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JUL 29 1968

EVALUATION OF ZIRCALOY-STAINLESS STEEL METALLURGICALLY BONDED JOINTS

Work performed under
Contract AT(30-1)-3374

with the New York Operation's Office
of the U. S. Atomic Energy Commission

by

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October 1968 **DISSEMINATION OF THIS DOCUMENT IS UNLIMITED**

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Abstract

Various nondestructive test methods were investigated for suitability for detecting unbonded areas in Zircaloy-stainless steel transition joints. Ultrasonic testing was found to be the preferred method.

Destructive and nondestructive tests were performed on metallurgically bonded Zircaloy-4 to type 316 stainless steel joints.

Tension testing of a full-size joint at 688-723°F demonstrated that the transition joint is capable of sustaining as much stress as an all Zircaloy assembly.

Cold working of joints to improve the mechanical properties of Zircaloy-4 was accomplished without damage to the diffusion bond in three out of six attempts. In the other three attempts, separation of the diffusion bond occurred over small areas of each joint.

Conclusions

1. The ultrasonic test has been proven superior to other nondestructive tests for the detection of unbonded areas in Zircaloy-stainless steel transition joints. This test is recommended for testing production joints.
2. A test procedure has been established and a standard has been developed which allows for a more stringent rejection level than the criterion of bond separation signals.
3. Attempts at cold working such joints to improve mechanical properties of the Zircaloy are not always successful. The probability of success depends on the cold work process used.
4. It was decided that it would be unsafe to install the Zircaloy-stainless steel pressure tubes in the Saxton reactor because of the presence of significant unbonded areas in the transition joint and the possible effect on the cyclic life of the assembly.
5. To prove the adequacy of a diffusion bonded transition joint for high pressure service, further investigation is recommended in area strain cycle fatigue.

I. Introduction

A. General

The evaluation of Zircaloy-Stainless Steel, metallurgically bonded joints, described in this report, was started under Westinghouse funding and continued under the Supercritical Technology Program, AEC contract AT(30-1)-3374. Under this contract, a supercritical, water cooled, in-pile loop will be designed, fabricated, and installed at the Saxton reactor. A pressure tube containing fuel assemblies will be installed in the existing reactor vessel. The irradiated fuel will be examined at the Westinghouse Post Irradiation Facility, and the loop performance will be evaluated.

The proposed design of the pressure tube incorporates a Zircaloy-4 to Type 316 Stainless Steel, metallurgically bonded, transition joint, to be made by the tandem extrusion of Zircaloy and Stainless Steel billets.

B. Description of Fabrication Procedure

Briefly, the fabrication procedure for a transition joint is as follows. A Stainless Steel billet and a Zircaloy billet are thoroughly cleaned and sealed in tandem position in a mild steel jacket. The angle at the Stainless Steel-Zircaloy interface determines the degree of taper. A 30° angle provides a taper about 50 times the wall thickness. (This angle was used in the joints evaluated in the program.) More obtuse angles are undesirable as they cause flow of jacket material into the interface. Since this portion would have to be removed by machining, the wall thickness would be reduced. The sealed billets are then extruded at about 1600°F . The mild steel jacket is then removed either by pickling with nitric acid or by machining. The resulting Zircaloy-Stainless Steel joint is then machined to the specified inside and outside diameters.

C. Summary of Previous Work

Previous evaluation work at WAPD demonstrated that this type of joint can operate safely at high temperatures and pressures under steady stress conditions. The feasibility of determining joint quality by nondestructive tests, as evidenced by the following results:

- a. Good sonic transmission was achieved.
- b. Resolution of interface signals was achieved.
- c. A serious unbond defect gave a simple "unbond" pattern as in Figure 4.
- d. When parameters were properly chosen, a perfect bond gave a "good joint" pattern.

Additional tests were deemed desirable to determine the strength of high-temperature joint in the axial direction, and to develop a nondestructive test standard.

Evaluation tests were performed on metallurgically bonded, Zircaloy-4 to type 316 Stainless Steel transition joints. Six tubular joints, approximately 30 inches long by 2-3/4 inches outside diameter by 0.35 inches wall thickness, were ultrasonically tested to determine bond quality. One joint was burst tested at 650°F. A second joint was thermally and pressure cycled, and destroyed for mechanical and metallographic tests.

Thermal cycling was carried out between 100°F and 625°F, and pressure cycling between 2000 psi internal and 2000 psi external. The joint was subjected to 20 thermal cycles and 30 pressure cycles. The performance of such a joint subjected to a large number of strain cycles has not been investigated.

The ultrasonic tests indicated that all the joints had a certain amount of non-bonded area in the Zircaloy-4-Stainless Steel interface.

The joint that was burst tested failed at an applied internal pressure of 16,100 psi. The Zircaloy end split longitudinally, but the joint itself did not fail.

The thermal and pressure cycling caused a slight increase in the outside diameter of the Zircaloy tubing; no other detrimental effect was observed.

The following conclusions were reached from the Westinghouse funded portion of the program:

1. Ultrasonic tests can detect non-bonded areas between the Zircaloy-4 and the Stainless Steel. Each of six joints tested had some amount of non-bonded area.
2. Before the ultrasonic test can be developed into a tool for accepting or rejecting future joints, the minimum required amount of bonding must be established.
3. A burst test at high temperature, and thermal and pressure cycling, have indicated that 100% bonding may not be necessary for satisfactory service performance of the joint under non-cyclic conditions.
4. The slight increase in the outside diameter of the Zircaloy end of the joint observed after thermal and pressure cycling, is attributed to the combination of thermal and pressure cycling, and to the anisotropic behavior of Zircaloy.
5. Tensile tests on the Zircaloy base metal indicated that the material met the minimum specified room-temperature properties.
6. Judging from the ultrasonic patterns, the three remaining joints appeared to have less bonded area than either the burst or thermal and pressure cycled joint. However, these joints would not behave as well under identical tests.

II. Development of a Nondestructive Test Standard

A. Previous Metallographic Work

Metallographic sectioning initially cast some doubt on the ultrasonic information obtained in the earlier work which had indicated sound joints. Joints which had been ultrasonically tested and approved, failed completely during sectioning. At first, this was attributed to rough handling of the joint, but such delicate cutting methods as Elox machining resulted in a similar separation of the joint. Nuclear Metals Incorporated, fabricators of the transition joints, had warned that the intermetallic bond line was brittle under certain conditions, and had suggested that metallographic procedures might not be conclusive. Accordingly, the investigation was directed along two different lines. One line of approach involved investigation of alternate nondestructive tests which might more significantly correlate with metallographic data than did the ultrasonic testing. The second line of approach assumed that the ultrasonic information was correct, and pursued further investigation of the metallography of the bond line and the stresses causing joint failure upon sectioning.

B. Methods of Testing the Metallurgical Bond

Several types of bonding tests are available: tests based on thermal conduction, on electrical conduction, and on stress wave conduction. All these tests are made at 90° to the plane of the joint. Penetration of the joint area by fluid penetrants, or by radiant energy, can provide significant results when conducted parallel to the joint plane. Each type of test has certain limitations and certain desirable features.

Generally, thermal tests are only useful for comparatively thin materials in which the thermal energy diffuses slowly. A true metallurgical bond is not required for thermal conduction. Electrical tests are limited by similar factors; they are not useful for delineating small non-bonded areas in a thick material which has good conductivity.

Ultrasonic tests might have similar limitations with a large, continuous, low frequency beam. However, using a narrow beam, pulsed energy, and high frequency solves the diffusion problem mentioned above. Ultrasonic waves can be reflected from sudden changes in acoustic impedance. However, small changes at the junction of two different metals must not be confused with the large change which would occur at a metal-air or metal-vacuum interface. In other words, an ultrasonic bond test at the wrong power level, or with an improper amplification, can give improper if not completely erroneous information.

Fluid penetrations can provide excellent bond information, if the area of interest is accessible, and if the proper technique is employed. Generally, the thinner the gap between unbonded materials, the greater is the capillary force to draw the penetrant.

Radiant energy is only useful as a test medium when there is an actual separation between unbonded layers. For bonds between concentric cylinders, X-rays have detected bond separation when the beam had sufficient energy to penetrate several thicknesses of the outer layer.

C. Methods Investigated

An eddy current device - the TOMBEC Model 600 (a 40 Kc instrument) with a small probe coil - was employed to evaluate an electrical test for lack of bond. Several known unbonded areas were employed for this test, including outer layer (stainless steel) thicknesses ranging from a few thousandths of an inch to more than a quarter-inch.

Maximum lift-off signal occurred at 8° to 9° phase angle. At this angle, lift-off appeared on the scale as a "minus" deflection. When scanning over a sector with two widely separated layers, a considerable signal was received where the separation was large and the test surface was close to the unbonded area. When testing a full joint with known unbonded areas, no signal was obtained except in a feathered edge a few mils thick. This edge was actually separated approximately $1/16$ inch. Even here, the signal strength was negligible, and with jigs to hold the coil in a constant relation to the joint, separated bond could be detected at the feathered edge. It was concluded that any lack of bond located well below the surface, could not be detected, even under ideal conditions, unless actual separation existed.

A thermal method, resembling the well-known "frost test", was investigated. The temperature-sensing material employed was an ester of cholesterol, one of a series of "liquid crystals" developed by Westinghouse Central Research Laboratories.

This family of organics is characterized by a mesomorphic state, a condition between solid and liquid in which the material exhibits strong optical activity. According to Ferguson², in this state, the molecule shape changes with slight temperature changes. This color range is reversible. Materials are available which cover the range from -20°C to $+250^{\circ}\text{C}$, in increments of from 3°C to 50°C .

Several alternate techniques were tried. Initially, one side of a transition joint sector was heated while the opposite side was monitored for any areas of lower temperature that might signify poor heat transmission and, therefore, lack of bond.

In the comparatively thick joint sections, heat transmission was relatively slow. The large heat sink of massive metal allowed the heat to diffuse uniformly before the temperature could be raised to the transformation temperature of the liquid crystal. This technique was abandoned in favor of one in which the joint was pre-heated almost up to the transformation temperature of the liquid crystal. The heat lamp was then waved, rather rapidly, over the surface being monitored. In a localized area of bond separation at the feathered edge of stainless steel, the color changed from colorless to red. This change disappeared rapidly when the heat source was moved away. When the heat source was allowed to dwell, the entire area assumed a similar color.

Thus, there is a transient temperature change as the heat source is rapidly applied and removed. If the thin upper layer of metal is bonded to a large heat sink by an efficient thermal conductor, its temperature does not fluctuate appreciably as the heat source is moved over it. However, if the upper layer is not bonded, but is separated by an insulating layer, such as air, its temperature rises rapidly upon heating, and falls just as rapidly when the heat source is removed. If the thickness and thermal conductivity of the upper layer of metal is sufficient for the layer to constitute a good heat sink, lack of bond will not be detected. Similarly, no indication will be obtained if the bond is not metallurgical, but is firm enough for efficient heat transfer. In this experiment, the range of

upper metal layer thicknesses over bond separations was too limited to assess accurately the thickness limit at which the technique becomes ineffective. One could conjecture that this thickness is on the order of 10-20 thousandths of stainless, using a 250-watt heat lamp. Thermal testing thus appeared to be limited to the feathered edge area where a simple dye-penetrant test could be effective. The thermal tests were therefore abandoned.

Tangential radiography was attempted on joints without known separation, and on a joint sector with a known separation. Good presentation was obtained for the sector. In the joint, it was possible to distinguish the density difference between the Zircaloy and the stainless. Therefore, it seems likely that any actual separation, if radiographed tangentially, should show clearly on the radiograph. Actual separations have not been demonstrated in transition joints except at regions near the edges of the joint. Therefore, radiographic investigations were inconclusive and were terminated.

D. Comparison of Ultrasonic and Metallographic Test Results

Metallographic information has been based primarily on sections which were cut longitudinally and which, therefore, experienced stresses quite unlike those experienced by the entire joint. After full testing with the ultrasonic method and with fluid penetrants, one section was cut by Elox machining to minimize mechanical stresses during sectioning. The uncut edge, which initially showed no penetrant indication of lack of bond, now showed a distinct penetrant indication of separation, extending approximately 1/4 inch back from the cut face as well as completely across the cut face. When the ultrasonic test was then repeated in this area, complete bond separation at the cut face, was indicated whereas it had previously shown only the normal bond reflections previously associated with strong bonds. This was conclusive proof that

destruction of the bond had occurred in the process of sectioning and was not a condition which had pre-existed.

This operation was repeated using a section of the joint which had been tested in tension in the direction of the pipe axis. The joint had proved to be quite sound and the ultrasonic test following the tensile test showed it to be bonded to the same extent as before the test. Sectioning, dye penetrant, post-sectioning ultrasonic tests, all confirmed the earlier results on this joint which had demonstrated its initial soundness but also showed separation in the immediate vicinity of sectioning. This contributed two elements to the logical progress of the investigation.

1. A transition joint which had proved its strength had been associated with a given ultrasonic test pattern both before and after testing.
2. Metallographic sectioning of this joint had caused destruction of the joint, presumably because of release of residual stresses.

Metallographic examination of the interface showed an inter-metallic layer over some 98% of the bond. Where joint destruction had occurred, the intermetallic layer had pulled away from the stainless steel but remained adhered to the Zircaloy. This again was evidence that bonding had once occurred but that subsequent stresses had destroyed the bond. Figure 1 demonstrates this condition. Figure 2 shows the intermetallic layer intact. Only very small areas were discovered in which bonding had not occurred. Figure 3 shows one of these areas. It must be assumed that areas of this sort cause the bond line reflections noted frequently in the ultrasonic test. Despite their existence to the extent of only 2% of the bond layers, they are so very small that for the most part they cannot be individually pinpointed by the relatively large ultrasonic beam.

Stainless Steel →

Zircaloy →

Mag. 200X

N-8386E

Fig. 1 Photomicrograph showing intermetallic layer separated from the stainless steel but still adhering to the Zircaloy. This is evidence that a bond was previously effected.

Stainless Steel →

Intermetallic Layer →

Zircaloy →

Mag. 200X

N 8386F

Fig. 2 Photomicrograph showing .0005" intermetallic layer between Zircaloy and stainless steel. This is a sample of sound bond.

Stainless Steel →

Intermetallic Layer →

Zircaloy →

Non-bonded Area

Mag. 200X

N-8386D

Fig. 3 Photomicrograph showing a small non-bonded area.

E. Preferred Nondestructive Test Method

The ultrasonic test demonstrated a clear superiority over all other methods investigated. Its penetration in Zircaloy, or in stainless steel of this grain size, is measurable in terms of many feet, rather than as mere fractions of an inch, as in the eddy current or thermal methods. Its time lag is in microseconds, rather than seconds as in the thermal test.

Choice of frequency for the test was based on several factors. Normally, the higher the frequency the greater the effect upon the sound wave of small or minor flaws in bonding. In order to obtain maximum resolution of signals close to the test surface, or of flaws close to each other, a narrow high frequency beam is desirable. Although frequencies between 10 Mc and 25 Mc were not evaluated, there is no evidence that they would be superior to 10 Mc. A trial at 25 Mc showed this frequency to be of little value. The highest frequency available on the WAPD instrument, as on many routine testing instruments, is 10 Mc. On this basis, a 10 Mc frequency was chosen.

In a bond test, the area of unbonding is a more important factor than size of any individual indication. Rather than employ overlapping scan which would assure detecting each individual indication, a grid scan was chosen which emphasizes area. The pattern most used was a 1" by 30° grid with recorded interrogations at each intersection.

Figure 4 illustrates the technique used. The "good joint" pattern shows sonic returns from the I.D. of the bonded tube and none from the Zircaloy-stainless steel interface. The "unbond" pattern shows sonic returns from the Zircaloy-stainless steel interface and none from the I.D. This indicates an acoustic impedance at the interface radically different from that of the

FIG.4 U. T. TECHNIQUE FOR BOND INSPECTION

stainless steel and hence a lack of bond. The intermediate pattern shows indications from both boundaries thus indicating that both bonded and unbonded areas are being interrogated. If all joints had shown ultrasonic test indications similar to the upper pattern or to the lower one, the test problem would have been much simplified. Instead, the center pattern was quite common.

At this time, it can be safely stated that both of the two upper patterns are associated with transition joints of proven strength. Thus the lower pattern, that of bond separation, is to be considered rejectable. To increase test reliability, a section of a known strong joint, the soundness of which was verified by metallography, has been adopted as a standard.

Interface signals exceeding those from the standard are bases for considering any joint unacceptable. This is to prevent any excessive increase in the small non-bond areas. Since it is not known how much area of bond separation is acceptable, none is allowable.

F. Recommended Nondestructive Test Procedure

The test itself was only slightly changed from the one used during the first investigation.

This procedure is the one found best using equipment available at WAPD:

Basic Instrument:	Sperry UM 700 Reflectoscope
Transducer:	10 Mc Flat Lithium sulfate masked to approximately 1/8" diameter
Coupling Technique:	Full immersion
Alignment:	Sound beam perpendicular to outer diameter of joint
Scan Pattern:	Grid 1" x 30° - record at grid intersections

Standard:

A known-good joint sample 98% bonded as ascertained by metallography of an adjacent surface

Acceptance Criteria:

No areas of bond separation (pattern similar to the lower one in Figure 4)

No bond interface signals significantly in excess of those in the standard, especially those 1" from the Elox cut at the centerline of the standard.

III. Tension Testing of a Full-Size Joint

A. Description of the Joint

This joint was made of Zircaloy-4 and type 316 stainless steel by the tandem extrusion method.^{1,3} It measured 2.751" O.D. x 2.026" I.D. x 33 15/16" long. The all-stainless steel extension was 10 15/16 " long, and the all-Zircaloy extension was 7 3/16" long.

In previous evaluation work¹, this joint had been subjected to the following pressure and thermal cycling:

- a. thermal cycled 20 times between 100 and 625°F in 15 minutes at a constant pressure of 2000 psi
- b. pressure cycled 30 times between 2000 psi external pressure to 2000 psi internal pressure in 15 minutes, at a temperature which varied from 450 to 625°F.

B. Test Procedure and Results

The joint was rigged with six strip heaters of 500W each and three thermocouples. One thermocouple was placed at each end of the transition joint and one at the middle, as shown in Figure 5. The joint was then covered with molded pipe insulation leaving exposed only sufficient material (approx. 4") for gripping by the tensile machine jaws. Figure 6 shows the joint as prepared for heating; Figure 7 shows the joint mounted on the tensile testing machine.

To avoid thermal shock the assembly was brought to the test temperature in four hours. Heat input was controlled with a Powerstat variable transformer. At the initiation of tension testing, the temperature readings were 688°F at one end, 712°F at the other end, and 723°F at the middle. This was the narrowest temperature range that could be obtained.

Figure 5: Location of the thermocouples in relation to the length of the bonded interface.

Fig. 6 Transition Joint as Prepared for Heating

Fig. 7 Transition Joint Mounted on the Tensile Machine

The assembly was tension tested using a Riehle universal testing machine of 200,000 pounds capacity. The joint failed at an ultimate stress of 61,200 psi. Failure occurred within the transition length but by normal tensile fracture, as shown in Figure 8, rather than by separation of the bonded material.

Failure was expected to occur within the transition length because the all-stainless and the all-Zircaloy extensions were taken up by the tensile machine jaws. Both the nature of the failure and the stress to failure indicate that this transition joint was strong as if it had been all-Zircaloy. The Saxton supercritical loop design is based on a joint having a minimum tensile strength of 51,000 psi at 675⁰F.

Fig. 8 Transition Joint After Tensile Failure
Zircaloy extension is at right.

IV. Cold Working of Transition Joints

A. Description of Processes Used

As part of a Westinghouse-funded program described in reference 1, six Zircaloy -4 316 stainless steel transition joints were purchased from Nuclear Metals, Inc. Three of the joints (No. 1, 3, and 5, see Table I) were cold worked using the tube reducing method. A brief history of the six transition joints through the program is given in Table I.

This method of cold working involves the reduction of both diameter and wall thickness with a mandrel and a pair of rolls. The Rockrite process, which was used in these three joints, uses a fixed tapered mandrel. Reciprocating motion of the rolls along the tube effects the reduction in diameter and wall thickness, thus producing the cold working.

Tube reducing has been the predominant method of cold working tandem extruded joints. The joint supplier claims success in well over 90% of the cold work operations using this method.⁽¹⁾

Subsequent ultrasonic inspection indicated that two of these were acceptable according to the criteria given in Section II F above. The third joint had a bond separation of approximately four square inches in area starting at the outside feather edge of the joint and extending several inches into the joint. This was not acceptable in accordance with recommended acceptance limits. These three cold worked joints were subsequently subjected to various destructive and nondestructive tests described above and in Section I C. above. (See Table I for condition and testing of each joint).

Table I

Transition Joint Histories

<u>Joint No.</u>	<u>As-Received Condition</u>	<u>Work and Testing Performed</u>
1	Cold worked to 12.1% reduction in area, using the tube reduction method.	* Ultrasonically and liquid penetrant inspected before and after cold working. Unbonded area found after cold working. Was sectioned for metallographic examination and tensile tests.
2	Annealed	** Ultrasonically and liquid penetrant inspected in the annealed condition. Cold worked after welding to closed end tube. Ultrasonically tested after cold working. Developed unacceptable defects during cold drawing.

<u>Joint No.</u>	<u>As-Received Condition</u>	<u>Work and Testing Performed</u>
3	Cold worked to 12.1% reduction in area using the tube reduction method.	* Ultrasonically and liquid penetrant inspected before and after cold working. Was burst tested at 554°F. The calculated hoop stress at failure was 44,900 psi.
4	Annealed	** Ultrasonically and liquid penetrant inspected in the annealed condition. Cold worked after welding to closed end tube. Ultrasonically tested after cold working. Joint failed while attempting to remove mandrel after cold drawing.
5	Cold worked to 12.5% reduction in area using the tube reduction method.	* Ultrasonically and liquid penetrant inspected before and after cold working. Thermal and pressure cycled. Ultrasonically, liquid penetrant and tension tested after the cycling tests. Calculated stresses at failure was 61,200 psi at 688°F.

<u>Joint No.</u>	<u>As-Received Condition</u>	<u>Work and Testing Performed</u>
6	Annealed	** Ultrasonically and liquid penetrant inspected in the annealed condition. Cold worked after welding to closed end tube. Ultrasonically tested after cold working. Developed unacceptable defects during cold drawing.

* Work performed under Westinghouse-funded program¹.

** Work performed under Contract AT(30-1)-3374.

As a part of the current AEC contract, the three remaining joints were welded to closed-end pressure tubes and cold drawn to improve the mechanical properties of the pressure tube and transition joint. The tube reducing process for cold working was not feasible since the pressure tube was closed at one end. The initial plans were to burst test one of three pressure tubes and install the two remaining tubes in the Saxton Reactor.

The cold working method used for the remaining three joints was of the cold drawing type. Cold drawing was accomplished by inserting a mandrel into the pressure tube and pushing the tube through a die by applying a force on the mandrel end extending out of the open end of the tube. The die size was designed to provide 12% reduction in area in one pass. This was the total amount of cold reduction intended for these joints.

The first drawing operation was characterized by several problems including failure of the lubricant and difficulty in removing the mandrel. The drawing operation was finally completed with no apparent damage to the transition joint bond. The joint (number 4) was later unintentionally unbonded by a rolling process using two skewed rolls for the purpose of freeing the mandrel. The rolls were advanced against the pressure tube so as to produce an expansion of the tube. Four passes through the rolls with a uniform advance of the rolls after each pass produced neither a measurable change in O.D. nor apparent damage to the transition joint. During the fifth pass, the bi-metallic joint failed completely.

After successfully drawing a test piece to confirm that solutions had been found to the earlier problems, the last two tubes (numbers 2 and 6) were drawn. During the drawing of both joints,

audible evidence of some unbonding was detected. Before these joints were drawn, a roughness was noted at the outside feathered edge of each joint which was evidenced by snagging cotton fabric drawn across this edge.

Ultrasonic inspection prior to drawing had indicated questionable bond areas in all three joints. All three joints were returned to WAPD for further inspection as described below.

B. Test Results on Cold Worked Joints

Each joint was immersed in a tank and tested under conditions described in Section II above.

The standard was set up and its highest interface signal was 1.9 inches base to peak. Interface signals in excess of this area are emphasized with parentheses. Separated areas are emphasized with underlining in Tables II through IV.

The relation this data bears to the diagrams in Figure 4 is as follows:

SEP represents primarily a pattern of separation as in the "unbond" pattern.

OK represents a pattern primarily like the "good joint" pattern.

DECIMALS represent the pulse height in instrument graduations of the highest unbond signal in a pattern of "indications at interface bond."

? represents a pattern which is confused due to surface waviness or other factors.

Table II
Ultrasonic Inspection Data for Transition Joint Number 2

	Inches												Angle
	0	30	60	90	120	150	180	210	240	270	300	330	
Inside Feathered Edge	1	.3NR	OK	OK	OK	OK	OK	OK	OK	OK	.3NR	.5NR	
	2	1.2NR	NEG	.5	.2NR	OK	.8NR	OK	OK	.6	.6	.6	.7
	3	.9	.6	OK	.5	.8	1.4NR	1.9NR	1.7	OK	1.2	.1	.1
	4	.2	NEG	.1	NEG	1.3	.8	1.4	.7	.6	1.1	.7	1.4
	5	.5	.1	.1	.9	1.0	.8	1.3	.9	NEG	1.0	1.1	.5
	6	1.0	NEG	.6	.3	.5	1.4	1.2	.6	OK	.5	.5	.5
	7	1.3	1.0	.3	.7	1.3	1.1	.5	.7	.3	1.3	1.4	.1
	8	OK	.9	.3	.9	.5	.3	.3	1.3	.9	1.2	.4	1.5
	9	NEG	.8	.5	1.2	1.0	.5	1.3	(2.4)	1.9	(2.0)	(2.1)	1.7
	10	1.1	.2	NEG	.5	.2	1.0	1.8	(2.1)	1.9	(2.1)	1.5	1.6
	11	1.7	.1	.4	.5	.1	.6	(2.0)	1.6	1.9	1.6	1.2	(2.0)
	12	.4	.87	.3	.4	.4	.4	1.3?	(2.0)	1.2	1.6	.9	1.7
	13	.3	OK	OK	.4	OK	.4	1.1?	1.3	.2	1.0	1.5	1.9NR
	14	1.3	<u>SEP</u>	<u>SEP</u>	1.0NR	OK	OK	?	.7	OK	(2.3NR)	(2.0)	NEG
	15	NEG	?	?	?	OK	OK	?	1.6NR	NR	<u>SEP</u>	<u>SEP</u>	OK
Outside Feathered Edge	16		<u>SEP</u>	<u>SEP</u>	?	OK	?	<u>SEP</u>	?				
	17		<u>SEP</u>	<u>SEP</u>	?	OK	?	<u>SEP</u>	?				

Instrument Parameters

Gain - 20
Rejection - 11:30
Pulse Length - Minimum
Frequency - 10 Mc
Collimation - Tight

Table III

Ultrasonic Inspection Data for Transition Joint Number 4

		Inches				Angle								
		0	30	60	90	120	150	180	210	240	270	300	330	
Inside Feathered Edge	1	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	
	2	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	
	3	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	OK	
	4	OK	<u>SEP</u>	(?)	OK	OK	OK	OK	OK	OK	OK	OK	OK	
	5	<u>SEP</u>	(?)	(?)	<u>SEP</u>	(?)	(?)	OK	(?)	(?)	(?)	(?)	<u>SEP</u>	
	6	(?)	(?)	(?)	(?)	(?)	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	
	7	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	(?)	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	
	8	<u>SEP</u>	<u>SEP</u>	(?)	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	(?)	(?)	<u>SEP</u>	(?)	<u>SEP</u>	<u>SEP</u>	
	9	(?)	(?)	(?)	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	
	10	<u>SEP</u>	<u>SEP</u>	(?)	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	
	11	(?)	<u>SEP</u>	(?)	<u>SEP</u>	<u>SEP</u>	(?)	(?)	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	
	12	(?)	(?)	(?)	(?)	<u>SEP</u>	<u>SEP</u>	(?)	OK?	OK?	<u>SEP</u>	(?)	<u>SEP</u>	
	13	(?)	<u>SEP</u>	(?)	(?)	(?)	(?)	<u>SEP</u>	OK?	OK?	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	
	14	(?)	<u>SEP</u>	<u>SEP</u>	(?)	<u>SEP</u>	(?)	(?)	(?)	(?)	<u>SEP</u>	(?)	(?)	
	15	<u>SEP</u>	(?)	.3	(?)	<u>SEP</u>	<u>SEP</u>	(?)	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	(?)	(?)	
	16	(?)	<u>SEP</u>	(?)	<u>SEP</u>	NR	NR	(?)	(?)	(?)	(?)	<u>SEP</u>	(?)	
	17	<u>SEP</u>	NR	NR	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	
	18	(?)	<u>SEP</u>	NR	(?)	(?)	(?)	<u>SEP</u>	(?)	(?)	(?)	(?)	(?)	
	Outside Feathered Edge	19	(?)	<u>SEP</u>	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)
		20	(?)	---	---	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)

Instrument Parameters

Gain - 20

Rejection - 11:30

Pulse Length - Minimum

Frequency - 10 Mc

Collimation - Tight

Table IV
Ultrasonic Inspection Data for Transition Joint Number 6

Inches	Angle												
	0	30	60	90	120	150	180	210	240	270	300	330	
Inside Feathered Edge	1	OK	NR	OK	OK	OK	OK	OK	OK	OK	OK	OK	
	2	OK	.7	1.4	.2	NR	.4	OK	OK	OK	.4NR	.2NR	1.1NR
	3	.8	.5	1.3	.8	.4	.5	1.2NR	1.0NR	1.2	.5	NEG	.4
	4	.8	.3	1.3	1.0	1.1	OK	.7	.3	.7	.5	.5	.3
	5	1.4	1.0	.5	NEG	.2	1.0	.6	NEG	.6	.7	.5	.6
	6	.2	1.2	.2	.2	.3	.7	NEG	.2	.3	.9	NEG	.5
	7	.8	NEG	1.2	.2	.4	1.1	.8	.1	1.2	.7	.9	1.0
	8	(2.1)	1.5	.7	1.3	.9	.5	.1	.5	.3	.7	.2	1.5
	9	1.9	1.9	(2.0)	1.3	1.4	(2.1)	1.9	1.7	.6	1.2	1.5	1.5
	10	1.7	1.6	1.7	(2.2)	1.8	(2.4)	1.9	(2.2)	1.8	1.6?	(2.0)	1.3
	11	(2.1)	1.7	1.7	1.0	1.7	(2.2)	1.1	1.1	1.4	1.8	.1	1.1
	12	1.7	1.4	1.7	1.5	1.6	(2.0)	1.0	1.5	.9?	1.4	1.3	.7
	13	1.2	1.0	.7	1.5	1.0	1.3	1.0	.8	.9	.6	.7	.7
	14	.9	.4	.8	1.2	1.3	.6	.9	1.2	1.2NR	.7	.7	NR
	15	OK	OK	(2.1NR)	OK	1.2	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	.1	OK	OK	OK
	16	OK	OK	OK	OK	OK	<u>SEP</u>	<u>SEP</u>	<u>SEP</u>	.3NR	NR	OK	OK
	17	OK				NR		<u>SEP</u>	<u>SEP</u>	OK			
Outside Feathered Edge													

Instrument Parameters

Gain - 20
Rejection - 11:30
Pulse Length - Minimum
Frequency - 10 Mc
Collimation - Tight

NR represents an unresolved signal as might be the case when one layer of metal is quite thin.

NEG represents an unbond signal negligible in amplitude.

The acceptance criterion specified in Section II F allows acceptance of minor areas with indications slightly in excess of the standard. Whether the areas in joints Nos. 2 and 6 are "minor areas" could be a matter of interpretation. It is true that prior to drawing, these joints had individual readings which exceeded the standard.

To clarify the situation further, tangential radiographs were taken of all three joints. While these were only a sampling, (one of each joint) they agree quite well with the U.T. information. Joint No. 4 showed clear, continuous separation. Joints Nos. 2 and 6 showed no obvious separation at all in the radiograph (the feathered edge was not x-rayed).

To summarize: Joint No. 4 was essentially completely separated. Joints 2 and 6 show unbonded areas 3 inches deep at the feathered edge. The remainder of the bond seemed to be intact. There were areas near the middle of each of these joints which exceeded slightly the indications from the standard. These indications probably do not represent serious flaws in the bond.

V. Final Decision on the Zircaloy - Stainless Steel Transition Joints
for the Present Program

The cold worked transition joints were rejected for use in the Saxton reactor; first, because defects present might propagate during cyclic loading, eventually causing complete failure of the joint; secondly, and of less importance, because it is uncertain whether the cold worked properties of Zircaloy-4 can be maintained in the reactor environment:

1. As noted above in Section IV, one transition failed completely during the last of five similar loading cycles while attempting to remove a mandrel.

In the Saxton reactor, a transition joint would be subjected to a small number of pressure and temperature induced strain cycles of fairly large magnitude. Vibration initiated by core coolant flowing past the pressure tube could also cause an almost infinite number of strain cycles of smaller, but perhaps of significant, magnitude.

One of the six transition joints, originally procured as part of a Westinghouse funded program, was subjected to 30 simulated reactor thermal and pressure cycles with no deleterious effects.

The bond in this joint was not perfect, but there were no unbonded areas of the size that developed in the cold drawing previously described.

In summary, there is not adequate experimental evidence that the damaged transition joints would survive in the reactor.

2. The transition joints and connecting pressure tubes were cold worked to enhance their mechanical properties. At normal operating conditions, the calculated maximum temperatures at the inside and outside of the pressure tube are 661 and 550°F respectively. There is contradictory data^{6,7,8} on the possible effect of these conditions on cold worked properties. Some data⁶ indicates no appreciable change over the 100 day design life of the pressure tube. Other data^{7,8} indicates that cold worked mechanical properties tend to revert to annealed properties within 100 days at temperatures above 600°F. If the later data is correct, the intended safety margin would be reduced. From a mechanical properties standpoint, the design would still be adequate for steady state conditions. However, a possible lower design margin coupled with uncertainties in behavior while subjected possible large numbers (thousands) of strain cycles increases the uncertainty.

The only alternative under the project schedule was to use an all stainless steel pressure tube.

The possibility of using a Zircaloy-2-1/2 Nb pressure tube during a later irradiation period has been studied.

VI. Further Work

Despite the disappointing behavior of the three joints cold worked by the cold drawing method, this type of transition joint fabrication remains promising. Therefore, further work is warranted to prove out its adequacy for high temperature, high pressure service. The following additional work would be of value:

a. Analysis (Computer Work)

Estimate the principal stresses at the interface and the pre-load stresses developed during post-extrusion cooling.

b. Mechanical Properties

Determine tensile strength and fatigue strengths and notch sensitivity of interface structure when the applied stresses are perpendicular to the interface.

c. Evaluation of Analysis

Select a theory of failure and compare the actual properties and principal stresses to develop a factor of safety applicable to service conditions.

d. Cyclic Proof Test

A transition joint will be subjected to two general types of cyclic loading:

1. High Level Cyclic Strains Cycling due to Start-up and Shut-down - Changes in strain level are due to pressure and temperature changes combined with differences in physical properties between stainless steel and Zircaloy, i.e., differences in the thermal expansion coefficient and modulus of elasticity. Such cycles would be limited in number, perhaps less than twenty.

2. Low Level Strain Cycling during Steady State Operation -
Such loadings would be due to self-excited vibrations precipitated by flowing coolant and coolant and small temperature fluctuations. The number of such cycles could be very large, i.e., 10^6 cycles.

A proof test program would subject at least two full size joints to 20 times the number of high level strain cycles expected in service and one times the number of low level strain cycles at a strain range twice that expected in service.

e. New Alloys

Since at the intended operating temperature ($> 600^{\circ}\text{F}$) the Zircaloy may not retain the increase in strength imparted by cold work, other zirconium alloys, e.g., Zr-2-1/2 Nb should be evaluated.

The objective would be to find an alloy which would not require cold work for the development of adequate strength.

f. Fabrication Methods

The use of explosive techniques to fabricate transition joints shows promise and should be investigated.

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