the simulator is 7.47 or 9.52 mm (0.294 or 0.375 in.). This distance, the diameter and sheath thickness of the FRS, and the length of extension of the copper conductors all significantly influenced our development of equipment and techniques for an alternate joining process, as will be discussed below. The length of the simulators and the size of the bundle of heaters also affected our decision to consider an alternate process to electron beam welding.

SELECTION OF JOINING TECHNIQUES

One of the primary considerations in our search for an alternative to electron beam welding of the FRS to a tubesheet was that we wanted the work to be done locally, specifically in the shop area where the bundle was to be assembled. This was to avoid the very real problems

Fig. 2 - Plan Layout of Approximately 1/6 of a 91-Rod Bundle Assembly (85 Rods Powered) of Fuel Rod Simulators for the Core Flow Test Loop.

that we had transporting the THORS bundles to California and back, namely physically moving the assembled but unwelded bundle by several means of transportation without moving the simulators with respect to the tubesheet or contaminating the weld joints with boron nitride insulation. For instance, in at least one of the THORS bundles, BN was vibrated out the end of the FRS onto the weld joint area during shipping. This resulted in pore formation during EB welding. The actual shipping and handling of the THORS bundles was only accomplished by very careful handlers from ORNL who accompanied each bundle and not by commercial freight handlers. Furthermore, if a leak developed after the bundle was returned to ORNL, or if one or more heaters failed and had to be replaced, we had to repeat the entire packing and shipping operation.

We considered several alternate joining processes at the start of this program: laser welding, brazing, and gas tungsten-arc welding. Pulsed ruby laser welding techniques had been developed by Estes for attaching the FRS to the tubesheet of the THORS bundle,⁵ but the reproducibility was not as good as with the EBW process. However, we decided not to pursue this technique for the CFTL bundles, not on the basis of those results, but because of interference caused by the relatively long copper conductors protruding from the end of the FRS. In the simulator for THORS this length is a maximum of 63.5 mm (2.50 in.), but in the heaters for CFTL the extension may be up to 190.5 mm (7.50 in.). The maximum working distance of the available laser welders (based on the focal length of the output lens) is only 94.8 mm (3.73 in.). Therefore, it is not possible to weld at a distance of 190.5 mm (7.5 in.). Although it might be possible to modify the optics of the laser by adding a longer focal length objective lens, we thought that this would also cause a proportional increase in spot size, resulting in less energy density and a decrease in weld penetration.

We considered brazing, but did not pursue it past conceptualization for three reasons. First we anticipated the difficulty of uniformly heating an entire test bundle, including a massive tubesheet, to the brazing temperature so that all the joints were satisfactorily brazed. Secondly, we were concerned that the release of moisture and absorbed gases from the BN insulation in the simulators would contaminate our brazing atmosphere, thereby reducing wetting and flow, unless a technique for extensive bake-out of the components could be developed. Finally, we could not visualize a repair technique for brazed bundles if a joint leaked or if one or more rods failed and had to be replaced.

Thus, it became apparent that only our third candidate process, gas tungsten-arc (GTA) welding, was left for development as an alternate process to electron beam welding for attaching fuel rod simulators to the tubesheet of a test bundle. This process has two advantages: it can be readily controlled to make high quality reproducible welds through the use of carefully developed procedures and automatic programmable equipment, and each FRS can be welded (and repaired if necessary)

individually. As will be discussed below, our major efforts to date have been in adapting this reliable process to the stringent space limitations in the CFTL bundle array.

DEVELOPMENT OF A TUNGSTEN ELECTRODE CARRIER

After considering the various geometric constraints on the weldment — small-diameter thin-wall heater sheath, close spacing between simulators, and lengthy projections from the center of each heater — it was obvious that no commercial tungsten-arc torch was available that could weld a joint at that location. We then set out to develop an electrode carrier for this particular application. The starting point for our efforts was a commercially procured welding head (Fig. 3) that we had used extensively in developing techniques for tube-to-tubesheet

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Fig. 3 — The Commercially Made Welding Head that Was Modified for Welding and Brazing of Fuel Rod Simulators.

welding inside the confining bore of a 15.88-mm-OD (0.625-in.), 2.84-mm-wall (0.112-in.) tube.⁷ This welding head provides rotary movement of a tungsten electrode along a weld joint via a hollow copper electrode carrier, which also conducts an inert shielding gas to protect the weldment from contamination. The rotation speed of the welding tip as well as the welding current cycle are precisely controlled through a 200-A dc solid-state programmable power supply.

Based on prior experience we selected the trepanned joint design shown in Fig. 4 for our preliminary development. This design has several advantages: (1) the groove corrects the mass imbalance (and thus the differing heat requirements) between the large tubesheet and the thin wall of the simulator, (2) the resultant edge joint is readily weldable, and (3) it is relatively easy to cut away the projecting weld bead for simulator removal and replacement, without having to deepen the trepan. However, note that this type of weld is difficult to inspect volumetrically, and there is a built-in crevice at the root of the joint. However, as in the previous work the surface of the tubesheet will be overlayed with type 308 stainless steel filler metal to minimize any hot-cracking tendencies in the weldments.

Our preliminary calculations on the size of a hollow electrode carrier that would clear both the central power leads wrapped with thermocouples and the adjacent simulators showed that even the diameter of the tungsten electrode required to carry adequate current was a factor in our design. We therefore made some welds using a manual GTA torch on two pieces of 0.51-mm (0.020-in.) stainless steel sheet clamped together in a vise to simulate the 1.02-mm (0.040-in.) edge joint. Welding currents of only 10 to 15 A were required. These low currents allowed the use of a 0.51-mm-diam (0.020-in.) tungsten electrode, and so we designed our tip for that size.

We also calculated that the electrode had to be angled slightly toward the central axis to center the arc over the 7.47-mm-diam (0.294-in.) simulator sheath. We accordingly designed and built our first electrode carrier according to the design shown in Fig. 5 with holes in the tip to contain a 0.51-mm-diam (0.020-in.) tungsten at an angle of 16° (Fig. 6).

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Fig. 4 - Joint Design Used in Developing Techniques for Attachment of Fuel Rod Simulators to the Tubesheet of a Test Bundle.

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Fig. 5 - Original Design of Tungsten Electrode Carrier for Arc Welding of Simulators to the Tubesheet.

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Fig. 6 - Tip of Copper Electrode Carrier Showing Tungsten Electrode (Arrow) Angled to Center the Arc over the Joint Between a 7.47-mm-Diam (0.294-in.) FRS and a Tubesheet.

We subsequently made a series of welds on single-joint prototypes (Fig. 7) in which the space envelope of the copper leads wrapped with thermocouples and a potential cable connector were represented by a stainless steel shaft. The quality of these very early welds was excellent, as determined by visual examination for bead geometry, helium mass spectrometer leak detection, and metallographic examination

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Fig. 7 - Weld Parameter Development Specimen in Which the Space on a Fuel Rod Simulator, Which Would be Occupied by the Conductor Extensions (Wrapped with Sheath Type Thermocouples), is Represented by the Stainless Steel Shaft. The simulator-to-tubesheet weld is indicated by an arrow.

(Fig. 8). The cross-sectioned weld was made with a weld current of only 7 A, a travel speed of 1.5 mm/s (3.57 in./min), and an arc length of 0.51 mm (0.020 in.). The total arc time, including a 1-s overlap, was only 16 s. Note that the width of the weld bead at any point is at least as thick as the wall of the simulator sheath.

Because of the high degree of success in these early welds, which were made to develop basic parameters, only one significant change has been made in the general design of the electrode carrier. We were not pleased with the electrode's degree of protection from atmospheric contamination. Therefore we modified the carrier by adding four radial

Fig. 8 -- Cross Section Through Simulator-to-Tubesheet Weldment in a Type 304L Stainless Steel Single-Rod Mockup Specimen. Note that the "tubesheet" (on the right) has not been surfaced with type 308 filler metal. Etchant 50HCl, 10HNO₃.

holes connecting to shallow longitudinal grooves on the outside of the tip (Fig. 9). This allows inert gas to flow from the bore of the carrier out between the tip and the fused quartz gas cup, resulting in improved gas coverage of the weldment. To prevent aspiration of air from the closed end of the gas cup, we seal this area with silicone rubber compound. Since this material makes it more difficult to change a gas cup, we would recommend using an O-ring instead of silicone at that location on a production electrode carrier.

The only other ways we have changed the electrode carrier are increasing the length to accommodate simulators with long electrical lead projections and including other 0.51-mm-diam (0.020-in.) holes drilled axially in the end. These latter holes are centered on a 9.52-mm (0.375-in) bolt circle so that simulators having an expanded end with that outside diameter can be welded.

FABRICATION AND TESTING OF MULTIROD ASSEMBLIES

The next step in our efforts to develop an alternate method for joining the FRS to a bundle tubesheet was to demonstrate that high-quality welds could consistently be made under the space limitations of an actual array of simulators. To accomplish this the positioning fixture shown in Fig. 9, which was used to weld all the single-rod assemblies, was modified to accept a 60.32-mm-diam (2.375-in) seven-rod assembly. We accomplished this by first removing the two V-blocks shown holding a single-rod assembly. We then replaced these with a large V-block such that each successive weld joint could be brought into position by rotating the test piece about its central axis, similarly to the rotation of the cylinder of a revolver into alignment with the barrel. Note that whether we are welding a single- or multiple-rod assembly, the welding head is precisely aligned with respect to the axis of the V-blocks, and both items are fastened with dowel pins to a base plate.

During the welding of the first of the seven-rod test assemblies (one is shown before welding in Fig. 10), we encountered a problem that has been the most difficult to solve in the entire welding study: the arcing from the bore of the copper electrode carrier to the thermocouples, which are wrapped around the tubular outer conductor of the

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Fig. 9 — Final Design of Tungsten Electrode Carrier, (a), with Addition of Longitudinal Grooves Connected to Radial Holes [Highlighted by Arrow in Close-up, (b)] for Improved Inert Gas Coverage. The part being welded was instrumented with thermocouples in the weld area to monitor the temperature of the spirally wrapped thermocouples in an actual PRS.

fuel rod simulator. This is very significant as it results in the destruction of one or more of the sensors that will eventually be used to monitor the temperatures inside the FRS during service. Furthermore, these temperature measurements are critical to the successful testing of the bundle.

We were aware of this potential problem from the beginning of this program and had accordingly designed our electrode carrier so as to maximize the distance between its bore and the thermocouples. The inside diameter of the electrode carrier was machined to 7.24 mm (0.285 in.) so that the distance between the carrier and the outside of

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Fig. 10 - Seven-Rod Test Piece Being Assembled for GTA Welding. The parts representing the fuel rod simulators are 9.52 mm (0.375 in.) in diameter. The arrow indicated where we had problems with arcing to the thermocouple.

the thermocouples wound on the lead-in [a diameter of about 5.3 mm (0.21 in.)] would be greater than the 0.51-mm (0.020-in) arc length. With these dimensions the radial separation would be 0.95 mm (0.038 in), and we would expect the arc to strike across the shorter distance to the weld joint. However, at this time arcing was to the thermocouples at the point where they exited from the tops of the test pieces before starting the spiral wrap (as indicated by the arrow in Fig. 10). The spacing may have been less at that location, or we could attribute the behavior to the vagaries of the arc during high-frequency initiation. For whatever the cause we began an extensive search for some way to prevent it. We tried a number of insulating materials, including mica, heat shrinkable tubing, and glass fiber tape, as shields between the electrode carrier and the thermocouples. However, our efforts were hindered both by the fact that the space for the barrier was very narrow, and the heat from the arc tended to decompose many of our insulating tapes or films. Thus, materials that were thin enough and flexible enough to fit in this narrow gap to prevent an accidental arc strike would generally still cause problems during welding.

Our solution to the arcing problem in the vicinity of the weld joint was to have very thin-walled quartz sleeves made in our glass shop for each FRS. The shields are about 25 mm (1 in.) long and extend beyond the weld area down into the top of the simulator, as shown in Fig. 11.

Although the quartz sleeves eliminated arcing in the weld area and along the length of the [25-mm (1 in.)] conductor extensions, the problem recurred when we began welding multirod assemblies with 114-mm (4.5-in.) extensions, as can be seen in Fig. 12. We tried to use heat-shrinkable tubing over the portion of the conductor and thermocouples extending beyond the quartz sleeve, but arcing occurred where there was a slight gap at the intersection of the two insulators. The inside of the electrode carrier was coated with an insulating paint (Glyptal) and a polymer film, but we were unable to obtain a layer of high enough quality to prevent arcing during high-frequency initiation. The problem was finally resolved by wrapping the extension (from beneath the quartz sleeve out to the tip) with at least two layers of the very thin polytetrafluoroethylene (PTFE) tape used by plumbers as a pipe thread seal.

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Fig. 11 - Quartz Sleeve Used to Protect the Thermocouples of an FRS From Arc Damage During Welding.

Fig. 12 - Seven-Rod Test Assembly with 114-mm (4.5-in.) Conductor Extensions Showing Where Arcing Has Occurred (Arrows) to the Thermocouples, Which Were Not Protected by the Quartz Sleeves.

Subsequent to these efforts we made further parameter development welds on seven-rod assemblies in which quartz sleeves were used to prevent arcing to the short tubular conductor wrapped with thermocouples. We then welded one seven-rod assembly of each size, that is with simulators of 7.47 or 9.52 mm (0.294 or 0.375 in.), according to the parameters listed in Table 1.

Table 1. Welding Parameters for Seven-Rod Test Assemblies^a

Parameter	Fuel Rod Simulator Size	
	7.47 mm (0.294 in.)	9.52 mm (0.375 in.)
Purge gas	Ar	Ar
Purge flow rate, ml/s (cfh)	79 (10)	79 (10)
Arc length, mm (in.)	0.51 (0.020)	0.51 (0.020)
Carriage rotation delay, s	1.5	1.5
Constant speed, r/s	0.12	0.07
Constant speed time, s	4.0	8.5
Upslope speed, r/s	0.12	0.07
Upslope speed time, s	4.0	8.5
Weld current, A dc	10.0	10.0
Finish slope time, s	3.0	3.0

^aEdge joint with total thickness of 1.02 mm (0.040 in.).

These assemblies (which had type 316 stainless steel simulator sheath material and type 308 cladding on the tubesheet) were checked for leakage by helium mass spectrometry. The assemblies were then gas tungsten-arc welded into test modules, such as the one shown in Fig. 13. Testing consisted of thermally cycling 500 times from 370°C (698°F) down to 100°C (212°F) with an internal pressure of 11.7 MPa (1700 psi). Once during each thermal cycle the pressure was briefly dropped to 0.34 MPa (50 psi). No leakage was detected in either assembly (as determined by helium mass spectrometry), either before or after this extensive test series.

Fig. 13 - Seven-Rod Test Assembly [7.47-mm-Diam (0.294 in.) Simulators] After 500 Thermal Cycles Between 370 and 100°C (698 and 212°F) with an Internal Pressure of 11.7 MPa (1700 psi). The simulators were machined from type 316 stainless steel bar, and the tubesheet was type 304L bar GTA weld surfaced with type 308 filler metal before machining the joint area.

After completion of the thermal and pressure cycle tests, the assemblies were sectioned for metallographic examination. As can be seen in the photomicrographs of Figs. 14 and 15, no discernable detrimental effects were apparent as a result of these tests. One notable

Fig. 14 — Cross Section of Typical GTA Weldment Between 9.52-mm-Diam (0.375-in.) Type 316 Stainless Steel Simulator Heater and Trepanned Weld Joint in Type 304 Stainless Steel Tubesheet Weld Surfaced with Type 308 Stainless Steel Filler Metal. Etchant 50HCl, 10HNO₃.

Fig. 15 — Cross Section of GTA Weldment in a Seven-Rod Test Assembly with 7.47-mm-Diam (0.294-in.) Type 316 Stainless Steel Simulated Heater and a Type 304 Stainless Steel Tubesheet, Which was Surfaced with Type 308 Filler Metal to Minimize any Hot-Cracking Tendencies. Etchant 50HCl, 10HNO₃.

difference in the two weldments is the bead contour. The weldment in the larger diameter simulator (Fig. 14) has a smooth circular geometry. Whereas, in the smaller diameter assembly (Fig. 15), the inner surface of the welds is flattened. This effect, which has caused no difference in test behavior, resulted from the very narrow space between the weldment and the central conductor in that design. The weld metal has solidified against the wall of the quartz sleeve, thereby altering the shape of the bead.

We conducted one final test to develop an alternate joining method for attaching fuel rod simulators to the tubesheets of test bundles. The rise in temperature of the thermocouples wrapped around the outer conductor as they were exposed to the welding arc was determined. This was done in response to a concern expressed by some instrumentation specialists that localized heating of a thermocouple to an undetermined high temperature might change its electrical properties and thus produce erroneous readings of internal temperature of the FRS. Single-rod test pieces were assembled with the usual spiral wrapped thermocouples. However, this experiment used only two thermocouples, and the hot junctions were located adjacent to the weld area rather than at lower levels inside the simulators. Since they would be used in an actual assembly, the quartz shields used to prevent arcing were used around the thermocouples; and by absorbing some of the radiant energy, they may have aided in reducing the temperature that would have been experienced. The parameters used were those listed above for welding of 7.47-mm-diam (0.294-in.) heaters.

The results of these tests were both surprising and encouraging because of the low temperatures measured. Of the six thermocouples monitored with an oscillographic recorder during three test welds, the highest temperature was 370°C (698°F). Also, three thermocouples (one in each test) had a maximum temperature of approximately 260°C (500°F). These results indicate that thermal radiation from the tungsten arc will not adversely affect the accuracy of the thermocouples inside the CFTL heaters.

BRAZING OF ELECTRICAL LEADS TO THE FUEL ROD SIMULATOR

As mentioned previously the task of joining the electrical power leads to these simulators is complicated by the fact that both connections must be made on one end of the rod so that the available space is even more limited. Several different techniques for lead attachment (including mechanical clamps and shape-memory alloy couplings) have been considered by others; they have also done a limited amount of manual brazing using a gas tungsten-arc torch heating source. Nevertheless, we have limited our work to the technique we consider most viable: automatic brazing by using a gas tungsten-arc heating source with a special electrode carrier similar to the one developed for simulator-to-tubesheet welding. This technique has the advantages of allowing low-resistance connections with high-temperature capability to be made at locations with limited access and to do so without problems of temperature control and heat-source positioning associated with manual torch brazing. By using an inert gas heating torch rather than the commonly used oxygas torches, the braze can be made without the use of a flux to protect the joint from atmospheric contamination, thereby eliminating flux removal or corrosion problems.

The electrode carrier designed especially for this application is shown in the center of Fig. 16 along with one of the shorter tips used for welding. Because the position of the lead termination on the conductor extensions on the FRS has not yet been determined (and the extensions might be at staggered intervals above the tubesheet), we have developed techniques to accommodate various lengths by using either long or short electrodes and gas cups, also shown in Fig. 16.

We have considered and tested several different terminations. The design shown in Fig. 17 is presently the most favored. To use this geometry the foot (indicated by an arrow in Fig. 18) is first brazed to a straight length of 5.18-mm-diam (0.204-in.) copper wire in a furnace. After bending to the proper radius (depending on the position of its FRS in the bundle), the subassembly is brazed to the tubular outer conductor of a heater. The connection to the central conductor is also made by brazing with a special CTA heating source in which the electrode is held

Fig. 16 — Tungsten Electrode Carriers Developed for Welding (Right) and Brazing of Electrical Leads to Conductors Extending from Fuel Rod Simulators (Left). Also shown are three fused quartz gas cups to maintain inert gas in the joint area during heating.

radially in the copper carrier. Brazed connectors of both types are shown in Fig. 18. Note that because of space limitations we were unable to design a foot of such size that the arc could be rotated in a circle around the tubular conductor. Instead the arc is held stationary at the point indicated in Figure 17, while the braze cycle is controlled by the programmable power supply.

We considered several different brazing filler metals as potential candidates for this application. We have selected two at this time. For the furnace braze of the foot to the end of the 5.18-mm-diam (0.204-in.) copper wire, which will connect to the outer conductor of the FRS, we have had good success using a piece of AWS-ASTM type BAu-4 wire (composition 82 Au-18 Ni, wt %). This alloy, which flows well on copper, has a liquidus of 950°C (1742°F). We have also obtained good results with type BVAg-8b (an alloy having composition of 71.5 Ag-28 Cu-0.5 Ni, wt %) for the actual attachment of the leads to the FRS.

Fig. 17 — Designs of Electrical Leads for the CFTL Showing the One for the Outer Tubular Conductor (Right) and the One for the Central Rod Conductor at Left. The location of the stationary tungsten arc on the foot of the outer conductor lead is indicated by an *.

Fig. 18 — Electrical Leads Brazed to Inner (Above) and Outer (Below) Conductors With a Gas Tungsten-Arc Heat Source and a Brazing Filler Metal of 71.5 Ag-28 Cu-0.5 Ni. The foot (arrow) of the lead for the outer conductor is vacuum-furnace brazed to the lead with 82 Au-18 Ni filler metal.

The 795°C (1463°F) liquidus of this alloy is sufficiently below that of the BAu-4 in the first braze. Consequently, we have not experienced remelting problems when the second of these brazes is conducted. We chose the alloy with a slight amount of nickel rather than the 72% Ag-28% Cu eutectic, which also flows well on copper, as the nickel improves wetting on oxide-bearing surfaces (such as on stainless steels). We thought that this alloy would therefore be more likely to flow on slightly oxidized copper parts resulting from incomplete inert gas coverage during heating.

To demonstrate that this brazing technique was applicable to multirod bundles and not just to single-heater assemblies, the mockup shown in Fig. 19 was constructed. This unit simulates a 25-rod segment of a test bundle with provisions for attaching leads to 13 of the FRS. The space limitations provided by the other simulators in an actual bundle are represented by brass rods machined in the shape of the copper electrical conductors. The curved electrical leads were prepared as outlined above with the addition of a plasma-sprayed coating of aluminum oxide on the foot to serve as an electrical insulator between conductors. Although it could not be used on an actual assembly, a simple fixture (Fig. 20) was designed and built to align the various components and to avoid potential arcing problems during heating. Although several problems arose during the demonstration, electrical leads were satisfactorily brazed to several "simulators" in the 25-rod mockup. This suitably verified the feasibility of this approach so that other more representative sections can be constructed and brazed.

SUMMARY AND CONCLUSIONS

We have developed an alternate method based on a special gas tungsten-arc heating source in place of electron beam welding for joining fuel rod simulators to the tubesheets of test bundles. By using equipment and procedures developed in this program, seven-rod prototypic assemblies having 7.47- or 9.52-mm-diam (0.294- or 0.375-in.) plugs representing simulators were fabricated and subsequently tested. No leakage was detected either before or after thermally cycling 500 times

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Fig. 19 — Mockup of 25-Rod Segment of a Test Bundle of Fuel Rod Simulators with 2 Electrical Leads in the Position Where They Would Be Brazed to the Conductors Extending from a Simulator. Some of the heaters in the array have been left out for clarity.

from 370°C (698°F) down to 100°C (212°F) with an internal pressure of 11.72 MPa (1700 psi), which was briefly dropped to 0.34 MPa (50 psi) during each cycle.

We have designed and built a modified version of the above electrode carrier for brazing electrical leads to the tubular conductors extending from the ends of the fuel rod simulators. Using this device

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Fig. 20 — Multirod Array of the Upper End of Fuel Rod Simulators with the Electrical Leads in Position for Brazing with the Tungsten-arc Heat Source.

as a heat source and a preplaced filler metal ring of 71.5% Ag-28% Cu-0.5% Ni alloy, we have successfully brazed heater leads to simulators in both single- and multirod-arrays.

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