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THE FABRICATION OF SUBASSEMBLIES FOR THE SUPERCRITICAL-WATER REACTOR

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THE FABRICATION OF SUBASSEMBLIES FOR THE SUPERCRITICAL-WATER REACTOR

J. R. Keeler and A. W. Hare

In studies of the fabrication of fuel subassemblies for the supercritical-water reactor, the limited ductility of stainless steel-UO₂ fuel sheet made the fabrication of corrugated-flat-plate-type subassemblies impractical. A fabricable MTR-type assembly, 5/8 in. square and 30 in. long, was developed. Methods for edge cladding fuel sheet were developed and a brazing alloy, GE-75, was found to be corrosion resistant in supercritical water.

INTRODUCTION

A feasibility study of a supercritical-water reactor ~~for aircraft propulsion~~ was undertaken by Pratt and Whitney. As part of this study, Battelle undertook the development of the fuel elements for this reactor.

Two basic problems were investigated in this work; the fabrication of stainless steel-clad fueled sheet, and assembly of the fueled sheet into a satisfactory fuel-element subassembly. Detailed studies on the fabrication of stainless steel-clad fueled sheet are in reports BMI-904 and BMI-913. The present report covers the development of the fuel-element subassembly for the reactor core.

Nuclear Development Associates, Inc., made the initial design studies on the fuel-element subassemblies. A proposed design was a corrugated-flat-plate-type subassembly approximately 1 in. square by 30 in. long. During the preliminary work on this type of a subassembly, it became obvious that the cored fuel sheet could not be corrugated with the sharp-radius bends necessary to avoid hot spots in the assembly.

A 1-in.-square MTR-type subassembly appeared to be more readily fabricated. Therefore, work on this type was initiated. As the investigation proceeded, an increase in the design life of the reactor was proposed, and the uranium loading was correspondingly increased by increasing the thickness of the stainless steel-UO₂ core in the fuel sheet from 8 mils to 12 mils. Because of this increased loading, self-shielding in the center of the 1-in.-square subassembly became excessive. Therefore, the cross section was reduced to approximately 5/8 in. square. Most of the work was directed toward fabricating this size subassembly.

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THE CORRUGATED-FLAT-PLATE DESIGN

In the initial design studies made by the Nuclear Development Associates, Inc., a corrugated-flat-plate fuel-element subassembly was proposed for the supercritical-water reactor. The core of the reactor was to contain 180 tubular subassemblies. Each subassembly would be 30 in. long and would contain about 4 sq ft of 0.020-in. -thick fuel plate. Figure 1 shows a cross section of this proposed corrugated-flat-plate design.

These subassemblies were to operate under conditions of very high power densities, high temperatures, and high neutron fluxes. Because of the critical heat-transfer conditions, extremely accurate dimensions were required. Heat-transfer calculations indicated that a 1 per cent change in the hydraulic radius of a flow channel would result in a 7 per cent change in the exit temperature of the coolant.

The fuel for the subassembly was 0.020-in. -thick stainless steel-clad sheet containing a core of stainless steel and UO_2 . This core was 0.008 in. thick and contained 30 w/o UO_2 in a matrix of Type 347 stainless steel. The cladding was 0.006-in. -thick Type 347 stainless steel.

Fuel-Sheet Fabrication

The fuel sheet was fabricated by powder-metallurgy techniques. The core materials were blended as powders, pressed into a compact, and sintered. The sintered compact was placed in a segmented stainless steel picture frame. Covers of stainless steel were then welded over the frame, and the pack was rolled to the desired thickness. For a complete report on the fabrication of fuel elements see BMI-904 and BMI-913.

Preliminary Bend Tests

In an effort to determine if a composite fuel sheet could be corrugated with the desired bend radii, a series of bend tests was made on short sections of the sheet. Specimens 1 by 0.5 by 0.020 in. were bent in a simple V-block with an included angle of 75 deg. Punches with various radii were used to determine the minimum bend radius that could be made without cracking the specimen.

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All dimensions in inches

FIGURE 1. CORRUGATED-FLAT PLATE ASSEMBLY

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None of the stainless steel-UO₂-cored samples could be bent to the desired 0.010-in. radius without severe cracking.

Identical bend tests were made at room temperature and at 600 F with no appreciable improvement in ductility.

Because of the difficulty encountered in the bend tests with stainless steel-UO₂ fuel sheet, a fuel sheet having a pure iron-UO₂ core was fabricated and tested. The test specimens with the iron core were more ductile than specimens with the stainless steel core and could be bent to approximately the required radius. In all of the tests, the bend was made parallel to the rolling direction of the clad sheet because the corrugations in the 30-in.-long elements would also be parallel to the rolling direction.

On the basis of the results of the preliminary bend tests with iron-UO₂-cored test specimens, a 10-in.-long die was made to corrugate the fuel sheet to the approximate size and shape required for a subassembly. One corrugation at a time was made in a press-brake-type die. Subsequent hot pressing or coining would have been necessary to obtain the degree of accuracy needed in the corrugated plates. Figure 2 shows the corrugating die. Although narrow widths of iron-UO₂-cored sheet could be bent to the desired dimensions, 10-in. lengths of this sheet cracked at the bends during corrugation.

Edge Sealing

While studies to develop a more ductile fuel sheet were being continued, the problems of edge sealing the fuel sheets prior to assembly, of joining the fuel sheet into a subassembly, and of selecting a suitable brazing alloy were investigated.

Because of the 30-in. length and extremely close dimensional tolerances of the assembly, it was not considered feasible to roll clad sheet to the finished dimensions. Therefore, the fuel sheet was rolled oversize and subsequently sheared and ground to the desired length and width. This exposed the core on all four edges. These exposed edges had to be sealed to protect the core from corrosion by the cooling water and to contain the fission fragments.

The most effective method for edge sealing the sheet was found to consist of spot welding a flat stainless steel wire to the edges of the fuel sheet and then brazing this wire to the edge. For brazing, the fuel sheet was placed on a flat graphite block which was coated with fine alumina powder. The alumina prevented the graphite from alloying with the stainless steel at the high brazing temperatures required. The brazing was done in

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Approx 1/2X

FIGURE 2. CORRUGATING DIE FOR 10-IN. -LONG PLATES

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an atmosphere of pure, dry hydrogen with either GE-62 or GE-75 brazing alloy. The compositions of GE-62 and GE-75 are 70 w/o nickel-19 w/o chromium-11 w/o silicon and 57 w/o nickel-13 w/o chromium-30 w/o germanium, respectively.

Two sizes of wire were tried. A flat wire, 0.020 by 0.010 in., was difficult to position on the edge of the sheet and tended to bow between spot welds. The application of powdered brazing alloy to the edge was also difficult. However, wire of this size resulted in a minimum of excess stainless steel obtained without subsequent grinding.

The best seal was obtained with a 0.020 by 0.064-in. flat wire. Figure 3 shows a section through such a seal. Removal of the excess stainless steel by grinding was difficult. However, because the 30-in. long sheet was flexible, a grinding jig clamped to the sheet rigidly and close to the edge made possible the removal of excess stock to within 3 to 4 mils of the surface of the sheet.

100X

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FIGURE 3. CROSS SECTION OF FUEL PLATE EDGE SEALED WITH
0.02 BY 3/64-IN. WIRE

Wire was brazed to the fuel plate with GE-75 alloy

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The work on the corrugated-flat-plate assembly was discontinued, as it became obvious that a cored fuel sheet could not be satisfactorily corrugated with the sharp-radius bends required.

MTR-TYPE DESIGN

The ductility of the fuel sheet containing UO_2 was insufficient to permit the fabrication of corrugations having the desired bend radius. Several alternative designs for the fuel assembly were studied for their heat-transfer capacity and nuclear and physical characteristics. An MTR-type design which had the necessary heat-transfer capacity and nuclear and physical characteristics was selected for development because of its simplicity and ease of fabrication.

The subassembly designed to replace the corrugated-flat-plate element contained a stack of 17 curved fuel plates, each with a radius of curvature of 1.02 in. and a plate spacing of 0.040 in. The fuel plates had a chord length of 0.942 in. and were 30 in. long and 0.020 in. thick with a cladding-to-core ratio of 6-8-6. The reactor with this type of subassembly had a calculated service life of approximately 100 hr. In order to increase the service life, the uranium loading in the reactor was increased. This change in design resulted in an increase in the thickness of the stainless steel- UO_2 core in the fuel plate from 0.008 in. to 0.012 in. Consequently, the self-shielding problems encountered with this type of fuel assembly were accentuated. In order to reduce the flux depression at the center of the subassembly, the over-all size of the subassembly was reduced to roughly a 5/8-in. square. A cross section of the resultant subassembly is shown in Figure 4.

Fuel-Sheet Fabrication

The methods of fabricating, cutting, grinding, and edge sealing the fuel sheets for the MTR-type subassembly were similar to those developed for the fuel plates of the corrugated-flat-plate type subassemblies.

After the edge-sealed fuel plates were ground to the desired length and width, they were curved in a press-brake die with a die radius of 15/16 in. A plate with a radius of curvature of 1.25 in. was obtained.

MTR $\frac{5}{8}$ -in. Fuel Element

All dimensions in inches

FIGURE 4. MTR-TYPE FUEL ASSEMBLY UTILIZING SLOTTED
SIDE PLATES TO OBTAIN THE DESIRED PLATE
SPACING

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Plate Spacing

Heat-transfer calculations indicated that the spacing between the plates in the MTR-type assembly was extremely critical. Small variations in plate spacing result in relatively large changes in the exit water temperature. It was therefore desirable to produce an assembly in which the variation in plate spacing was ± 0.0005 or less.

Several methods for spacing fuel sheets were considered. These included spot-welded projections, slotted side plates, T- and L-shaped edges, dimples, rolled ribs, and washers. Only the first three were investigated experimentally.

Short lengths of stainless steel wire, having a diameter equal to the desired plate spacing, were spot welded to the fuel sheet. Welds were made at the ends of each section of wire. Figure 5 shows a section through a weld nugget. A minimum length of $3/16$ in. was required to avoid deforming the center portion of the wire excessively. Some burrs were formed during the spot-welding operations, but these could be removed by filing. Table 1 shows thicknesses of wire-type projections on eleven $5/8$ -in.-wide by 30-in.-long unfueled plates for one subassembly.

TABLE 1. MEASUREMENTS OF SPOT-WELDED
WIRE PROJECTIONS

Plate	Thickness of Wire Projections, in.			
	Average	Mode	Maximum	Minimum
1(a)	0.0234	0.0235	0.0239	0.0228
2	0.0308	0.0307	0.0315	0.0299
3	0.0308	0.0312	0.0320	0.0297
4	0.0310	0.0310	0.0318	0.0297
5	0.0308	0.0310	0.0318	0.0297
6	0.0310	0.0314	0.0315	0.0302
7	0.0306	0.0303	0.0315	0.0295
8	0.0308	0.0308	0.0314	0.0300
9	0.0308	0.0313	0.0315	0.0295
10	0.0308	0.0310	0.0315	0.0302
11(a)	0.0233	0.0231	0.0240	0.0228

(a) Plates 1 and 11 had 0.025-in. projections.

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FIGURE 5. CROSS SECTION THROUGH SPOT-WELD NUGGET

Top, as polished; bottom, etched with Marbles reagent

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Each plate had 48 projections spaced (two rows of 24) approximately 1-1/4 in. on center along the length of the sheet, and 1/16 in. from the edges. The initial wire diameter was 0.032 in., except on Plates 1 and 11, which had 0.025-in. -diam wire spacers.

The height of the projections was 0.001 to 0.003 in. less than the initial wire diameter, but the maximum variation from the average for the 432 projections was only 0.0013 in. The range from maximum to minimum height of the projections on all of the plates was 1.9 mil. Similar measurements on the plates for five other assemblies showed ranges of 1.5, 2.7, 2.3, 2.2, and 3.0 mils from maximum to minimum.

Of the methods investigated for spacing plates, the use of spot-welded projections appeared to be the most feasible. The use of slotted side plates to obtain the desired plate spacing was also investigated. This method of assembly appeared to be particularly desirable because it offered a possibility of reducing the leakage between adjacent channels. By providing a close fit between the edge of the fuel plate and the slots, a labyrinth-type seal might be effected.

Calculations at Pratt and Whitney indicated that the leakage between channels would be negligible if the dimensional tolerances of the edges of the fuel plate and of the width of the grooved slots were held to within ± 0.0002 in. Figure 4 shows a proposed design with slotted side plates.

In the Pratt and Whitney shops, it was possible to machine slotted side plates 30 in. long with slots 0.026 ± 0.0002 in. in width. However, efforts to grind the thickness of edge-sealed fuel plates to such close tolerances at Battelle were unsuccessful. Because of the comparatively great length and the thin section, jigging was extremely difficult. Tolerances of ± 0.002 in. were the best that could be obtained.

An additional difficulty was encountered in assembling close-fitting parts. Plates 0.021 to 0.0215 in. thick could be assembled easily in the 0.026-in. slots, but plates 0.023 to 0.025 in. thick could not be inserted in the slots. Oversize plates were hand honed (with considerable difficulty) to a size that would allow them to be inserted in the slots.

Grinding difficulties also made the use of H- or U-shaped plates appear impractical. Several 10-in. lengths of H- and U-shaped plates were made by brazing wide edge-sealing strips on the sides of the fuel sheet. Efforts to grind these plates to close tolerances were unsuccessful.

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Jigging and Brazing Subassemblies

The jigging and brazing of the subassemblies was done in a U-shaped graphite block. For assemblies with plates spaced by means of spot-welded projections, the curved plates were stacked one upon the other between two flat side plates. A 3/64 by 0.020-in. flat wire was spot welded 1/4 in. up from the bottom edge of the flat side plates. This wire served as a rest for the bottom curved plate and prevented the curved plate from contacting the bottom of the jig. The curved plates were held in position by spot welding a flat wire to the side plate at the junction of the edges of the top curved plate and the side plate.

Nickel shims were used to prevent any contact between the stainless steel and the graphite jig. A corrugated nickel shim was placed between the graphite jig and one flat nickel shim to facilitate assembling the components and also to allow for thermal expansion. Figure 6 shows a cross section of an MTR-type subassembly in the jig prior to brazing. An end view of a brazed 30-in. -long subassembly is shown in Figure 7.

The powdered brazing alloy was applied to the edges of the plates as a slurry in a vehicle of Acryloid and toluene. Assemblies were brazed in which every plate was joined to the side plates; others were made with only the top and bottom plates brazed to the side plates. In the latter case, the interior plates were tack brazed to the side plates at one end but were free to expand independently of the side plate. Because of the large thermal gradients expected between individual plates and particularly between the fueled plates and the unfueled side plates, this type of joining appeared desirable.

The jigging and brazing of assemblies with grooved side plates was similar to that of the assemblies with flat side plates.

A 30-in. -long unfueled subassembly also was made by using a pre-formed stainless steel tube to contain the curved plates. The sides of the preformed tube were flat; its top and bottom surfaces had a radius identical with that of the curved fuel plate. The curved plates, with attached wire spacers, were stacked one upon the other and the entire stack was slipped into the preformed tube. The curved plates were held in position in the tube by tack brazing at one end. Figure 8 shows an end view of the preformed-tube subassembly.

FIGURE 6. CROSS-SECTIONAL VIEW OF A SUBASSEMBLY
PRIOR TO BRAZING

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3-1/2X

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FIGURE 7. END VIEW OF BRAZED 30-IN.-LONG SUBASSEMBLY WITH PLATES SPACED BY MEANS OF PROJECTIONS

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3-1/2X

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FIGURE 8. END VIEW OF SUBASSEMBLY MADE WITH PREFORMED OUTER TUBE

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Orificing

Heat-transfer calculations indicated that the flow in the various channels of a subassembly would not be uniform and that orificing of each channel would be required. A limited amount of work was done on the attachment of an orifice plate to the entrance end of a subassembly.

An orifice plate was slotted to accommodate the ends of the curved fuel plates, and orifices of the desired size and number were drilled into each channel. This plate was jugged in position at the end of a short section of a subassembly and brazed in place with GE-75 alloy.

A thick paste of MgO was forced into the orifice holes prior to brazing in order to prevent the brazing alloy from filling these holes. Inspection of the brazed assembly showed that the MgO was effective in preventing clogging of the orifice holes, but that the brazing alloy applied had been insufficient to obtain a complete seal between the ends of the fuel plates and the orifice plate.

Measurement of Plate Spacing

The measurement of plate spacing in the brazed subassemblies was difficult because of the small opening (0.033 by 0.625 in.) and the 30-in. length of the channel.

Volume measurements could be made in cases where each channel was sealed, but such measurements gave only an average spacing over the entire length. Table 2 shows the results of volumetric measurements on a completely brazed assembly. In cases where only the top and bottom plates were brazed, the individual channels were not sealed from each other and volumetric measurements could not be used.

Go-no-go-type gages were tried but were not entirely successful. In this method, beads of various diameters were fastened to a wire and slipped through the channel. The internal projections used to space the plates caused considerable difficulty with the gage catching on the projections. In addition, this type gage gives only an indication of the minimum spacing between plates.

A pneumatic gage for measuring plate spacing was under development when the project was concluded. The apparatus consisted of a source of dry nitrogen; a sensitive, vane-type flowmeter; a mercury manometer; and a 30-in.-long stainless steel tube with an outside diameter of 0.020 in.

TABLE 2. VOLUMETRIC MEASUREMENTS OF A
MTR-TYPE SUBASSEMBLY

Channel	Intended Spacing, in.	Average Spacing, in.
1	0.0250	0.0256
2	0.0325	0.0322
3	0.0325	0.0310
4	0.0325	0.0280
5	0.0325	0.0407
6	0.0325	0.0303
7	0.0325	0.0303
8	0.0325	0.0299
9	0.0325	These channels were not completely sealed from each other
10	0.0325	
11	0.0250	

The stainless steel tube was sealed at one end. A 0.004-in. -diam hole was drilled through the walls of the tube 1/4 in. in from the sealed end. Small stainless steel fins were soldered to each side of the tube midway between the holes. These fins prevented the stainless steel tube from rotating within the channels and also kept the holes perpendicular to the axis of the channels.

The apparatus was calibrated by placing the finned end of the tube between two ground flats which were a known distance apart. For every particular flowmeter reading there was a definite pressure reading.

Changes in plate spacing of 0.0001 in. could be detected, but the range of the instrument was only 0.0008 in. Efforts to extend this range were not completed.

Thermal-Cycling Tests

A preliminary investigation was made to determine the ability of an MTR-type completely brazed subassembly to withstand the complex stresses caused by thermal cycling and thermal gradients within the reactor. For these tests two 10-in. -long subassemblies were used. The two subassemblies were 1 in. square and 5/8 in. square in cross section, respectively; in both samples all of the fuel plates were brazed to the side plates.

The subassemblies were cycled 36 times from 1200 to 450 F. The thermal-cycling operation consisted of heating the subassemblies to 1200 F and air quenching to establish a thermal gradient between the sides and the center of the assembly.

The assemblies were heated in a muffle furnace to 1200 F. They were then removed and compressed air was blown against only the sides of the assembly. When the temperature at the center of the assembly reached approximately 450 F, the sample was returned to the furnace, and the cycle was repeated. Examination of the subassemblies indicated no gross warpage or distortion.

In addition to the thermal-cycling tests, these subassemblies were subjected to a 24-hr thermal-gradient test. One end of the subassembly was heated to 1200 F with a gas burner; the other end was held at 440 F. Temperatures of 1200 F at the center of the assembly and 1030 F on the sides were measured at the hot end of the assembly. No visible warpage of channel spacing was observed after this treatment.

BRAZING ALLOYS

The selection of a brazing alloy for edge sealing fuel plates and for joining fuel plates into a suitable subassembly was a major problem in the development of the fuel elements. The alloy must be resistant to corrosion in supercritical water at temperatures up to 1350 F and pressures of 5000 psi. It also must have sufficient strength to withstand the shear and tensile stresses caused by thermal gradients within the subassembly, and the thermal-neutron-absorption cross section should be as low as possible.

Silver solders and the brass and bronze brazing alloys could not be used because of their poor corrosion resistance, low strength, or high cross sections; consideration was therefore given to the high-temperature brazing alloys similar to Nicrobraz produced by Wall-Colmoloy Company and to the brazing alloys developed by the General Electric Company for the direct-air-cycle reactor.

A number of alloys were prepared and the properties of each investigated.

Melting-Point Determinations

Table 3 shows the composition, melting point, flow characteristics, suggested brazing temperature, and approximate remelt temperature of each alloy.

The melting point of each alloy was determined by thermal analysis. A thermocouple was sandwiched between two small pieces of the brazing alloy being tested. This sandwich was inserted in a small platinum envelope and heated at a very high rate. The temperature curve was recorded on a high-speed recording potentiometer. The melting point of the brazing alloy was then readily determined from this curve.

Remelt-Temperature Determination

The approximate remelt temperature of each brazing alloy was determined by using 1-in. -long T-joints brazed with the various brazing alloys. Figure 9 shows the assembly used to determine the remelt temperatures.

This assembly was placed in a furnace at 2500 F. The temperature of the T-joint was measured by using a thermocouple which was attached directly adjacent to the fillet of the brazed joint. The remelt temperature was assumed to be that temperature at which the heavy base of the T-joint became separated from the top of the T-joint.

The remelt temperatures are recorded in Table 3. These temperatures were determined by using stainless steel T-joints which were brazed at the suggested brazing temperatures in an atmosphere of dry hydrogen for 15 min.

The remelt temperatures will necessarily vary with the brazing conditions. Brazing T-joints at higher temperatures for longer periods of time will result in higher remelt temperatures. Conversely, brazing a joint at the suggested brazing temperature for a shorter period of time will result in a lower remelt temperature. This condition is due to the increase of the alloying of the brazing material with the base metal as the brazing temperature is raised and the time of brazing is increased.

Shear Tests

On the basis of the results of preliminary corrosion studies, the most promising brazing alloys were selected for shear and tensile tests. The

TABLE 3. BRAZING-ALLOY PROPERTIES

Braze	Composition, w/o								Melting Point, F	Flow Characteristics	Brazing Temperature, F	Remelt Temperature, F
	Cu	Ni	Cr	Mn	Pd	Cb	Ge	Si				
1	--	64	25	--	--	--	--	11	1948	Good	2200	2387
2	--	59	30	--	--	--	--	11	1922	Good	2200	2430
3	--	54	35	--	--	--	--	11	1971	Good	2200	2407
4	--	40	20	--	40	--	--	--	2261	--	--	--
5(a)	--	57	13	--	--	--	30	--	1922	Good	2150	2413
6	--	46	46	--	--	--	--	8	2511	--	--	--
7(b)	80	20	--	--	--	--	--	--	2091	Good	2200	2335
8	--	70	19	--	--	--	--	11	1960	Good	2200	2325
9	--	40	--	--	60	--	--	--	2271	Good	2300	--
10	50	--	--	--	50	--	--	--	2164	Good	2275	2460
11	85	--	--	15	--	--	--	--	1771	Good	1900	2435
14	45	--	--	10	45	--	--	--	1961	Good	2200	2245
15	47.5	--	--	5	47.5	--	--	--	2026	Good	2200	2200
16	--	40	15	10	35	--	--	--	2153	Good	2250	2385
17	--	40	10	20	30	--	--	--	2146	Good	2250	2382
18	--	48	--	--	--	52	--	--	2134	Poor	2250	--
19	--	35	--	10	55	--	--	--	2129	Good	2250	2333
20	--	30	--	20	50	--	--	--	2082	Good	2250	2270
21	100	--	--	--	--	--	--	--	1981	Good	2150	--

(a) GE-75.

(b) GE-62.

FIGURE 9. JIG AND T JOINT USED TO DETERMINE THE REMELT TEMPERATURES OF BRAZES

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shear-test specimen consisted of two pieces of stainless steel, 0.084 in. thick, 7/8 in. wide, and 3-1/2 in. long. A slot 0.084 in. wide by 9/16 in. long was machined in the end of one of the plates. The edge of the unslotted plate was slipped into this slot to a depth of 1/2 in., thus forming a cross joint. This joint was then brazed with the particular brazing alloy to be tested. Figure 10 shows a brazed shear-test specimen. The shear strengths of the various alloys were calculated on the basis of a joint area of 0.084 sq in.

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FIGURE 10. SHEAR-TEST SPECIMEN FOR TESTING BRAZED STAINLESS STEEL JOINTS

Duplicate specimens were exposed for 1 month in degassed water at 1350 F and 5000 psi. Tables 4 and 5 show the results of the shear tests of several of the brazing alloys.

The shear strengths of the specimens brazed with GE-75 and with pure copper did not decrease after exposure to the corrosive medium. GE-62 showed a decrease of approximately 6 per cent. The other alloys, variations of the GE-62 composition, exhibited a decrease in shear strength of 15 to 20 per cent.

Further corrosion studies on the pure copper indicated a dissolution of the copper in the high-pressure high-temperature water. Apparently, the fillets of the copper-brazed shear-test specimens were large enough to prevent the attack of the corrosive medium from penetrating to the interfaces

TABLE 4. THE PHYSICAL PROPERTIES OF BRAZING ALLOYS BEFORE AND AFTER 4 WEEKS' EXPOSURE TO
DEGASSED SUPERCRITICAL WATER AT 1350 F AND 5000 PSI

Braze	Composition, w/o	Average Shear Strength				Average Tensile Strength			
		As Brazed At Room Temperature, psi	Number Tested	After Corrosion, psi	Number Tested	As Brazed, psi	Number Tested	After Corrosion, psi	Number Tested
1	64 Ni-25 Cr-11 Si	25,850	4	20,700	2	51,700 ^(a)	--	33,300	1
2	59 Ni-30 Cr-11 Si	27,200	4	21,400	2	--	--	--	--
3	54 Ni-35 Cr-11 Si	20,800	4	20,000	2	--	--	--	--
5 ^(b)	57 Ni-13 Cr-30 Ge	29,100	6	29,100	2	74,000	2	72,000	2
8 ^(c)	70 Ni-19 Cr-11 Si	26,250	4	24,750	2	--	--	--	--
21	100 Cu	23,800	1	23,750	2	58,100	2	52,000 1-week test 39,000 4-week test	1 1

(a) Calculated tensile strength based on the shear-strength data: shear stress is approximately one-half the tensile stress.

(b) GE-75.

(c) GE-62.

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TABLE 5. PHYSICAL PROPERTIES OF BRAZING ALLOYS

Braze	Composition, w/o	Average Shear Strength At Room Temperature, psi	Number Tested	Average Tensile Strength			
				At Room Temperature, psi	Number Tested	At 1350 F, psi	Number Tested
1	64 Ni-25 Cr-11 Si	25,850	4	51,700 ^(a)	--	36,800	1
2	59 Ni-30 Cr-11 Si	27,200	4	--	--	--	--
3	54 Ni-35 Cr-11 Si	20,800	4	--	--	--	--
5 ^(b)	57 Ni-13 Cr-30 Ge	29,100	6	74,000	2	26,900	2
8	70 Ni-19 Cr-11 Si	25,850	4	--	--	--	--
10	50 Cu-50 Pd	--	--	--	--	23,700	1
11	85 Cu-15 Mn	41,900 ^(c)	--	83,800	2	23,400	2
14	45 Cu-10 Mn-45 Pd	16,900 ^(c)	--	33,800	2	24,100	2
15	47.5 Cu-5 Mn-47.5 Pd	27,950 ^(c)	--	55,900	2	13,800	2
16	40 Ni-15 Cr-10 Mn-35 Pd	--	--	--	--	29,000	2
17	40 Ni-10 Cr-20 Mn-30 Pd	20,700 ^(c)	--	41,400	1	31,300	1
19	35 Ni-10 Mn-55 Pd	32,000	1	64,000 ^(a)	--	27,000	2
20	30 Ni-20 Mn-50 Pd	--	--	--	--	25,600	2

(a) Calculated tensile strength based on the shear-strength data: shear stress is approximately one-half the tensile stress.

(b) GE-75.

(c) Calculated shear strength based on the tensile data: shear stress is approximately one-half the tensile stress.

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of the joint. This shielding action would explain why the shear strengths of the copper-brazed test specimens were the same, both before and after being exposed to the corrosion tests.

Tensile Tests

In addition to the shear tests, tensile tests were made on several of the brazing alloys. The tensile specimens were prototypes of the standard tensile-test specimens.

Butt joints of 1/2-in. -diam stainless steel rod were brazed with each alloy. The specimen was then machined to 1/4 in. in diameter with the brazed joint at the center of the reduced section. Tables 4 and 5 show the results of the tensile tests.

Tensile specimens brazed with GE-75 showed a decrease in strength of only 2.7 per cent after 4 weeks' exposure. Specimens brazed with Alloy 1 and with copper showed decreases of 40 per cent and 33 per cent, respectively.

Corrosion Tests

In addition to the shear tests and tensile tests, corrosion studies were made on 1-in. -long T-joints brazed with the various brazing alloys. These T-joints were corrosion tested in 1350 F degassed water at 5000 psi for a period of 1 month. The extent of corrosion in several of the alloys can be seen in Figure 11.

No attack is visible in the joint brazed by GE-75, but the joint brazed with Alloy 3 shows severe attack of the fillet. The joint itself, however, does not appear to have been attacked. Less severe attack is evident in the joints brazed with copper-palladium and copper-nickel.

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100X

As Polished

N7826

a. Brazed With GE-75

100X

As Polished

N7825

b. Brazed With Alloy 3

100X

As Polished

N7830

c. Brazed With Alloy 10

100X

As Polished

N7827

d. Brazed With Alloy 7

FIGURE 11. CORROSION IN T-JOINT SPECIMENS BRAZED WITH VARIOUS ALLOYS EXPOSED TO 1350 F WATER AT 5000 PSI FOR 1 MONTH

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CONCLUSIONS

The fabrication of corrugated-flat-plate-type subassemblies was impractical because of the limited ductility of the fuel sheet. An MTR-type assembly $5/8$ in. square by 30 in. long could be fabricated. Of the three methods investigated for obtaining accurate plate spacing in the MTR design, the spot-welded-projection method appeared most practical. A method for edge sealing (flat stainless steel wires brazed to edge) roll-clad fuel sheet was developed, and a corrosion-resistant brazing alloy (GE-75) for joining the assembly was found.

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