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AEC Research and
Development Report

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KNOLLS
ATOMIC POWER
LABORATORY

*Development
of a
Transition Joint
Between Zircaloy-4
and
Ni-Cr-Fe (Alloy 600)*

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**G.E. Halm
E.O. Porter**

November 2, 1964

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DEVELOPMENT OF A TRANSITION JOINT BETWEEN
ZIRCALOY-4 AND Ni-Cr-Fe (ALLOY 600)

G. E. Halm, E. O. Porter

November 2, 1964

UNC. E. O. Porter
Authorized Classifier

12/17/64
Date

General Electric Company
KNOLLS ATOMIC POWER LABORATORY
Schenectady, New York
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ABSTRACT

A procedure was developed for making joints between Zircaloy-4 and Ni-Cr-Fe (Alloy 600), using the friction-welding process. When exposed to operating conditions not exceeding 1000F, joints produced by this process exhibited tensile and fatigue properties equal to those of the Zircaloy base material; when subjected to bending or impact loads, however, the joints were not satisfactory because of lack of ductility. Nevertheless, they were considered adequate for the intended application since substantial mechanical support could be provided in the component design to prevent loading of the joints by bending or during impact.

Five processes were investigated for making a joint of this type: friction welding, eutectic bonding, coextrusion, explosive bonding, and flash welding. Only the friction-welding process produced usable joints. The eutectic-bonding process produced joints that were too brittle to evaluate; these joints actually failed during cooling or sectioning for metallurgical examination. The coextrusion process produced satisfactory joints with two exceptions - reduced fatigue strength after exposure to 680F ammoniated water and bond-layer cracking as revealed by metallurgical sectioning. The explosive-bonding process was not sufficiently developed to yield joints acceptable for mechanical testing. Flash welding produced joints with low ductility in bend-testing and with reduced tensile strength; this process was investigated only to a limited extent because of time limitations and progress made with other processes.

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DEVELOPMENT OF A TRANSITION JOINT BETWEEN
ZIRCALOY-4 AND Ni-Cr-Fe (ALLOY 600)

G. E. Halm, E. O. Porter

INTRODUCTION

In recent years there has been an ever increasing demand for developing methods of joining dissimilar metals. Specific properties, for which a manufacturer has to pay a premium price in money or time, may be required in a small area of a designed component. This is true in not only the chemical, aircraft, and nuclear industries, but in others as well. To lower manufacturing costs and to simplify design problems, simple methods for making a transition from the "exotic" material to one that is more commonplace are often desirable. The extent of some of this work is described in References 1 through 4. The investigations range from friction welding to use of powder metallurgy techniques.

The objective of the program reported herein was to develop a procedure for making a sound metallurgical joint between Zircaloy-4 and Ni-Cr-Fe (Alloy 600) in a tubular configuration within the size ranges of 0.190-in. OD x 0.098-in. ID and 1.400-in. OD x 0.800-in. ID.

The minimum acceptable properties of the joints were established to be those equivalent to the minimum properties of the Zircaloy base material as tabulated below.

1. Mechanical properties (minimum)

	<u>Room Temperature</u>	<u>600F</u>
Tensile strength (ultimate), psi	67,500	31,000
Yield strength (0.2% offset), psi	38,600	15,000
Elongation in 1 in., % (minimum)	16	24
Reduction in area, % (minimum)	24	-

2. Fatigue strength - equal to Zircaloy-4

3. Corrosion resistance - equal to Zircaloy-4 and Ni-Cr-Fe in 680F ammoniated water with pH 10.

4. Pressure/temperature cycling - ability to withstand a minimum of 10,000 external pressure/temperature cycles of 0 to 1800 psig and 120 to 600F.

This report summarizes the process development, test procedures, and results for each of the processes investigated.

SCOPE OF PROGRAM

The scope of the program was:

1. A review of previous work done, to produce a similar joint between Zircaloy-2 and Type 304 stainless steel and to evaluate the applicability of this technique to the joining of Zircaloy-4 and Ni-Cr-Fe.
 2. Production of joints by:
 - a. Eutectic bonding
 - b. Flash welding
 - c. Explosive bonding
 - d. Coextrusion
 - e. Friction welding.
 3. Evaluation of promising joints by subjecting them to the following tests:*
- a. Dye-penetrant test
 - b. Helium leak test
 - c. Radiography test
 - d. Tensile test at room temperature and 600F
 - e. Bend test
 - f. Corrosion resistance test
 - g. Thermal cycling test
 - h. High-pressure/temperature cycling test
 - i. Fatigue test.

DISCUSSION

This section summarizes the results obtained with each type of joint evaluated. Detailed results are included in Appendices B through E.

Previous KAPL Work on Zircaloy-2 to Type 304 Stainless Steel Transition Joints⁵

Prior work at KAPL had resulted in the fabrication of Zircaloy to Type 304 stainless steel transition joints by a procedure that produced bonding of the materials through the formation of a eutectic by the application of heat and pressure within a vacuum. These joints were formed by mating an external cone on the stainless steel tube to an internal cone on the Zircaloy tube (see Figure 1). While applying a light load (an

*The evaluation of each process was pursued only to the point of determining the applicability of that process. Therefore, it will be noted that joints from all processes were not subjected to all tests. Details of the test procedures and equipment are found in Appendix A.

axial compressive load of ~100 gm) to maintain contact between the cones, the temperature of the joint was increased to 1832F by use of an induction coil. Under these conditions a Zr-Ni-Fe eutectic was formed to bond the tubes together.

During development of this fabrication procedure, it was observed that the tensile strength of these joints was a function of the thickness of the "bond" (eutectic) layer, with strength decreasing as thickness of bond increased. To produce satisfactory joints, it was found necessary to maintain the bond thickness at a 0.001 in. maximum. The application of low axial pressure to the joint assisted in the control of bond thickness by expelling excess eutectic from the joint.

Joints made of Zircaloy and Type 304 stainless steel by this process exhibited the following properties:

	<u>Room Temperature</u>
Tensile strength (ultimate), psi	57,000
Yield strength (0.2% offset), psi	35,000
Corrosion resistance in 680F ammoniated (pH 10) pure water	Borderline acceptable compared with that of Zircaloy
Ductility	Failure of joints occurred by brittle fracture in the bond.

Results of the above work and a knowledge of the characteristics of both Zircaloy and Ni-Cr-Fe alloy indicated that a satisfactory joint between these materials might be attained by use of a process that produced a thin bond layer. Since the attainment of ductility within the joint was a formidable problem, however, the selection of processes to be evaluated was aimed at those known to produce thin bond layers. For those involving welding, only processes that produced very rapid heating and cooling cycles were considered.

Process Evaluations

For reasons of material and equipment availability, as well as economy, a joint size of 0.190-in. OD x 0.098-in. ID was selected as the standard upon which to compare process capabilities.

1. Eutectic Bonding

Using the above-mentioned Zircaloy to Type 304 stainless steel transition joint process, the eutectic bonding of Zircaloy and Ni-Cr-Fe was attempted. The first joints made showed the formation of the eutectic layer to be so rapid at the bonding temperature (1832F) that attempts to keep it at an acceptable thickness would have been impracticable. Increasing the axial load on the joint, and maintaining

4.

FIGURE 1. Schematic of Conical Tapered Joint Design
Used for Eutectic-Bonding Process.
KS-56131 Unclassified

Joint Design

As-Welded

Machined Transition Tube

FIGURE 2. Schematic of Joint Design Used
for Flash-Welding Process.
KS-56132 Unclassified

exacting temperature control, had no noticeable effect on the rate of eutectic formation. All resulting joints failed during cooling or during sectioning for metallurgical examination. Since it was obvious that acceptable joints could not be made by this process without extensive development work, it was decided that further work with this process would be terminated.

2. Flash Welding

The resistance welding process used to make the Zircaloy to Ni-Cr-Fe transition joints was flash welding. The rods to be welded were clamped in welding dies; a voltage was applied, and as one piece moved forward and contacted the other, flashing occurred until the temperature of the rods reached the weld temperature. Then high force was applied, thus forging the rods together and completing the weld.

After establishing a welding procedure (Appendix B lists the work done to develop the welding parameters), 50 samples were made, and the joint design detailed in Figure 2 was developed. Thirty of the welded samples were drilled and turned to the 0.190-in. OD x 0.098-in. ID test sample. From the test data included in Appendix B, the properties of a transition joint made by the flash-welding process can be summarized in Table 1.

TABLE 1. FLASH WELDING - SUMMARY OF TENSILE TEST RESULTS

<u>Test</u>	<u>Test Results (avg), psi</u>	<u>Minimum Requirements, psi</u>
Ultimate tensile strength		
at room temperature	61,600	67,500
at 600F	32,400	31,000
0.2% offset yield strength		
at room temperature	53,100	38,600
at 600F	24,500	15,000
Bend test: all samples failed in the welds at permanent deflections <0.200 in.		
Corrosion resistance: acceptable.		
Thermal cycle test: no failures.		

Figure 3 shows a photomicrograph of a typical bond layer in flash-welded transition joints. The bond-layer thickness ranges from

1 to 4 μ . The angular crystals, to be noted in Figure 3, were analyzed by electron-microprobe analysis and identified as titanium nitride. The titanium nitride is present in the Ni-Cr-Fe alloy as a contaminant (as evidenced in metallographic examination) and apparently accumulates at the weld boundary during the upsetting process. These nitride inclusions could have contributed to the low tensile strength observed.

Evaluation of several of the joining processes progressed simultaneously. At the time of the completed evaluation of the flash-welded samples, two other processes - coextrusion and friction welding - appeared more promising. Therefore, it was decided to terminate work with the flash-welding process.

3. Explosive Welding

The process of explosive welding utilizes high-explosive detonation to drive two materials together with such force that when closure geometry is correct the oxide films are removed and a bond is effected. To make a weld, the pieces are machined, cleaned, assembled, enclosed and evacuated in a rubber sock, and subjected to an explosive force in a tank of water.

The selection of the explosive-welding process for transition joint fabrication was based on work conducted by Battelle Memorial Institute (BMI).⁶ This approach to cold-bonding dissimilar materials had been successfully demonstrated by the formation of bonds between Zircaloy-2 and Type 410 stainless steel tubing. Therefore, a contract was placed with BMI to conduct a limited investigation on the feasibility of using the explosive-welding process to fabricate joints between Zircaloy-2 and Ni-Cr-Fe alloy. Appendix C, a summary of a report of this investigation,⁷ is described as follows:

- a. Multiple variations of weld parameters, joint designs, and explosive charge configurations were investigated. The work indicated that explosive bonding of Zircaloy to Ni-Cr-Fe alloy may be feasible.
- b. The use of an intermediate layer of 0.0007-in. chromium was necessary to prevent the formation of intermetallic compounds.
- c. Process parameters were not developed to the point of producing joints satisfactory for mechanical testing.

At the time the feasibility report was issued, the nearly completed evaluation of the coextruded and friction-welded transition joints indicated that an acceptable transition joint could be developed from one of these methods, with a minimum of time and cost. Since it was evident that considerable development effort would be required to develop the parameters of the explosive-welding process, the investigation was terminated.

Unclassified

14578-4;J4416-2(2)Bright Field 250X

FIGURE 3. Flash Weld. Zircaloy-2 to Ni-Cr-Fe (Alloy 600) Bondline.

KS-56133

Unclassified

FIGURE 4. Schematic of Joint Design Used for Evaluation of Coextrusion Process.

KS-56134

Unclassified

4. Coextrusion

The coextrusion process used to produce Zircaloy-4 to Ni-Cr-Fe alloy transition joints was accomplished by the hot extrusion of an evacuated steel pack enclosing cleaned shaped bars (see Figure 4), with mating surfaces abraded to remove oxides.

A reduction of 4 to 1 through the extrusion die breaks up the remaining oxide films on the base materials, or the oxygen is absorbed by the Zircaloy, permitting clean metal contact under high pressure and formation of a thin intermetallic bond layer. Extrusion of the matching cones on the starting materials results in a tear-drop-shaped interface between the Zircaloy and Ni-Cr-Fe alloy, which produces a tapered transition joint when the center of the extruded bar is removed (Figure 4).

Fifty coextruded joints were fabricated. Details of the test results of joints evaluated are listed in Appendix D. The properties of the coextruded transition joints are summarized in Table 2.

TABLE 2. COEXTRUSION PROCESS - SUMMARY OF TENSILE TEST RESULTS

<u>Test</u>	<u>Test Results*</u> <u>(avg). psi</u>	<u>Minimum</u> <u>Requirement, psi</u>
Ultimate tensile strength		
at room temperature	79,700	67,500
at 600F	38,100	31,000
0.2% offset yield strength		
at room temperature	63,000	38,600
at 600F	33,100	15,000

Bend test: acceptable.

Corrosion test: acceptable.

Thermal cycle test: no failures - acceptable.

High-pressure/temperature cycling test: no failures -
acceptable.

Fatigue test: Rotating beam tester with an applied stress
amplitude of 54,000 psi.

<u>Fatigue Specimen Test Conditions</u>	<u>Fatigue Strength</u>
As-received	Equivalent to Zircaloy
After corrosion exposure	Less than Zircaloy
After high-pressure/temperature cycling	Less than Zircaloy

*See Appendix D, "Fatigue Test Results," p. D.3, for
numerical data.

Unclassified

A. Coextruded-Longitudinal 1 hr at 1200F.

B. Coextruded-Transverse 1 hr at 1200F.

C. Coextruded-Transverse 1 hr at 1300F.

D. Coextruded-Transverse 1 hr at 1400F.
(Bond layer width $\rightarrow$ 0.003 in.)

FIGURE 5. Heat-Treated Coextruded Transition Joints.
KS-56136

Unclassified

17469-3; J5184-2(20L); BF; 2000X

17469-4; J5184-1(20T); BF; 2000X

17470-1; J5184-5(21T); BF; 2000X

17471-2; J5184-5(22T); BF; 2000X

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FIGURE 6. Bond Layer Cracks in Coextruded Transition Joint Evident after 600F Tensile Test.

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To determine the effect of heat treatment on this type of joint, a set of coextruded joints was heat-treated for 1 hr in a vacuum ($<0.05\mu$) at 1200, 1300, and 1400F. The photomicrographs (see Figure 5) revealed that as temperatures were increased, the bond layer became progressively thicker and more prone to cracking. This test demonstrated that the effects of time at elevated temperatures were significant and that heat treatment of the coextruded transition joints must be limited to about 1 hr at 1000F to minimize damage to the joints.

The evaluation of the coextruded transition joint showed it to be of acceptable quality, except for reduced fatigue strength after exposure to operating temperatures (see discussion in Appendix D, "Fatigue Test Results," p. D.3) and the bond-layer cracking revealed by the metallurgical sectioning of the tensile-tested specimens (see Figure 6). For example, four coextruded transition joints, which had been corrosion-tested for 38 days in 680F water, failed after <1000 cycles at a stress amplitude of 54,400 psi, whereas similar joints without the corrosion test history failed after 30,000 cycles or greater.

5. Friction Welding

The friction-welding process develops the heat required to make a weld by rotating one piece against the other while the two

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pieces are forced together under high pressure. When a predetermined amount of upset is accomplished, the welding process is terminated automatically. To ensure welds of consistent quality, the faces of the Zircaloy and Ni-Cr-Fe alloy to be welded must be carefully prepared. A surface finish of 32 μ in. was used in this program. Inert gas shielding was not required because all the initially melted surface and contaminants are expelled from the weld zone during welding. The parameters of the friction-welding procedure used in this program were recorded on a high-speed recorder, supplying an exact record of the weld. The records were utilized as a "nondestructive test" of the weld quality by comparing them with similar records of the destructive-tested procedure qualification weld joints. The joint design and finished transition joints are shown in Figure 7.

Thirty-five joints were fabricated. Details of the test results of the joints evaluated are presented in Appendix E. The test results are summarized in Table 3.

FIGURE 7. Schematic of Joint Design
Used for Friction-Welding Process.
KS-56137 Unclassified

TABLE 3. FRICTION-WELDING PROCESS - SUMMARY OF TENSILE TEST RESULTS

Test	Test Results (avg), psi	Minimum Requirements, psi
Ultimate tensile strength		
at room temperature	71,100	67,500
at 600F	31,800	31,000
0.2% offset yield strength		
at room temperature	53,700	38,600
at 600F	24,100	15,000

Bend test: all joints bent over 0.375-in. centers failed through the weld; joints were bent over 1.25-in. centers without weld failure (see Appendix A for test description).

Corrosion resistance: acceptable.

Thermal cycle test: no failures.

High-pressure/temperature cycling test: no failures - acceptable.

Fatigue testing: rotating beam tester with an applied stress amplitude of 54,400 psi.

Specimen Test Condition	Fatigue Strength
As-received	Equivalent to Zircaloy
After corrosion exposure	Equivalent to Zircaloy
After high-pressure/temperature cycling	Equivalent to Zircaloy

Figure 8 presents photomicrographs of a typical bond layer in friction-welded transition joints. The void-free bond layer ranges from 1/2 to 1 μ in width. To determine the effect of heat treatment on this type of joint, a set of friction-welded joints was heat-treated as described for the co-extruded transition joint. The tests demonstrated that the same temperature restriction as for the coextruded joints, a maximum of 1000F for 1 hr, must be applied to the friction-welded joint to prevent excessive bond growth. As shown in Figure 8, the heat treatment of the friction-welded transition joints did not result in the voids and the cracks noted in the photomicrographs of the coextruded joint although the bond did grow in width.

Evaluation of the friction-welded transition joints indicated a joint of acceptable quality if the component design provided support for the joints to prevent bending. However, the joints did exhibit low ductility failures when struck with a hammer blow at the bond interface.

CONCLUSIONS - BASED ON DEVELOPMENT WORK AND SCHEDULAR REQUIREMENTS

1. If the joints can be supported or protected against transverse shock loads, several methods can be used for producing them. The most satisfactory joint is produced by the friction-welding process, since this joint meets all criteria. The next best is the coextruded joint, which is lacking in fatigue strength after corrosion testing. Acceptable joints could probably be produced by flash-welding if the process were developed further.
2. All procedures evaluated resulted in a weld joint characterized by a bond layer that exhibited low ductility and provided an area susceptible to failure. It is concluded, therefore, that while the friction-welded joints are considered acceptable for the application, additional effort should be expended to develop a method for making more ductile transition joints between these two materials.
3. Because of the results obtained, and because of time limitations, it was concluded that the production components should be made by the friction-welding process.

PRODUCTION RESULTS

An order was placed for transition joints of four different sizes as shown and tabulated in Sketch 1.

SKETCH 1. Types of Production Transition Joints.

Unclassified

Ni-Cr-Fe Alloy 600—

Zircaloy-2—

22009(1); Bright Field; 2000X

A. As-Welded Friction Weld.

Ni-Cr-Fe Alloy 600—

Zircaloy-2—

17748(1) L; Bright Field; 2000X

B. Friction-Welded Joint after 1 hr at 1200F.

Ni-Cr-Fe Alloy 600—

Zircaloy-2—

17748(2) L; Bright Field; 2000X

C. Friction-Welded Joint after 1 hr at 1300F.

FIGURE 8. Photomicrographs of Friction-Welded Transition Joints.
KS-56138

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Technical Problems Encountered

Procurement and Testing of Item 1 (Sketch 1)

Machining. Difficulty was encountered in maintaining concentricity requirements (0.002-in. TIR) between the different-sized holes of Item 1. This difficulty was finally overcome by machining a bushing that was placed inside the first hole drilled (0.205-in. diam) to locate the second hole (0.162-in. diam) in relation to the first. Then, after both holes had been drilled and reamed to size, the outside was turned down, using the holes for centering.

Testing. Forty-five components were purchased. All parts were subjected to, and passed, dye-penetrant, radiography, and helium leak tests, and (except as noted in Table 4) a 3-1/2 day, 680F water corrosion test. Ten of the parts were subjected to a tensile test with the results recorded in Table 4.

TABLE 4. TENSILE TEST RESULTS OF ITEM 1 OF PRODUCTION
TRANSITION JOINTS (SKETCH 1)

Specimen No.	0.2% YS, psi	TS, psi	EL, %*	RA, %*	Failure Location
Specification	38,600	67,500	16	24	-
1-1	43,000	70,000	21.1	37.3	Zircaloy
1-2**	45,400	70,300	14.4	39.1	Zircaloy
1-3	45,100	68,900	-	-	Weld
1-4	†	73,400	-	-	Weld
1-6	49,700	72,100	13.9	24.8	Zircaloy
1-12	49,500	72,700	18.8	37.6	Zircaloy
1-14	52,100	71,900	19.3	26.3	Zircaloy
1-26	47,500	71,400	21.9	34.3	Zircaloy
1-36	53,200	72,500	18.9	33.3	Zircaloy
1-45**	45,400	70,300	14.4	41.2	Zircaloy
Average	47,877	71,350			

*Reported for information only.

**These samples were not corrosion-tested prior to tensile test. All other samples were corrosion tested.

†Slippage of specimen in fixture prevented accurate recording of yield point.

YS = Yield strength EL = Elongation
TS = Tensile strength RA = Reduction of area

All welds failed at a strength above the required tensile strength although two (1-3 and 1-4) failed in the weld. The reason for the weld failure is not clearly understood. It is felt, however, that the weld strength is very close to that of the Zircaloy and that it would not be surprising to experience an occasional weld failure. These welds were considered acceptable for the application.

Figure 9 is a photograph of typical tensile specimen failures. The failure in these specimens is located in the Zircaloy portion. The weld joint is clearly distinguishable.

Procurement and Testing of Item 2 (Sketch 1)

Machining. Machining problems were also encountered with this item. The diameter of the hole was so small (0.098 in.) that the TIR tolerance (0.002 in.) could not be maintained with conventional machining. As a result, deep hole drilling was tried. However, even use of the deep hole drilling process could not consistently produce holes with a runout of <0.006 in. Therefore, tolerances were relaxed to this capability limit.

Testing. The first six specimens were produced with conventional machining practices. Two were tensile-tested and found to lack concentricity; three were used for mockup work; and one was used as a corrosion specimen standard. Of the remaining 49, six were tensile-tested. Results of all tensile tests are contained in Table 5. All samples passed dye-penetrant, radiography, corrosion, and helium leak tests.

TABLE 5. TENSILE TEST RESULTS OF ITEM 2 OF PRODUCTION
TRANSITION JOINTS (SKETCH 1)

Specimen No.	0.2% YS, psi	TS, psi	EL in Zircaloy, %*	RA in Zircaloy, %*	Failure Location
<u>Specification</u>	<u>38,600</u>	<u>67,500</u>	<u>16</u>	<u>24</u>	-
2-1	43,000	70,000	-	37.5	Zircaloy
2-2	34,000	55,300	-	-	Weld**
2-7	47,100	67,500	-	-	Weld
2-14	52,500	70,800	20.0	35.8	Zircaloy
2-15	46,800	70,900	6.5	17.7	Zircaloy
2-17	44,100	70,600	21.0	38.2	Zircaloy
2-28	44,900	71,000	21.5	39.0	Zircaloy
2-46	41,400	71,900	21.5	36.5	Zircaloy

*Reported for information only.

**Lack of concentricity resulted in low strength

Procurement and Testing of Item 3 (Sketch 1)

After extensive testing and evaluation of the effects of weld configurations, including welding of tubes, it was concluded that specification requirements for mechanical properties could not be met. The vendor's equipment was not large enough to produce the energy and force necessary for making a weld of this size. The vendor felt that welds with tensile strengths in excess of 50,000 psi could be made, and on that basis, produced 11 transition joints.

These parts were welded, machined to drawing requirements, and tested by KAPL. All parts passed dye-penetrant, ultrasonic, radiography, and helium leak tests, and a 3-1/2-day corrosion test in 680F water. None passed the tensile test, however, and only two exceeded an ultimate tensile strength of 40,000 psi. Tensile test results on the seven specimens are presented in Table 6. All failures exhibited little or no ductility.

TABLE 6. TENSILE TEST RESULTS OF ITEM 3 OF PRODUCTION
TRANSITION JOINTS (SKETCH 1)

<u>Specimen No.</u>	<u>Ultimate Tensile Strength, psi</u>
3-1	62,200
3-4	38,000
3-6	28,800
3-7	16,200
3-11	19,600
3-12	42,800
3-13	38,600

NOTE: In all specimens
failure occurred at weld.

The application for this joint was one that did not require a great deal of tensile strength; it was therefore decided to subject one specimen to a torsion cycling test since such testing would be more representative of the stress the joint would receive in service. The tube was twisted in one direction to a stress of 24,000 psi and then brought back to zero stress. This cycle was repeated 19,952 times with no effect on the weld. The part failed in a section of Zircaloy that had been welded on one end to hold the tube in the test fixture.

From an engineering point of view, the part would have been satisfactory for service. While the test was being performed, however, the

Unclassified

FIGURE 9. Tensile Tested Specimens (Dwg 116C1174, Rev. 0,
Group 1, as modified by I.V. 5, NPD-5636, Item 1).
KS-55121

Unclassified

Ni-Cr-Fe (Alloy 600)

Zircaloy-4

FIGURE 10. Specimen 4-13. Showing "As-Friction Welded"
Transition Joints.

KS-55602

Unclassified

part was redesigned to give a smaller cross-sectional area, and the properties of the resultant welded joints were much more consistent although still below original specification requirements. Since mechanical properties were more consistent, it was decided to use the newly designed part for production.

Procurement and Testing of Item 4 (Sketch 1)

This item constituted the redesigned joint with a reduced cross-sectional area, as mentioned previously. Figure 10 shows an "as-friction-welded" transition joint. Note the expulsion of the softer, more ductile Zircaloy-4. Welding and machining posed no problem, and 11 pieces were welded.

All parts passed dye-penetrant, radiography, and helium leak tests, and the 3-1/2 day, 680F water corrosion test. Tensile test results were as shown in Table 7.

TABLE 7. TENSILE TEST RESULTS OF ITEM 4 OF PRODUCTION
TRANSITION JOINTS (SKETCH 1)

<u>Specimen No.</u>	<u>Ultimate Tensile Strength, psi</u>
4-4	65,500
4-5	60,140
4-6	61,900
4-7	51,500
4-8	60,100
4-9	<u>57,200</u>
Average	59,390

NOTE: In all specimens
failure occurred at weld.

All failures exhibited little or no ductility (see Figures 11 and 12). One specimen (4-11) was torsion-tested to failure at 63,000 psi. These properties (tensile and torsion) were determined to be acceptable for the application, and the parts (4-10 and 4-12) were used for production.

FINAL CONCLUSIONS

The friction welds made between Ni-Cr-Fe (Alloy 600) and Zircaloy-4 are sound, meet the mechanical properties of Zircaloy-4, and have corrosion resistance and fatigue strength equivalent to those of Zircaloy-4. Weld parameters are critical, however, and joint size is limited by the energy available in the welding equipment, as evidenced by the lower tensile strength of the large transition joints (Tables 6 and 7).

KAPL-3073

Unclassified

Ni-Cr-Fe (Alloy 600)

Zircaloy-4

FIGURE 11. Specimen 4-4. Showing Tensile
Test Break Through the Weld.

KS-55601

Unclassified

Ni-Cr-Fe (Alloy 600)

Zircaloy-4

FIGURE 12. Specimen 4-4. Showing Fracture
Surfaces after Tensile Test.

KS-55603

Unclassified

APPENDIX A. DESCRIPTION OF EVALUATION TEST PROCEDURES USED ON DEVELOPMENT SPECIMENS

TEST SPECIMEN

All sample joints evaluated during development were received at KAPL from the vendors as solid bar stock. The sample bars were then machined to simulate the smallest transition joint, 0.190-in. OD x 0.098-in. ID x ~8-in. long, as required by the design.

NONDESTRUCTIVE TESTS

After machining, all samples were helium-leak-tested, and the external surface of the joints was dye-penetrant-inspected before acceptance for additional testing.

Helium leak test: maximum acceptable leak rate - 5×10^{-8}
atm cc/sec.

Dye penetrant test: no defect permitted.

TENSILE TESTS

Tensile specimens consisted of 8-in. tubing lengths, with the joint approximately centered along the length of the specimen. For the room-temperature tests, a 2-in. extensometer was placed on the specimen so that the joint was located in the middle of the gage. The readout of the extensometer was monitored for strain. For the 600F tests, the specimen was clamped in the machine so that the joint was in the middle of the length of tubing between the jaws; during the test, the crosshead motion was monitored. The tests were performed at a crosshead speed of 0.02 in./min. The elevated temperature tests were performed in an argon atmosphere.

In the tensile tests, only failure location and ultimate tensile strength indicate qualities of the joint. The yield strength and elongation were reported for information only, since they are complicated functions of the Zircaloy and Ni-Cr-Fe base materials and of the weld metal.

BEND TESTS

The bend tests were performed on specimens in the as-welded condition at room temperature. A schematic diagram (Figure A.1) shows the method of

loading. The joint was located in the center between the two inner loads. The deflection rate (at the location where an inner load is applied) was 0.02 in./min. Autographic records of load vs deflection at the inner load were obtained and used to calculate the results of the tests. The first two tests were performed with the distance between the inner loads set at 1.25 in. The two friction-welded specimens tested did not fail after the specimens were deflected more than 1/2 in.; so the remaining friction-welded specimens were tested with the inner loads set at 0.375 in. in an attempt to induce failure at the joints. The results tabulated in Appendices B, D, and E. give the maximum stresses reached during the tests and were calculated from the elastic formula:

$$S = \frac{MC}{I} ,$$

where S = nominal maximum stress
 M = maximum bending moment reached in the center section
 C = outer diameter/2
 I = moment of inertia.

The final stress was calculated from the same formula, but the bending moment used was the value at the termination of the test. When the specimens fail at the maximum load, the two stresses are identical.

THERMAL CYCLING TESTS

Thermal cycling tests were performed on as-welded samples. Specimens were sealed in an ampule filled with argon at 1/3 atmospheric pressure for testing.

Two thermal cycling conditions were utilized: Condition 1 consisted of 500 cycles from 170 to 600F (at ~3 cycles/hr). Condition 2 consisted of 1000 cycles from 500 to 1000F (at ~6 cycles/hr). After each thermal cycling condition, specimens were helium-leak-checked to determine whether a leakage path had developed across the wall of the specimen because of cracking induced by thermal cycling.

FATIGUE TESTS

Fatigue tests were performed on specimens at room temperature in an R. R. Moore rotating bending fatigue machine. These tests impose a constant bending moment across a 3/4-in.-long gage length while the specimen is being rotated. The joints were centered in the middle of the gage length. Specimens of Zircaloy-2 (without a joint) were tested and the results used for comparison (see Figure A.2).

FIGURE A.1. Schematic of Bend Test.
KS-56139 Unclassified

FIGURE A.2. Tubular Weld Fatigue Specimen.
KS-56140 Unclassified

CORROSION TEST

Specimens of the transition joints were exposed to static corrosion for varying periods in 680F water with an initial chemistry as follows:

1. Ammoniated	pH 10
2. Hydrogenated, cc/kg of water	30
3. Resistivity, ppm ($\text{cm} \times 10^3$)	40 to 44
4. Chloride, ppm	0.1
5. Fluoride, ppm	0.1

The specimens corroded were:

1. Solid transition joints.
2. 0.190-in.-OD $\times$ 0.098-in.-ID tubes with welded ends.
3. Longitudinal sections of the transition joints.

After the exposure period, the transition joints were examined at 30X magnification to determine the extent of corrosion attack. Specimens 1 and 2 were used for further testing after corrosion exposure. Specimen 3 was exposed for 90 days and analyzed by the electron microprobe to evaluate long-term attack at the transition-joint interface.

PRESSURE/TEMPERATURE CYCLING TEST

The cycling facility was a completely automated, simultaneous, temperature and pressure cycling unit. Heat and pressure were supplied in a steam pressurizer constructed of 6-in. Schedule-160 carbon-steel pipe. Specimens were thermally shocked by permitting the pressurizer to blow down through the test section. By valve manipulation (see Figure A.3), the test section was placed on line with the pressurizer and thereby subjected to line pressure. As its heat source, the pressurizer had a 9-kw immersion heater and three 1-kw strip heaters attached to the outside diameter. A differential-pressure cell measured and controlled the pressurizer liquid level. The operating saturation conditions were controlled by an on-off temperature controller.

The test section was depressurized by proper valve manipulation - permitting the test section, but not the pressurizer, to vent to drain. The specimens were cooled by pumping cold (80F) demineralized water (pH 7) through the section with a centrifugal pump. Four air-operated, on-off valves were employed to perform the cycling. A 6-cam industrial timer was used to control the four valves.

Test Section Description

Five friction-welded and five coextrusion-welded specimens, 0.190-in.-OD $\times$ 0.098 in.-ID, were tested in one holder designed so that the tubings would be pressurized externally as in actual service. The ten 0.190-in.-OD pieces $\times$ 0.098-in.-ID tubes were seal-welded at the Zircaloy end. The Ni-Cr-Fe alloy end of the five friction-welded specimens was then seal-welded into one end of the test section housing, and the Ni-Cr-Fe alloy end of the five coextrusion-welded specimens was seal-welded into the other end of the housing.

The housing itself, a cylinder constructed of Ni-Cr-Fe alloy, had five penetrations at each end for the specimens and five pipe thread penetrations in the cylindrical section for combined steam and water inlets and outlets and for a thermocouple connection. The housing was fabricated from two machined halves with generous radii on the inside to avoid thermal stresses at the connection of the flat head and barrel section. All pipe threaded connectors to the housing were fabricated from Ni-Cr-Fe alloy and were seal-welded to it. Figures A.4 and A.5 show the small specimens installed in the housing. Figure A.6 shows the pressure-temperature cycling facility.

Cycle Description

The cycle began with the test section at $\sim$ 120F and 0 psig. High-pressure steam at 620F and 2000 psig was passed through the test section, rapidly heating it. The pressure and temperature were permitted to build up to a maximum of 605F and 1800 psig and held for a period of 1 min, 40 sec. The test specimen was then cooled rapidly to $\sim$ 120F, and the cycle repeated. Total cycle time was 4 min.

A.6.

SEQUENCE OF VALVE OPERATION

Valve No.	Cycle				
	Heatup	Pressurizing	Depressurizing	Cooldown	Heatup
1	Open	Open	Close	Close	Open
2	Open	Close	Open	Close	Open
3	Close	Close	Close	Open	Close
4	Close	Close	Close	Open	Close

FIGURE A.3 Schematic Diagram of Test Facility
for Cyclic Testing Transition Joints.
KS-56141 Unclassified

FIGURE A.4. Transition-Joint Pressure-
Temperature Cycling Test.
KS-56142 Unclassified

Unclassified

FIGURE A.5. Test Autoclave
for Transition Joint.
KS-31744 Unclassified

FIGURE A.6. Area View of Pressure-
Temperature Cycling Facility.
KS-31745 Unclassified

APPENDIX B. FLASH-WELDED TRANSITION JOINT EVALUATION

FLASH-WELDING PROCESS DEVELOPMENT

As noted in the body of this report, the objective was to produce a sound, satisfactory weld joint between Zircaloy and Ni-Cr-Fe (Alloy 600). Flash welding was selected as one of the processes to be tried because of its capability for welding dissimilar materials and the fact that the actual weld is formed very rapidly, thus promoting a narrow width weld.

Flash welding is done by clamping the two work pieces in the welding dies of the machine so that they are not touching. A voltage is applied across the work pieces, and one piece is moved toward the other. As the high spots of the interfaces touch, the voltage causes a current to flow. Because of the restricted path, the current density is sufficiently high to cause the metal at these points to become molten and to be expelled. The moving work piece moves steadily forward; new spots carry the current, become molten, and are expelled. This action continues in rapid succession until the temperature of the work pieces at their interfaces reaches welding temperature.

As welding temperature is reached, the moving work piece is greatly accelerated and the flashing stops. A high force is instantaneously applied, forging the pieces together and completing the weld.

The purpose of the flashing action is twofold. First, it gets rid of all the surface metal which may contain dirt and scale. Second, and of more importance, it generates heat and distributes it uniformly in the work pieces. Thus, flash-welding, unlike other forms of resistance welding, generates the required heat mostly by the flashing action and only slightly by the actual resistance of the work pieces themselves. The upsetting action forges the weld and in so doing squeezes out any impurities, thus producing a clean inclusion-free weld.

Five feasibility samples were made by the process, and their physical properties found to be promising. Further evaluation was necessary to establish consistency of weld quality and to determine other physical properties. The feasibility tests had indicated that a weld tensile strength of 60,000 psi could be attained. This strength became the minimum objective in establishing parameters. Table B.1 illustrates the effect of weld parameter variables on tensile strength.

TABLE B.1. EFFECT OF WELD PARAMETER VARIABLES ON TENSILE STRENGTH OF FLASH-WELDED JOINTS

Test No.	Pressure, psi		Current Cutoff, in.	Flash Time, sec	Top Switch	Forge Delay	Overhang, in.		Die Operation, in.		TS, 1000 psi
	Initial	Final					Ni-Cr-Fe	Zircaloy	Initial	at "0"	
1	30	50	1/64	2.5	8	4	3/32	11/32	7/16	1/4	43
2	30	50	1/64	2.5	8	4	3/32	11/32	7/32	1/4	52
3	30	50	1/64	2.5	8	1	3/32	11/32	7/32	1/4	53
4	35	60	1/64	2.5	8	1	3/32	11/32	7/32	1/4	56
5	40	65	1/64	2.5	8	1	3/32	11/32	7/32	1/4	56
6	35	60	1/32	2.5	8	1	3/32	11/32	7/32	1/4	55.5
7	35	60	0	2.5	8	1	3/32	11/32	7/32	1/4	53
8	35	70	1/32	2.5	8	1	3/32	11/32	7/32	1/4	59
9	35	80	1/32	2.5	8	1	3/32	11/32	7/32	1/4	54
10	35	70	1/32	2.5	8	1	5/32	9/32	7/16	1/4	62
11	35	70	1/32	2.5	8	1	5/32	9/32	7/16	1/4	58.2
12	35	70	1/32	2.5	8	1	5/32	9/32	7/16	1/4	58
13	35	70	1/32	2.5	8	0	5/32	9/32	7/16	1/4	58
14	35	70	1/32	2.5	8	1	3/16	1/4	7/16	1/4	49
15	35	70	1/32	2.5	8	1	5/32	9/32	7/16	1/4	51
16	35	70	1/32	2.5	8	0	5/32	9/32	7/16	1/4	67
17	35	70	1/32	2.5	8	0	5/32	9/32	7/16	1/4	53
18	35	70	1/32	2.5	8	0	5/32	11/32	1/2	5/16	48
19*	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	57
20	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	57
21	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	57
22	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	57
23	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	57
24	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	57
25	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	57.4
26	35	70	1/32	2.5	8	0	9/64	19/64	7/16	1/4	58.7
27	35	70	3/64	2.5	8	0	9/64	19/64	7/16	1/4	60.6
28	35	70	3/64	2.5	8	0	9/64	19/64	7/16	1/4	57.2
29	35	75	3/64	2.5	8	0	9/64	19/64	7/16	1/4	59
30	35	75	3/64	2.5	8	65	9/64	19/64	7/16	1/4	65
31	35	75	3/64	2.5	8	65	9/64	19/64	7/16	1/4	60
32	35	75	3/64	2.5	8	65	9/64	19/64	7/16	1/4	60

*At this point five welds were made consecutively, using the same settings as were used for Sample 19. The strengths were: 57,400, 56,000, 51,000, 53,300, 52,000 psi. A slight misalignment of the two pieces, noted in all samples, introduced an error in the tensile test. It was also noted that the dies did not grip the work properly at the weld line. The dies were reworked and realigned. On Tests 1 through 24, the end preparation of the Ni-Cr-Fe was a 22-deg chamfer with a 1/16-in. center flat. In Tests 25 through 32, the angle was the same, but the center flat was decreased to 0.015 in. (see Figure 2).

TS = tensile strength

The following parameters were selected for the final samples:

Initial pressure	35-lb gage
Final pressure	75-lb gage
Current cutoff, in.	3/64
Flash time, sec	2.5
Top switch	No. 8
Forge delay	0
Overhang, in.	
Ni-Cr-Fe	9/64
Zircaloy	19/64
Die operation, in.	
Initial	7/16
At "0"	1/4

During production of the final samples, one tensile test was made and results were recorded after every 10 samples made. The average ultimate tensile strength of these samples was 62,800 psi.

TEST RESULTS

Fifty samples were made, using the above selected parameters, and 30 samples machined to 0.190-in. OD $\times$ 0.098-in. ID for use in the evaluation testing. Results of the testing of these samples are contained in Tables B.2, B.3, and B.4.

Tensile Tests

Tensile tests were run to determine the strength of the joint in the "as-welded" condition. As can be seen in Table B.2, the two joints averaged 61,600-psi ultimate tensile strength and were fairly consistent. Both samples failed, however, in the weld, with almost no ductility.

One additional sample (R1) was corrosion-tested at 680F in ammoniated water with pH 10 (15 to 30 cc H₂/kg) for 14 days, prior to tensile-testing. The corrosion test apparently had little if any effect on the joint since the ultimate tensile strength was only slightly lower (58,400 psi) than the average for as-fabricated specimens (61,600 psi). This could have resulted from a normal scatter.

Samples R19 and R15 were cycled 500 times between 170 and 600F. Sample R15 was then given an additional 1000 cycles between 500 and 1000F to determine the effects on the joint of starting and stopping thermal cycles. As may be seen in Table B.2, there was no significant effect on the mechanical strength of the joint. Ultimate tensile strength and yield strength of the joint at 600F were found to be equivalent to those of Zircaloy-4, but the joint still lacked ductility.

TABLE B.2. TENSILE TEST RESULTS OF FLASH-WELDED JOINTS

Nominal Strain Rate: 0.4%/min

Specimen No.	Condition	Test	0.2% Offset YS, 10 ³ psi	UTS, 10 ³ psi	EL, %	Failure Location
		Temp, F				
R6	As-fabricated	75	51.8	61.0	2.0	Weld
R8	As-fabricated	75	54.4	62.2	2.0	Weld
	Average	75	53.1	61.6	2.0	
R1	Corrosion-tested	75	53.0	58.4	0.9	Weld
R19	Thermal-cycled (1)	75	57.2	63.8	1.6	Weld
R15	Thermal-cycled (2)	75	57.8	65.7	1.6	Weld
R11	As-fabricated	600	25.2	32.8	8.6	Zircaloy
R10	As-fabricated	600	23.8	32.0	>6.2	None*
	Average	600	24.5	32.4	-	

*Test stopped after maximum load because of slippage in the grips.

TABLE B.3. BEND TEST RESULTS FOR FLASH-WELDED JOINTS

Specimen No.	Stress, 10 ³ psi*		Permanent Deflection, in.
	Maximum	Final	
<u>1.25 in. Between Center Loads</u>			
R16	103	103	0.07
R17	116	116	0.19
Average	110	110	0.13
<u>0.375 in. Between Center Loads</u>			
R18	100	100	0.11

*Calculated by elastic formula.

Note: All failures were at the weld.

TABLE B.4. THERMAL CYCLE TEST RESULTS OF FLASH-WELDED JOINTS

Specimen No.	500 Cycles 170 to 600F	1000 Cycles 500 to 1000F
R19	X*	-
R15	X	X*
R21	X	X

*Tensile-tested after this test.

X = Tested, no failure.

Bend Test Results

All specimens failed at the weld joint. Results are contained in Table B.3.

Thermal Cycle Test

Thermal cycle tests were run on three specimens as indicated in Table B.4. These tests did not affect joint properties.

Corrosion Test Results

Three flash-welded samples were corrosion-tested in 680F ammoniated and hydrogenated water (pH 10) to determine:

1. The effect of the corrosive media on the weld joint.
2. Whether the composition of the weld bondline would change during exposure.

No evidence of corrosive attack was observed on any of the specimens. One specimen, tensile-tested after 14 days' exposure, proved to be satisfactory (see Table B.2). Two additional tubular specimens were helium-leak-tested after 90 days' exposure, and no leaks were observed.

Electron-microprobe analyses were taken across the weld joint for Fe, Ni, Cr, and Zr prior to corrosion testing, and after 90 days' exposure. One specimen (R2) was used for this evaluation. Micro-Vicker's hardness impressions were used for positioning the specimen so that the same area could be analyzed after testing (see Figure B.1). Results of these analyses indicated no depletion of the four major constituents in the bondline area. The data are contained in Table B.5.

Test results showed that exposure to ammoniated, hydrogenated water with pH 10, at 680F, for periods of time up to 90 days, had no effect on the properties of Zircaloy-2 to Ni-Cr-Fe flash-welded transition joints.

Unclassified

A. Before Corrosion Test.

B. After 90 Days' Exposure.

FIGURE B.1. Photomicrograph of Corrosion-Tested Transition Joint (Flash-Welded).
KS-49859

Unclassified

TABLE B.5. RESULTS OF ELECTRON-MICROPROBE ANALYSIS OF RESISTANCE-WELDED JOINTS BEFORE
AND AFTER 90-DAY EXPOSURE TO 680F AMMONIATED, HYDROGENATED WATER WITH pH 10

Element	Test Days	Matrix	Element Weight Percent at Distance from Weld, μ									Matrix
		Ni-Cr-Fe,										Zircaloy-2,
		wt %	8	6	4	2	0	2	4	6	8	wt %
Zircaloy*	0	0.5	3.1	3.5	5.5	40.0	70.4	86.4	92.1	92.8	94.0	98.3
	90	0.5	3.2	3.5	4.5	8.1	72.9	94.0	94.9	95.2	96.3	97.2
Iron*	0	6.5	6.3	6.3	6.0	4.1	1.5	0.3	0.2	0.2	0.2	0.1
	90	6.5	6.5	6.4	6.4	6.0	1.9	0.4	0.3	0.2	0.2	0.1
Nickel**	0	74.9	74.0	74.0	68.8	54.0	20.0	1.5	1.1	0.9	0.7	0.5
	90	75.6	74.8	74.2	75.2	73.7	40.3	7.8	2.4	1.5	1.4	0.5
Chromium**	0	15.4	15.0	15.2	15.3	14.8	2.6	0.2	0.2	0.2	0.1	0.1
	90	15.5	15.4	15.4	15.5	15.4	14.8	1.8	0.4	0.2	0.2	0.2

*Zircaloy and iron run together.

**Nickel and chromium run together.

APPENDIX C. EVALUATION OF EXPLOSIVE WELDING FOR MAKING ZIRCALOY-2, Ni-Cr-Fe (ALLOY 600) TRANSITION JOINTS

INTRODUCTION

A program was carried out to demonstrate the feasibility of using explosive techniques for joining Zircaloy-2 to Ni-Cr-Fe (Alloy 600).

PROCESS DESCRIPTION

Explosive Welding

In explosive welding, the detonation of a high-explosive charge is used to drive two materials together with sufficient force so that when closure geometry is correct the oxide films are removed by a variation of the Munroe effect; this action permits bare metal to contact bare metal and thus effect a bond. The joining is accomplished at ambient temperature; consequently, heat-affected zones and/or intermetallic formations are kept to a very minimum.

The explosive-welding process is primarily a velocity-dependent process, and the variables that must be controlled and balanced to effect welding are those affecting the velocity of interface closure. The closure velocity is controlled primarily by material thickness, explosive-charge density (grams of explosive per square inch of specimen surface area), and initial clearance between the materials to be joined. These were the variables investigated during this study, along with three types of specimen geometries.

Specimen Geometry

Three types of specimen designs were investigated. The first consisted of a Zircaloy-2 rod inserted into an Ni-Cr-Fe tube, the second of an Ni-Cr-Fe rod inserted into a Zircaloy-2 tube, and the third of a Zircaloy-2 rod or tube inserted into a chromium-plated Ni-Cr-Fe tube.

Explosive Charge Configurations

Two types of explosive-charge configurations, contact and standoff, were used during this testing. The contact charge configuration was obtained by wrapping an envelope of sheet explosive tightly around the outside diameter of the specimen assembly; the standoff charge configuration

was obtained by positioning the evacuated specimen assembly in a steel backup die and placing a rod-shaped charge of Primacord into the center of the inside diameter of the specimen assembly. The contact charge configuration was used to join the Ni-Cr-Fe tube to Zircaloy-2 rod, Zircaloy-2 tube to Ni-Cr-Fe rod, and chromium-plated Ni-Cr-Fe tube to Zircaloy-2 rod specimen Ni-Cr-Fe assemblies. The standoff charge configuration was used to join the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 tube specimens. In all cases, the specimens were impacted by submerging them in a tank of water and detonating the charge.

EXPERIMENTAL RESULTS AND DISCUSSION

It was concluded from preliminary tests that bonding of Ni-Cr-Fe to Zircaloy-2 was possible, using explosive techniques. However, a considerable amount of intermetallic was formed at the joint interface. It was suspected that this intermetallic was primarily the result of diffusion of the nickel in the Ni-Cr-Fe into the Zircaloy-2 (see Figure C.1). An effort was made to investigate means of eliminating the formation of the intermetallic at the joint interface by varying the wall thickness of the Ni-Cr-Fe tube, the initial clearance at the joint interface, and the charge density.

It was concluded from these tests that a charge density of 2 gm/in.² was necessary for the geometry employed. The initial clearance between the specimen components was found to have an effect on the amount of intermetallic compound formed at the joint interface. The smaller this initial clearance, the less the amount of intermetallic that was formed. However, it was not possible to prevent completely the formation of the intermetallic at the joint interface even by reducing the initial clearance to as little as 0.0015 in. Thus, it appeared that other factors, such as diffusion of the nickel from the Ni-Cr-Fe into the Zircaloy-2, were involved in the intermetallic formation. Results are shown in Figures C.2 and C.3.

An attempt was made to retard the diffusion of the nickel from the Ni-Cr-Fe into the Zircaloy-2 by reducing the energy input into the Ni-Cr-Fe component of the specimen assembly. This was accomplished by reversing the material geometry so that during explosive joining a Zircaloy-2 tube was collapsed around an Ni-Cr-Fe rod rather than collapsing an Ni-Cr-Fe tube over a Zircaloy-2 rod.

These experiments showed that for this specimen design a charge density of 2 gm/in.² was excessive and resulted in a rupturing of the Zircaloy-2 tubing. The initial clearance between the specimen components was again found to have an effect on the amount of intermetallic formed at the joint interface. The smaller the initial clearance, the

Unclassified

Ni-Cr-Fe Alloy 600—

Intermetallic—

Zircaloy-2—

RM23304;100X

FIGURE C.1. Intermetallic Compound Formation at Interface of Explosively Joined Ni-Cr-Fe (Alloy 600) Tube to Zircaloy-2 Rod Specimen Ni-Cr-Fe.
KS-56143

Unclassified

Ni-Cr-Fe Alloy 600—

Intermetallic—

Zircaloy-2—

RM23644;250X

FIGURE C.2. Interface of Explosively Joined Ni-Cr-Fe (Alloy 600) Tube to Zircaloy-2 Rod Specimen Having an Initial Clearance of 0.0025 in. (Note small amount of intermetallic formation present at joint interface.)
KS-56144

Unclassified

Ni-Cr-Fe Alloy 600—

Intermetallic—

Zircaloy-2—

RM23464;250X

FIGURE C.3. Interface of Explosively Joined Ni-Cr-Fe (Alloy 600) Tube to Zircaloy-2 Rod Specimen Having an Initial Clearance of 0.019 in. (Note extensive amount of intermetallic formation present at joint interface.)
KS-56145

Unclassified

less the amount of intermetallic formed. Although the amount of intermetallic formed at the joint interface could be slightly reduced by reversing the specimen component geometry and reducing the energy input into the Ni-Cr-Fe member, it was not eliminated. It was apparent that an appreciable nickel transport was still taking place.

An attempt was made to prevent the diffusion of the nickel from the Ni-Cr-Fe into the Zircaloy-2 by introducing a barrier layer into the joint interface. This was accomplished by electroplating a layer of chromium (nominally 0.0005 in. thick) onto the inside diameter of the Ni-Cr-Fe tube.

Eleven specimens were prepared for these experiments. Two were made of chromium-plated Ni-Cr-Fe tubes over Zircaloy-2 rods; the remaining nine consisted of chromium-plated Ni-Cr-Fe tubes over Zircaloy-2 tubes. With the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 rod specimens, the initial clearance and charge density were varied from 0.005 to 0.003 in. and from 1-1/2 to 1 gm/in.², respectively. With the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 tube specimens, the thickness of the Zircaloy-2 tubes was varied from 0.015 to 0.051 in.; the initial clearance between specimen components varied from 0.002 to 0.013 in. The charge used to bond the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 tube specimens was changed from a contact to a standoff configuration. In this arrangement, the charge was positioned into the inside diameter of the specimen assembly, which was supported by a Type 304 stainless steel backup die.

The results obtained with the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 rod specimens revealed that a gross rupturing of the chromium plate, as shown in Figure C.4, occurred with this particular specimen design, using a contact charge configuration. The results obtained with the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 tube specimens, using a standoff charge configuration, indicated that good bonds with no intermetallic at the joint interface could be obtained for Zircaloy-2 tube thicknesses <0.030 in. The thickness of the chromium plate on the inside diameter of the Ni-Cr-Fe tube was found to vary from ~0.00018 to 0.00420 in. Bonding was found to be best where the thickness of the chromium plate was <0.0007 in., as shown in Figure C.5. In those areas in which the thickness of the chromium plate was >0.0007 in., a rupturing of the chromium occurred during joining, as shown in Figure C.6. The thickness of the Ni-Cr-Fe tube did not appear to be a significant factor for this particular specimen design or charge configuration.

It was concluded from these experiments that the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 rod specimen design was not satisfactory since the reduction of the Ni-Cr-Fe tube over the Zircaloy-2 rod resulted in a gross rupturing of the chromium plate. The thickness of the chromium

Unclassified

Ni-Cr-Fe Alloy 600—

Chromium Plate—

Zircaloy-2—

RM23712;500X

FIGURE C.4. Joint Interface of Explosively Joined Chromium-Plated Ni-Cr-Fe (Alloy 600) Tube to Zircaloy-2 Rod Specimen. (Note gross rupturing of chromium plate which occurred. A contact charge configuration was employed.)

KS-56146

Unclassified

Ni-Cr-Fe Alloy 600—

Chromium Plate—

Zircaloy-2—

RM23903;250X

FIGURE C.5. Explosively Joined Chromium-Plated Ni-Cr-Fe (Alloy 600) to Zircaloy-2 Specimen in which Thickness of Chromium Plate is <0.0007 in. KS-56147

Unclassified

Ni-Cr-Fe Alloy 600—

Chromium Plate—

Zircaloy-2—

RM24561;100X

FIGURE C.6. Explosively Joined Chromium-Plated Ni-Cr-Fe (Alloy 600) to Zircaloy-2 Tube Specimen in which Thickness of Chromium Plate is >0.0007 in. (Note that chromium plate bonded to both Ni-Cr-Fe and Zircaloy-2 and ruptured through itself.)

KS-56148

Unclassified

plate on the inside diameter of the Ni-Cr-Fe tube was found to be a significant factor since good bonds were achieved only in those areas in which the thickness of the chromium plate was 0.0007 in. or less. For the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 tube specimen design, the thickness of the Ni-Cr-Fe tube was insignificant, since the tube was supported by a steel die during joining.

The results of the tests conducted with the various types of specimen designs revealed that in all cases some bonding was achieved. The Ni-Cr-Fe to Zircaloy-2 system has been the only system of eight different material combinations tested during previous explosive-joining studies using evacuated assemblies in which intermetallic formation was encountered. It is suspected that this intermetallic formation was the result of diffusion of nickel from the Ni-Cr-Fe into the Zircaloy-2. Nickel is a fairly active atom, and since it is considerably smaller than the zirconium, diffuses quite rapidly into it. The explosive joining was conducted at ambient temperature under water, and the mass of the specimens impacted was quite small. Therefore, any extensive temperature rise at the bond interface, which may have occurred as a result of the detonation, would have been of extremely short duration. It would not appear that this temperature rise would have been maintained for a length of time sufficient to account for the amount of diffusion obtained, unless the temperature rise was near or above the melting point of the interface system.

With the chromium-plated Ni-Cr-Fe tube to Zircaloy-2 tube specimen design, using a standoff charge configuration, the wall thickness of the Zircaloy-2 component proved to be a controlling factor in achieving bonding. It was found that for a Zircaloy-2 tube-wall thickness of >0.030 in., no bonding was achieved. The thickness of the chromium plate was also found to be rather irregular, varying from a maximum of 0.0042 in. to a minimum of 0.00018 in. The presence of the chromium plate in the joint interface did prevent the formation of the intermetallic. In those areas in which the thickness of the chromium plate was >0.0007 in., however, the chromium had a tendency to rupture, thereby resulting in a weak bond; in those areas in which the chromium plate was <0.0007 in., good bonding was achieved.

CONCLUSIONS

It can be concluded from this study that it is possible to join Ni-Cr-Fe to Zircaloy-2 by using explosive techniques. The introduction of a chromium barrier layer into the joint interface can prevent intermetallic formation. The thickness of this chromium barrier, however, should be as uniform as possible, with a maximum thickness of ~ 0.0007 in. to permit the achievement of sound bonds.

Other process parameters, while certainly not brought to an optimum state during this preliminary study, appear to be satisfactory for employing explosive-joining techniques for bonding Ni-Cr-Fe to Zircaloy-2.

APPENDIX D. DISCUSSION AND TEST RESULTS OF TRANSITION JOINTS PRODUCED BY THE COEXTRUSION PROCESS

INTRODUCTION

The coextrusion process, which had been used successfully for producing joints between Zircaloy-2 and Type 304 stainless steel⁷ and between Ni-Cr-Fe and Zircaloy material, had been found to be rather costly and time-consuming. Since the process required further evaluation for a new application, it was decided to initiate a program for producing and testing transition joints by the coextrusion process for cross-comparison purposes. The process and test results are described below.

Description of the Coextrusion Process

Solid billets are machined to the desired diameter and end configuration, and then cleaned and inserted into steel cans. The cans are evacuated at about 1500F. The extrusion ratio used may vary between 2:1 and 4:1, depending on the vendor and his equipment. After extrusion, the steel cans are removed by pickling in $\text{HNO}_3\text{--H}_2\text{O}$, and the coextruded piece is machined and inspected. The resultant joint is elongated in nature (see Figure 4, p. 7). The length of the joint depends on the end configuration and extrusion ratio used.

Test Results

Tensile Test Results

Table D.1 contains the results of tensile tests performed on specimens as-fabricated and after thermal cycling, and the results of hot tensile tests. All test results were within requirements except for ductility. The ductility as measured in these samples is not a true reading in that readings taken across the joint reflect the elongation of the Zircaloy, the weld joint, and the Ni-Cr-Fe. Since all materials do not yield at the same stress level, the elongation reading is biased and was used for reference only.

None of the coextruded specimens failed in the joint. However, metallographic examination after testing revealed the presence of numerous small cracks perpendicular to the interface (see Figure 5, p. 9). The cracks shown in Figure 5 are those present after testing at 600F. Room-temperature tensile specimens showed the same type of cracks except that they were slightly longer and extended out of the bondline area.

TABLE D.1. TENSILE TEST RESULTS OF COEXTRUDED JOINTS

Nominal Strain Rate: 0.4%/min

Specimen No.	Condition	Test Temp, F	0.2% Offset YS, 10 ³ psi	UTS, 10 ³ psi	EL, %	Failure Location
9	As-fabricated	75	67.6	83.0	9.4	Zircaloy**
13	As-fabricated	75	58.3	76.3	9.4	Zircaloy**
	Average	75	63.0	79.7	9.4	
16	Thermal-cycled (1)	75	62.7	82.2	10.2	Zircaloy**
17	Thermal-cycled (2)	75	49.6	70.9	10.9	Zircaloy**
4	As-fabricated*	600	33.9	36.0	NO	Zircaloy thread
4	Retested	600	NO	34.7	4.7	Zircaloy
12	As-fabricated	600	33.0	41.7	6.2	Zircaloy
14	As-fabricated	600	32.4	40.2	5.8	Zircaloy
	Average	600	32.7	38.8	5.6	

* Specimen fractured in Zircaloy-2 threads in first loading, was retested, and fractured in Zircaloy-2 section. Total plastic elongation accumulated in both loadings was 4.7%.

** In gage.

NO Not obtained.

Bend Tests

Results of bend tests are contained in Table D.2. These tests were performed on specimens in the as-welded condition at room temperature. A schematic diagram of the test used is shown in Figure A.1, Appendix A. None of the coextruded joints failed in bending. However, metallographic examination of the joints revealed the presence of cracks similar to those noted after tensile testing.

Thermal Cycling Tests

Thermal cycling test results are contained in Table D.3. No cracks were observed in joints after thermal cycling. In addition, thermal cycling prior to tensile testing did not cause early joint failure. The change in properties noted in Specimen 17, Table D.1 (lower yield and tensile strengths), was probably caused by the stress relieving effect of thermal cycling to 1000F.

TABLE D.2. BEND TEST RESULTS OF COEXTRUDED JOINTS.

Specimen No.	Stress, 10 ³ psi*		Permanent Deflection, in.
	Maximum	Final	
<u>1.25 in. Between Center Loads</u>			
C1	143	143	0.27
<u>0.375 in. Between Center Loads</u>			
C3	138	105	1.01
C6	137	96.6	1.02
Average	138	100.8	1.02

* Calculated by elastic formulas.

Note: No specimens failed during bend test.

TABLE D.3. THERMAL CYCLING TEST RESULTS FOR COEXTRUDED JOINT

Specimen No.	500 Cycles 170 to 600F	1000 Cycles 500 to 1000F
C16	X*	-
C17	X	X*
C18	X	-

* Tensile-tested after this test.

X = Tested under the above condition.

Note: No specimens failed during cyclic test.

Fatigue Test Results

Fatigue test results of coextruded joints are contained in Table D.4. Tests were performed on this joint with samples in five different conditions:

1. As-welded.
2. After 14 days' exposure to 750F steam.
3. After 14 days' exposure to 680F ammoniated water.
4. After 38 days' exposure to 680F ammoniated water.
5. After 10,000 pressure/temperature cycles.

TABLE D.4. FATIGUE TEST RESULTS ON COEXTRUDED JOINTS

Stress Amplitude = 54,400 psi

Specimen No.	Cycles to Failure (X 1000)	Failure Location
	As-Welded	
CO-EX-5	8	In weld through Zircaloy-2
CO-EX-7	45	In weld through Zircaloy-2
CO-EX-8	43	In weld through Zircaloy-2
CO-EX-10	30	In weld through Zircaloy-2
<u>After 14 Days in 750F Steam</u>		
CO-EX-23	13	In weld through Zircaloy-2
CO-EX-24	21	Collet on Zircaloy-2 side
<u>After 14 Days in 680F Ammoniated Water</u>		
CO-EX-26	7	In weld through Zircaloy-2
CO-EX-27	12	In weld through Zircaloy-2
<u>After 38 Days in 680F Ammoniated Water</u>		
CO-EX-13*	<1	All in weld as shown
CO-EX-15	<1
CO-EX-16	<1	
CO-EX-18	<1	
CO-EX-20**	2	
CO-EX-21**	8	All in test section as shown
CO-EX-22**	3
CO-EX-23*,**	3	
<u>After 10,000 Pressure/Temperature Cycles</u>		
4	6	In weld through Zircaloy-2
9	4	In weld through Zircaloy-2
17	†	

* See Figure D.1

** Tested as solid rods; all others tested as tubes.

† Failure occurred during the specimen machining operation.

Figure A.2 (Appendix A) is a sketch of the type of specimen used for fatigue testing. Failures occurred at the tip of the weld and across the Zircaloy-2 as shown in Figure D.1, solid Sample 23.

Photomicrographs of the section of joint below the failure revealed the same type of cracking noted in the bend and tensile test specimens. It is thought that the cracks initiated in the joints of the coextruded specimens during testing and then propagated across the least fatigue-resistant component (Zircaloy-2). In cyclic strain fatigue tests at room temperature, the fatigue strengths (stress ranges) of Zircaloy-2 at 10^3 and 10^4 cycles are $\sim 120,000$ and $90,000$ psi.⁸ The fatigue strengths of Ni-Cr-Fe at the same number of cycles are $\sim 140,000$ and $105,000$ psi.⁹

As noted in Figure D.1, the fatigue failures initiated at a point where the Ni-Cr-Fe tube tapered down to a small thickness. Where there is a thin layer of Ni-Cr-Fe over the Zircaloy, the strain in the former material must match that of the Zircaloy. This gives an axial stress of

$$\frac{E_i (\alpha_i - \alpha_{Zr})}{1 - V} \Delta T = 210 \Delta T$$

in the thin layer of Ni-Cr-Fe, which explains why failure initiates repetitively at the same point in the coextruded joint. The fatigue strength of the coextruded joint seems to be lowered further by metallurgical changes which take place at elevated temperature. It is postulated that the diffusion of Ni, Cr, and Fe from the Ni-Cr-Fe into the intermetallic layer and the associated growth of the layer are accelerated by exposure to elevated temperatures. The Ni-Cr-Fe is also weakened by loss of the alloying elements. This, coupled with the high localized stress discussed above, results in premature failure during fatigue testing, as reflected by the significantly lower fatigue strength of samples exposed to elevated temperature (corrosion and pressure-temperature testing). Failure of the corrosion-tested and pressure-temperature-tested tubular specimens followed the weld joint (see Figure D.1, Sample 13); the solid specimens propagated through the Zircaloy.

Results of the fatigue tests are plotted on Figure D.2. The band enclosed by dotted lines is that developed for Zircaloy-2. Note that those specimens exposed to elevated temperatures are predominantly at or below the lower fatigue curve level.

Corrosion Tests of Coextruded Joints

During the evaluation program, the corrosion resistance of the coextruded transition joints was determined to be acceptable as follows:

Unclassified

FIGURE D.1. Fatigue Failures in Coextruded Ni-Cr-Fe (Alloy 600) to Zircaloy-4 Welds, Corrosion-Tested.
KS-53760

Unclassified

FIGURE D.2. Fatigue Strength of Joints.
KS-56149

Unclassified

1. Under 30X magnification, no evidence of corrosive attack was observed after:

14 days in 750F steam

14 and 38 days in 680F ammoniated water.

2. Microprobe analysis of the bond layer of a coextruded joint resulted in the same analysis as for the flash-welded and friction-welded bond layer.

APPENDIX E. PROCESS DESCRIPTION AND EVALUATION TEST RESULTS OF THE FRICTION-WELDED TRANSITION JOINTS

DESCRIPTION OF FRICTION-WELDING PROCESS

The friction-welding process is unique in that the heat necessary for welding is generated by sliding friction between the two parts. One part is rotated at a predetermined rate of speed and forced against the mating surface of the other part (see Figure 7, p.12). Important variables are:

1. Speed of rotation.
2. Amount of thrust and rate of pressure application.
3. Amount of upset of the parts.
4. Time of contact between parts.

Each of the variables differs for different material and size of joint and must be established for each design. Once a set of parameters has been established, and held constant, results are consistent. Detailed technical discussions and descriptions of the process have been covered in other technical publications.^{3,4,10}

TEST RESULTS

All tests were conducted on specimens of 0.190-in. diam.

Tensile Test Results

In general, tensile tests were run on tubular specimens of 0.190-in. OD x 0.098-in. ID, ~6 in. long: 3 in. of Ni-Cr-Fe and 3 in. of Zircaloy. Welding parameters were varied as data were accumulated in an effort to obtain better weld properties. All tensile data presented in Table E.1 are described as "early type," "Type A," Type B, and "final type" friction-welded joints. These designations merely indicate that different weld parameters were used to make the joint. As can be seen from the table, a satisfactory weld joint was developed.

Figure E.1 shows the welded joint of the "final type," after tensile testing. No cracking is evident, as was noted in the coextruded joints.

Bend Tests

Bend test results are contained in Table E.2. Unfortunately, loads were not recorded for the "final type" weld; deflections were recorded,

TABLE E.1. TENSILE TEST RESULTS OF FRICTION-WELDED JOINTS

Nominal Strain Rate: 0.4%/min

Specimen No.	Condition	Temp, F	0.2% Offset YS, 10^3 psi	UTS, 10^3 psi	EL, %	Failure Location
<u>Early Type Friction-Welded Joints</u>						
F4	As-fabricated	75	36.0	49.8	3.9	Weld
F1	Corrosion-tested	75	37.0	54.2	3.1	Weld
<u>Type A Friction-Welded Joints</u>						
F7A	As-fabricated	75	41.8	56.5	3.9	Weld
F17A	Thermal-cycled (1)	75	40.6	61.0	3.1	Weld
F18A	Thermal-cycled (2)	75	39.8	62.6	4.7	Weld
F15A	As-fabricated	600	21.4	29.4	9.1	Zircaloy
F16A	As-fabricated	600	22.9	30.1	10.1	Zircaloy
<u>Type B Friction-Welded Joints</u>						
F23D	As-fabricated	75	39.1	59.2	4.7	Weld
F24B	As-fabricated	75	41.0	58.4	2.0	Weld
F31B	Thermal-cycled (1)	75	40.3	56.1	3.9	Weld
F32B	Thermal-cycled (2)	75	40.5	59.7	4.7	Weld
F25B	As-fabricated	600	24.1	31.8	9.6	Zircaloy
F26B	As-fabricated	600	24.1	31.7	10.1	Zircaloy
<u>Final Type of Friction-Welded Joints (0.190-in.-OD x 0.098-in.-ID)</u>						
F1	As-fabricated	75	54.2	70.7	13.3	Zircaloy
F2	As-fabricated	75	53.2	71.5	12.5	Zircaloy
Average		75	53.7	71.1	12.9	

Unclassified

19198; Bright Field; 2000X

FIGURE E.1. Final Type of Friction-Welded
Joint after Room-Temperature Tensile Test.
KS-56150

Unclassified

TABLE E.2. BEND TEST RESULTS OF FRICTION-WELDED JOINTS

Specimen		<u>Stress, 10³ psi</u>		Permanent	Failure
<u>No.</u>	<u>Friction Weld</u>	<u>Maximum</u>	<u>Final</u>	<u>Deflection, in.</u>	<u>Location</u>
<u>1.25 in. Between Center Loads</u>					
F3	Early Type	105	75.4	0.74	Did not fail
F27B	Type B	103	95.8	0.56	Did not fail
<u>0.375 in. Between Center Loads</u>					
F21A	Type A	87.9	87.9	0.08	Weld
F28B	Type B	79.9	79.9	0.04	Weld
F3	Final Type	-	-	0.098	Weld
F4	Final Type	-	-	0.072	Weld

however, and although the specimens failed in the weld when bent with 0.375 in. between loads, they were felt to be satisfactory since the permanent deflection was equal to or better than that of the Types A and B welds.

Thermal Cycling Test Results

Thermal cycling apparently had no deleterious effects on the specimens for the number of cycles and temperatures investigated. As with the coextruded specimens, there was no noticeable effect on mechanical properties (see Table E.3).

TABLE E.3. THERMAL CYCLING TEST RESULTS*

Specimen No.	Friction Weld	500 Cycles	1000 Cycles
		170 to 600F	500 to 1000F
F17A	Type A	X**	-
F18A	Type A	X	X*
F19A	Type A	X	X
F31B	Type B	X**	-
F32B	Type B	X	X*
F35B	Type B	X	X

* No specimens leaked after testing.

** Tensile-tested after this test.

X = Sample tested under above conditions; no failure.

Fatigue Test Results

Fatigue test results are contained in Table E.4. It can be seen that fatigue strength of the weld joint was much more satisfactory than that obtained for the coextruded joint. The exposure to the elevated temperatures of the corrosion test did not affect fatigue strength noticeably. All failures occurred outside the weld areas, even in the Types A and B weld joints which were substandard in tensile tests.

TABLE E.4. FATIGUE TEST RESULTS ON FRICTION-WELDED JOINTS

Stress Amplitude 54,400 psi Except Where Noted

<u>Specimen No.</u>	<u>Cycles to Failure (× 1000)</u>	<u>Failure Location</u>
<u>As-Welded</u>		
F-13-A	1300*	Collet on Zircaloy-2 side
F-14-A	10	
F-33-B	168**	
F-34-B	30	Knurl on Zircaloy-2 side
<u>After 14 Days in 680F Ammoniated Water</u>		
F-X	39	Collet on Zircaloy-2 side
F-Y	33	Knurl on Zircaloy-2 side
<u>After 90 Days in 680F Ammoniated Water</u>		
F-2	37	Collet on Zircaloy-2 side
<u>After 38 Days in 680F Ammoniated Water</u>		
F-10 [†]	65	Gage section - 1/8 in. from weld
F-11 [†]	69	Gage section - 1/16 in. from weld
F-12 [†]	81	Gage section - adjusted to weld
F-13 [†]	34	Knurled section
<u>After 10,000 Pressure/Temperature Cycles</u>		
1	62	Knurled section
2	23	Knurled section
3	55	Knurled section

*Stress amplitude - 37,400 psi.

**Stress amplitude - 45,400 psi.

[†]Tested as solid rods; all others tested as tubes.

Corrosion Test Results

The friction-welded transition joints were available early in the program so that long-term corrosion exposure tests were completed. The friction-welded specimens and flash-welded transition joints were exposed in the same autoclave, with all test conditions the same (see Appendix B, "Corrosion Test Results," p. B.5).

The longitudinally sectioned specimen was analyzed by electron microprobe before and after the 90-day corrosion period. Results of the microprobe analyses are contained in Table E.5.

The electron-microprobe analysis of the joint indicated that the corrosive exposure had not depleted the bond layer of any of the four major constituents. After a 90-day exposure, the tubular samples were helium-leak-tested with no leaks observed. After each period of exposure, all samples were viewed under 30X magnification, and no evidence of corrosive attack was observed.

TABLE E.5. RESULTS OF ELECTRON-MICROPROBE ANALYSIS OF FRICTION-WELDED JOINTS

Element	Test Days	Matrix	Element Weight Percent at Distance from Weld, μ									Matrix
		Ni-Cr-Fe,										Zircaloy-2,
		wt %	8	6	4	2	0	2	4	6	8	wt %
Zircaloy*	0	0.5	2.4	2.8	3.2	6.3	63.2	85.3	88.6	91.6	93.9	98.0
	90	0.5	3.0	3.2	3.6	5.2	75.8	93.3	93.7	95.5	95.2	99.0
Iron*	0	6.7	6.5	6.5	6.4	5.9	2.0	0.5	0.3	0.1	0.2	0.1
	90	6.8	6.5	6.4	6.4	5.8	1.6	0.4	0.2	0.2	0.2	0.1
Nickel**	0	74.9	74.2	74.5	74.2	74.2	28.4	3.3	2.5	2.2	0.9	0.5
	90	75.4	75.7	75.7	74.3	44.9	6.3	2.6	2.0	1.4	1.2	0.5
Chromium**	0	15.6	15.3	15.2	15.1	14.9	5.8	0.5	0.2	0.1	0.1	0.1
	90	15.4	14.8	14.7	14.2	11.0	1.2	0.5	0.2	0.2	0.2	0.1

*Zircaloy and iron run together.

**Nickel and chromium run together.

APPENDIX F. REFERENCES

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