NUCLEAR WELDING, APPLICATION FOR AN LMFBR*

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ABSTRACT

Many studies have predicted that the Liquid Metal Fast Breeder Reactor (LMFBR) will serve as a vital segment of our electrical energy system late in this century. This reactor concept has design requirements and service conditions that demand extremely high reliability. Fabrication of an LMFBR system is discussed, with emphasis on areas where joining innovations have been introduced. Each major component of the system, including reactor vessel, intermediate heat exchanger, steam generator, and sodium-containment piping, is treated separately. Development of special filler metals to avoid the low elevated-temperature creep ductility obtained with conventional austenitic stainless steel weldments is reported. Bore-side welding of steam generator tube-to-tube sheet joints with and without filler metal is desirable to improve in-spectability and eliminate the crevice inherent with face-side weld design, thus minimizing corrosion problems. Automated welding methods for sodium-containment piping are summarized; they minimize and control distortion and ensure welds of high integrity. Selection of materials for the various components is discussed for plants presently under construction, and materials predictions are made for future concepts.

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INTRODUCTION

The production and utilization of energy in the United States are topics of high current interest.\(^1\)–\(^3\) Figure 1 traces the sources and consumption of energy in the United States\(^2\) for the period from 1850 to 1990. Total energy consumed has risen steadily (with the exception of a period during the great depression), and trends indicate accelerated increases in demand. The contribution of nuclear power at the present time is only approximately 5% of the total energy consumed (Fig. 1).

The projected electrical generating capacity in the United States has been forecast\(^3\) for the years 1970–2020; total generating capacity is projected to increase tenfold during that period (Fig. 2). The contribution of fossil-fueled plants could eventually decrease because of supply limitations of oil and natural gas and the many alternate uses for coal. Nuclear power can fill the large and ever-increasing gap between total demand and available supply of conventional (nonnuclear) power. The light-water reactors (LWR) will satisfy much of the near-term demand curve until limited available fuel supplies are exhausted. Being “burners” of nuclear fuel, LWRs cannot proliferate endlessly because of the fixed supply of natural fuel. Breeder reactors, on the other hand, can circumvent the problem. By transmutation of naturally abundant fertile isotopes to fissile isotopes which can be used as fuel, the breeder reactors can create more fuel than they consume, and supply fuel to satisfy projected power needs for several thousand years.\(^1\)–\(^5\) The High-Temperature Gas-Cooled Reactor (HTGR) is a “high-gain converter” which produces nearly as much fuel as it consumes. It therefore can supply significant amounts of energy as great as the breeder reactors can in the long term.

The projections shown in Fig. 2 do not include possible technological breakthroughs that might make alternate energy sources, such as nuclear fusion
or solar energy, feasible. Although these sources are desirable, the uncertainties involved prohibit planning on their availability.

THE LIQUID METAL FAST BREEDER REACTOR (LMFBR)

The components of an LMFBR system are shown schematically in Fig. 3. Flowing liquid sodium is heated by the fuel in the reactor vessel, flows through primary system piping to intermediate heat exchangers (IHX), where heat is transferred to sodium in the secondary system and is finally pumped back to the reactor vessel. The IHX isolates the radioactive primary sodium from the secondary sodium facilitating routine maintenance of the secondary systems. In the secondary system, heated sodium from the IHX(s) is pumped to the steam generator(s) and returns to the IHX(s). The steam produced runs a conventional turbine generator.

LMFBR demonstration plants worldwide are compared in Fig. 4. At the present time, the U.S.'s Clinch River Breeder Reactor Plant (CRBRP) is in the design stage and will be preceded by the Fast Flux Test Facility (FFTF), a materials testing reactor which does not produce steam. The discussions below are primarily aimed at the CRBRP, although many of the observations and conclusions apply equally to the FFTF and other worldwide demonstration projects.

The primary material of construction for the sodium pressure boundaries is austenitic stainless steel, with ferritic steel used in the steam generator and steam piping.

AUSTENITIC STAINLESS STEEL WELDING

Despite the wide usage of austenitic stainless steels in chemical processing and petrochemical systems, few data are available on the high-temperature behavior of stainless steel weld deposits. Creep and cyclic loadings (fatigue and creep-fatigue) data are keys to predicting the service behavior of welds.
These loading conditions will force materials to strain, and good ductility—the ability to deform without fracturing—is a property of key importance. The limited creep ductility data available show a high degree of scatter; many creep failures involve strains on the order of 1% total elongation. As a result of the low creep ductility problem, an extensive stainless steel welding study is in progress at the Oak Ridge National Laboratory (ORNL), involving characterization of ferrite morphology, effects of electrode coatings, and effects of slight compositional differences on properties.

FERRITE MORPHOLOGY

In order to avoid the occurrence of hot-cracking (fissuring) in austenitic stainless steel weldments, it is common practice to assure that the weld deposit contains a small amount of δ-ferrite. The relative amount of ferrite in the austenite matrix depends upon the composition of the weld deposit. Also, the morphology and distribution of the ferrite phase vary with welding process and welding conditions within a given process.

The microstructure present in several different types of austenitic stainless steel weldments has been carefully characterized to determine whether at least part of the observed property variations can be attributed to microstructural differences. The difference in chemical composition of the filler metals used for four typical welds cause the overall mean ferrite content to vary from 3.1 to 8.2 ferrite number (FN) as measured by the quantitative television microscope (QTM). These results could not be predicted accurately from the existing Schaeffler, McKay, or similar diagrams.

Further investigation revealed substantial variations in ferrite content from weld to weld produced under identical conditions, from location to location along the center line of a particular weld, and from point to point within a particular transverse weld cross section, as shown in Fig. 5.
Also, the distribution and morphology of the ferrite present varied substantially in each of the mentioned locations. The ferrite was always located at dendritic or cellular dendritic substructure boundaries, forming a more or less continuous network.

Mechanical properties tests indicated that the ferrite plays a major role in the fracture process at elevated temperatures. The fracture path almost exclusively followed the location of austenite-ferrite boundaries in the as-deposited weld metal, and the fracture surface reproduced the solidification substructure in detail.

EFFECTS OF TYPE OF ELECTRODE COATING

Traditionally, shielded metal-arc electrode coatings are first evaluated on such practical grounds as ease of deposition, bead contour, arc stability, deposition efficiency, and ease of slag removal. Satisfactory bend and tensile properties of the weld are also mandatory. The collection of long-time creep data was not of major concern in the past because the applications have not required such data. The influence of particular flux coverings on the creep-rupture properties had received minimal attention. For this reason, ORNL obtained creep data at 1200°F (649°C) on the type 308 stainless steel weld metal deposited with the three most common types of E308 covered electrodes, having the "lime," "lime-titania," and "titania" type coverings. These are general classes of stainless steel electrode coating formulas that are well known and accepted throughout the welding industry. Each manufacturer has his own proprietary formulations, but the lime-type covering generally contains more calcium carbonate (limestone) and calcium fluoride (fluorspar) than the titania-type covering, and the titania-type covering contains more titanium dioxide (titania). The lime-titania covering is a compromise between the others.
Typical creep behavior for weld deposits made with each type of coated electrode is summarized in Fig. 6. The weld metal deposited from "lime" electrodes generally had the shortest rupture times and the greatest total elongation at each stress level. The deposits from lime-titania and titania-covered electrodes behaved nearly identically, rupturing with low ductility in long-term tests. The minimum creep rate and the tertiary creep behavior of the deposits from lime-covered electrodes differ markedly from those from the other types. The lime deposit has little steady-state or secondary creep strain, while the other electrode deposits remain in second-stage creep for relatively long periods of time, but have less third-stage creep. The total elongations of all three deposits tend to approach zero for rupture times of the order of 1000 hr.

SLIGHT COMPOSITIONAL VARIATIONS

Previous work on compositional effects on stainless steel welds has usually been concerned with the influence of such elements as S, C, P, and Si on hot-cracking tendency, tensile strength, tensile ductility, and impact behavior. In a separate study at ORNL,\textsuperscript{12} we determined the effects of various amounts of these same elements on the 1200°F (649°C) creep-rupture properties of type E308 weld deposits. Boron was also included in the experiments because it has been reported\textsuperscript{13} to improve the creep resistance of various ferrous alloys. A series of experimental electrode batches was made by an industrial electrode manufacturer from the same heat of type 308 stainless steel core wire, but with several slightly different covering formulations to produce variations of deposit content of the elements mentioned above. In all cases, the coverings were of a typical lime-titania formulation because of its ac/dc, all-position characteristics. The adjusted deposit composition of each experimental batch of electrodes met the AWS A5.4-69 specification.
The creep behaviors of these welds were all similar at high stresses at 1200°F (649°C). Differences in creep behavior of the various deposits were apparent at low stress and the resulting longer rupture times. Table 1 shows the results of the creep tests run at 1200°F (649°C) under the relatively low 20,000 psi (138 MPa) static stress. The deposit with the highest carbon content proved to be much stronger than the standard deposit under these conditions. Lowering the carbon content below the standard did not appear to have any significant effect on the rupture life of the deposit, but it did increase rupture ductility. Adding boron to the type E308 deposit significantly improved both the rupture life and the rupture ductility. Lowering the amount of silicon in the type E308 deposit markedly increased the ductility but decreased the rupture life. There seems to be very little effect of sulfur content variations.

At a lower stress level of 18,000 psi (124 MPa) it became apparent that additions of phosphorus and boron significantly strengthen the weld deposit and add resistance to creep embrittlement.

BEHAVIOR OF OPTIMIZED ELECTRODE

An optimized E308 stainless steel electrode that produced deposits containing 0.007% B, 0.06% Ti, and 0.04% P was produced by an industrial manufacturer. It has been designated type 308 CRE stainless steel for the controlled residual elements it contains. We conducted an extensive mechanical properties and metallographic investigation of welds deposited in 2 3/8-in.-thick (60 mm) type 304 stainless steel plate with a double U-groove joint preparation. The test specimens were taken from different locations within the weld and were categorized according to distance from the nearest plate surface regardless of the side of the mid-plane from which they came. They are designated L1 for surface specimens, L2 for one-third thickness specimens, and L3 for midplane specimens.
The superior elevated-temperature ductility of the type 308 CRE stainless steel composition is evident in Fig. 7. All the total strain data for CRE weld metal are contained in a scatter band when plotted against rupture time; comparable scatter bands are given for standard commercial weld metal and earlier developmental welds in the ORNL program. The lowest observed total creep strain for a CRE all-weld-metal specimen is 12%. Internal cracks did not develop at interphase boundaries.

The microstructure varied systematically through the thickness of the weld. In the initial passes at the center of the weld dislocation densities are highest, dislocation loops form, cell structures form, and $M_23C_6$ carbide precipitates on austenite-ferrite interfaces as a result of numerous thermal and mechanical cycles experienced during multipass welding. The carbide precipitate density, loop density, and dislocation density decrease gradually toward the surfaces of the weld where less thermal and mechanical cycling occurs. Near the surface few dislocation loops and no precipitate are present, and the dislocation density is about a factor of 2.8 lower than near the center of the weld. The dislocations near the surface are generally straight, with only a hint of crude cell structure.

The systematic variations in creep properties at small and large strains and in tensile properties are at least partly attributable to these microstructural variations. Weld metal from initial passes tends to be stronger than that from the final passes.

AUSTENITIC STAINLESS STEEL COMPONENTS

The primary material of construction for the sodium containment of today's LMFBR, as mentioned earlier, is austenitic stainless steel. Thus, the metallurgical considerations discussed above for welds are relevant to the fabrication of the reactor vessel, intermediate heat exchangers, pumps, and primary and secondary sodium piping.
REACTOR VESSEL

A schematic of the CRBRP reactor vessel is shown in Fig. 8. It is roughly 55 ft tall and 20 ft in diameter (17 by 6 m) and is constructed of type 304 stainless steel plate, nominally 2 3/8 in. (60 mm) thick. Sodium, flowing at a rate of $41.5 \times 10^6$ lb/hr (5230 kg/sec) enters the reactor at 730°F (388°C), passes through the core, and leaves the reactor at 995°F (535°C). The reactor vessel for the FFTF is nominally the same size and operates at essentially the same temperatures. It was fabricated by a commercial manufacturer* using type 308 CRE coated electrodes for all structural welds. A view of one of the shell courses under construction is shown in Fig. 9.

INTERMEDIATE HEAT EXCHANGERS

A schematic of one of the three intermediate heat exchangers for the CRBRP is shown in Fig. 10. It is roughly 48 ft tall and 9 ft in diameter (15 by 2.7 m). It is a counterflow shell-and-tube design with the primary sodium on the shell side. Again, the FFTF uses a similar design. Figure 11 shows an IHX for FFTF under construction at a commercial manufacturer's plant.15

A distinctive feature in U.S. designs of both IHXs and steam generators for LMFBR service is the "bore-side" tube-to-tubesheet weld. Figure 12 shows the bore-side weld compared with the conventional face-side weld. The bore-side weld is desirable to avoid the presence of the crevice between the outside of the tube and the tubesheet, and to provide a joint that is amenable to radiographic inspection. It is, however, a costly and difficult weld to produce, since the welding head must be inserted inside the bore of the tube, through a tubesheet that was over 6 in. thick for FFTF, and that will have similar thickness for CRBRP. Depending upon the type of welding equipment

used and the size and wall thickness of the tubing for CRBRP, filler metal may be added to the weld joint at additional cost and with some procedural complication. Inert gas shielding is used on the outside of the tube to protect the root of the weld from oxidation. Radiographic inspection to nuclear core requirements is performed by inserting the radiation source, either a radioisotope "pill" or an x-ray tube of the "pencil-anode" type, into the bore of the tube and exposing film placed around the weld joint outside the tube.

PUMPS

A schematic of one of the six pumps (three primary and three secondary) for CRBRP is shown in Fig. 13. It is approximately 57 ft tall and 12 ft in diameter (17 by 3.7 m). It is a free-surface centrifugal unit driven by a 500-hp (373 KW) variable speed motor, capable of 33,700 gpm (2.13 m³/sec). Figure 14 shows one of the FFTF pumps under construction at a commercial manufacturer's plant.¹³

SODIUM PIPING

A schematic plan view of the heat transport system arrangement for CRBRP is shown in Fig. 15. The primary and secondary hot-leg piping is 36 in. (0.91 m) in diameter, while the primary and secondary cold-leg piping is 28 in. (0.71 m) in diameter. Large expansion loops are included in the design to accomodate thermal expansion. Sodium piping for the FFTF is somewhat smaller, 28 in. in diameter for the hot legs and 16 in. (0.41 m) in diameter for the cold legs.

The sodium piping for an LMFBR provides a challenging design situation. The wall thickness of the piping is in fact determined by a compromise between two contradictory considerations. Loading from the internal pressure, gravity, and particularly thermal expansion, calls for increased wall thickness, while the thermal excursions due to rapid changes in coolant temperature during normal start-ups and shutdowns, as well as off-normal conditions, makes a thin wall
desirable. Thus, the wall thickness of all primary sodium piping for FFTF is a modest 3/8 in. (9.5 mm) (see Fig. 16).

The use of large diameter, thin-walled pipe demands that the pipe welds be of high integrity. Further, diametral shrinkage must be minimized in these welds to avoid the stress concentrations that result from geometric discontinuities. Both these considerations may be resolved in part by the use of automated orbital pipe welding. The reproducibility and process control that can be achieved with an automated process cannot be matched by manual techniques. Further, by careful selection of welding process variables (heat input, number of passes, etc.), diametral shrinkage can be reduced to acceptable levels.

Another factor that must be considered is the present and future availability of skilled construction welders to accommodate the increasing demand for their services. A potentially serious shortage is predicted, but automated welding, if applied on a large scale, can achieve higher productivity than comparable manual techniques.

Figure 16 shows a portion of the primary piping for FFTF under construction at a commercial manufacturer’s plant.*

FERRITIC STEEL WELDING

Whereas types 304 and 316 stainless steels can be welded without preheat or postweld heat treatment, ferritic steels cannot. The added requirements for process control and fabrication complications are not trivial in fabricating components for nuclear service.

However, the relative susceptibility of the austenitic stainless steels to corrosive attack in water containing chlorides and/or caustic limits the use of these materials in steam generations systems. They can be used in dry steam (e.g., superheaters) if precautions are taken to avoid carryover from the

supersaturated ("wet") portions of the system. The conservative approach is to use ferritic steels for the entire steam system. Such an approach is planned for the CKBKP.

STEAM GENERATORS

A schematic of one of the nine steam generators (six evaporators and three superheaters) for CRBRP is shown in Fig. 17. Each unit is approximately 65 ft in length and 4 ft in diameter (20 by 1.2 m) and each is constructed entirely of 2 1/4 Cr-1 Mo steel. Since the FFTF has no steam generators, the design will be verified by model and full-scale tests before CRBRP operations commences. Each unit has 757 tubes and therefore 1514 bore-side tube-to-tubesheet welds.

The desirability of bore-side welds is perhaps most vividly illustrated by the experience with the Alco/BLH steam generator. This unit was performance tested at the Liquid Metal Engineering Center, and subsequently destructively examined at the Oak Ridge National Laboratory. It was of bimetallic construction, using type 316 stainless steel for all sodium-exposed surfaces and Inconel alloy 600 for all steam/water-exposed surfaces. Faulty tube-to-tubesheet welds, however, allowed sodium-water contact, and caustic stress-corrosion cracking progressed from the tube-to-tubesheet crevice throughout the 6-in.-thick (0.15-m) tubesheet, finally linking with the outer surface of the unit (Fig. 18).

TRANSITION JOINTS

The use of austenitic steels in the sodium system and ferritic steels in the steam system necessitates transition joints between these two materials, usually near the inlet and outlet of the steam generators. Although such joints have been used for many years, the factors that control their performance are poorly defined. Typically, the filler metal used has a thermal
coefficient of expansion intermediate to the joined austenitic (high) and ferritic (low) steels. Thermal cycling can lead to low-ductility failure near the fusion line in the ferritic steel.\textsuperscript{24}

**MATERIALS CONSIDERATIONS**

Throughout the above discussion, the materials of construction for both FFTF and CRBRP were identified without justification for their selection. Clearly, the process of materials selection is a complex one, and many different factors must be considered.\textsuperscript{25,26}

Austenitic stainless steels have several significant advantages over other materials for use in the sodium systems of an LMFBR; high-temperature design ASME Code rules are established, a large mechanical properties data base exists, product forms are readily available, strength is adequate, and corrosion and mass-transfer resistance is suitable. However, there are persistent problems with the use of unstabilized austenitic steels, which have been known and endured for years, particularly the material's susceptibility to stress-corrosion cracking and intergranular attack.

The use of 2 1/4 Cr-1 Mo ferritic steel for steam generators imposes a limitation on the maximum steam temperature that can be used. This limitation is due to the decrease in strength of that material at temperatures above 850°F (454°C). Such considerations indicate that the materials selection process will be continually reviewed, and that as service experience is gained in the demonstration plants, and as alloy development continues, alternate materials may show advantages that would lead to their use in future LMFBR plants.

**SUMMARY**

The energy demands of the United States are projected to increase. Nuclear power, in the form of the LMFBR, will likely be called upon to fill the gap between demand and supply.
The LMFBR is a sodium-cooled reactor system, which can produce electrical power and breed, assuring the capability for energy production to meet projected needs.

A typical system consists of a reactor vessel, intermediate heat exchanger(s), pump(s), sodium piping, and steam generator(s). The United States' effort centers around the FFTF, a non-steam-producing test reactor and the CRBRP, a large-scale demonstration reactor. The primary material of construction for the sodium-containment is austenitic stainless steel, with ferritic steel used in the steam system.

Conventional austenitic stainless steel weldments must be carefully analyzed when used in critical applications at elevated temperatures because generally they have low ductility in creep-rupture tests. The ferrite level is influenced by composition and varies with welding process, from weld to weld produced by a given process, and from location to location within a given weld. The low-ductility fracture path almost exclusively follows the austenite-ferrite boundaries.

Shielded metal-arc electrode coatings strongly influence the creep-rupture properties of austenitic stainless steel weldments. Lime-covered electrodes produced welds that were weaker but more ductile than either lime-titania or titania-covered electrode welds. Variations in the amounts of S, C, P, Si, and B affected the creep-rupture properties of austenitic stainless steel welds. An optimized electrode composition, designated "CRE" (for controlled residual elements), was developed; it produced deposits containing 0.007% B, 0.06% Ti, and 0.04% P. Compared with standard commercial weld metal, the CRE material exhibits equivalent strength and superior creep-rupture ductility.

The fabrication of each major component for an LMFBR is described. Bore-side tube-to-tubesheet welds are used for both intermediate heat exchangers
for FFTF and steam generators for CRBRP. Automated welding is highly desirable for critical sodium piping welds.

Austenitic-ferritic transition joints are required in current systems, and the factors that control their performance are poorly defined.

The selection of materials for a given component will be continually reviewed, and alternate materials may eventually show advantages that would lead to their use in future LMFBR plants.

ACKNOWLEDGMENTS

The breadth and duration of the work described in this paper preclude individual recognition of all who have contributed to its progress. The cooperation and counsel of staff members of Combustion Engineering, Inc., Chattanooga Division, Westinghouse-Tampa Division, Foster Wheeler Corporation, and Westinghouse Advanced Reactors Division have been invaluable. Within the Oak Ridge National Laboratory, members of many groups, including Welding and Brazing, Mechanical Properties, Metallography, Electron Microscopy, and the Reports Office have contributed.
REFERENCES


Table 1. Effect of Compositional Variables on the Creep Properties of Shielded Metal-Arc E308 Stainless Steel Welds at 1200°F (649°C) and 20,000 (138 MPa)

<table>
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<th>Compositional Variables</th>
<th>Rupture Time (hr)</th>
<th>Total Elongation (%)</th>
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<tr>
<td>Standard lime-titania covering(^a)</td>
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<td>Carbon, %</td>
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\(^a\)0.044% C, 0.47% Si, 0.012% P, 0.016% S, 0.001% B.
FIGURE CAPTIONS

Figure 1. United States Energy Sources and Consumption.

Figure 2. Projected Generating Capacity for the Years 1970–2020.

Figure 3. The Liquid Metal Cooled Fast Breeder Reactor.

Figure 4. Comparison of Demonstration Plants Worldwide.

Figure 5. Variation in Ferrite Distribution in one Cross Section of a Gas Metal-Arc Weld Sample. Etchant: KOH, K3Fe(CN)6.

Figure 6. Elongation Versus Time for Experimental Stainless Steel Deposits at 1200°F (649°C) and 18,000 psi (124 MPa).

Figure 7. Ductility in Creep-Rupture Tests of Type 308 Stainless Steel Welds.

Figure 8. Schematic of CRBRP Reactor Vessel.

Figure 9. Fabrication of a Shell Course of the FFTF Vessel.

Figure 10. Schematic of CRBRP Intermediate Heat Exchanger.

Figure 11. Fabrication of an IHX for FFTF.

Figure 12. Tube-to-Tubesheet Welds for LMFBR Intermediate Heat Exchangers and Steam Generators.

Figure 13. Schematic of CRBRP Primary Sodium Pump.

Figure 14. Fabrication of a Primary Sodium Pump for FFTF.

Figure 15. Schematic of CRBRP Heat Transport System Arrangement.

Figure 16. Fabrication of a Portion of the Primary Sodium Piping for FFTF.

Figure 17. Schematic of CRBRP Steam Generator.

Figure 18. Section of Alco/BLH Steam Generator Tubesheet.
Fig. 1. United States Energy Sources and Consumption.
Fig. 2. Projected Generating Capacity for the Years 1970–2020.
Fig. 3. The Liquid Metal Cooled Fast Breeder Reactor.
### COMPARISON OF DEMO PLANTS WORLD WIDE

<table>
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<tr>
<th></th>
<th>UK PFR</th>
<th>French PHENIX</th>
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<td>3</td>
</tr>
<tr>
<td>Number of units or modules</td>
<td>99</td>
<td>108*</td>
<td>18*</td>
<td>24*</td>
<td>9*</td>
<td>9*</td>
</tr>
</tbody>
</table>

*Equivalent = 200 MW(e) doubling, 150 MW(a) power.

*One loop on standby.

*Three evaporators, three superheaters, three reheaters - one each per loop.

*Thirty-six evaporators, 36 superheaters, 36 reheaters - 12 each per loop.

*Nine evaporators, nine superheaters - three each per loop.

*Twelve evaporators, 12 superheaters, two each per loop.

*Three evaporators, three superheaters, three reheaters - one each per loop.

*Six evaporators, three superheaters - two evaporators and one superheater per loop.

- Fig. 4. Comparison of Demonstration Plants Worldwide.
Fig. 5. Variation in Ferrite Distribution in one Cross Section of a Gas Metal-Arc Weld Sample. Etchant: KOH, K₃Fe(CN)₆.
Comparison of Commercial Coatings at 1200°F and 18,000 psi.

Fig. 6. Elongation Versus Time for Experimental Stainless Steel Deposits at 1200°F (649°C) and 18,000 psi (124 MPa).
Creep Ductility of CRE Type 308 Stainless Steel Weld Metal.

**Fig. 7.** Ductility in Creep-Rupture Tests of Type 308 Stainless Steel Welds.
Fig. 8. Schematic of CRBRP Reactor Vessel.
Fig. 9. Fabrication of a Shell Course of the FFTF Vessel.
Fig. 10. Schematic of CRBRP Intermediate Heat Exchanger.
Fig. 11. Fabrication of an IHX for FTFF.
Fig. 12. Tube-to-Tubesheet Welds for LMFBR Intermediate Heat Exchangers and Steam Generators.
Fig. 13. Schematic of CRBRP Primary Sodium Pump.
Fig. 14. Fabrication of a Primary Sodium Pump for FFTF.
Fig. 15. Schematic of CRBRP Heat Transport System Arrangement.
Fig. 16. Fabrication of a Portion of the Primary Sodium Piping for FFTF.
Fig. 17. Schematic of CRBRP Steam Generator.
Fig. 18. Section of Alco/BLH Steam Generator Tubesheet.