NASA TECHNICAL MEMORANDUM

NASA TM X-2118

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THERMAL CYCLING TEST ON A 3-INCH-DIAMETER COLUMBIUM - 1 PERCENT ZIRCONIUM TO 316 STAINLESS STEEL TRANSITION JOINT

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1970

1. Report No. NASA TM X-2118	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle THERMAL CYCLING TEST ON A 3-INCH-DIAMETER COLUMBIUM - 1 PERCENT ZIRCONIUM TO 316 STAINLESS STEEL TRANSITION JOINT		5. Report Date November 1970
		6. Performing Organization Code
7. Author(s) Harry M. Cameron		8. Performing Organization Report No. E-5798
		10. Work Unit No. 120-27
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The effect of thermal cycling on the integrity of a Cb-1Zr-to-stainless-steel 3-inch (~8-cm) diameter tubular coextruded joint was investigated. The joint was cycled 78 times between 300° and 1550° F (149° to 843° C) and 500 times between 1450° and 1600° F (788° to 871° C). Extensive post-test examination revealed no metallurgical changes or deterioration of the bond between the two metals. Some diametral contraction was measured in the transition area.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Bimetal joint Transition joint Refractory metal - to stainless steel joint	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	11	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151

fold of the Solar Heat Receiver and the stainless-steel recuperator; and between the Cb-1Zr exit manifold of the receiver and the Hastelloy turbine scroll. A description of the engine can be found in reference 1. Although the design refers to a radioisotope heat source system, the same basic engine is used in the solar power system.

Fusion welding Cb-1Zr to stainless steel results in very brittle intermetallic compounds being formed. This joining technique therefore cannot be utilized unless the application is one in which no stress exists. Several methods, however, have been developed to join such dissimilar metals, two of which are brazing and coextrusion. A coextruded bimetal transition joint was chosen for the previously described application because it offered the most promising solution to the accommodation of the difference in thermal expansion characteristics which will be operating on the transition joint during its service life.

An orbiting Brayton engine will undergo repetitive $1\frac{1}{2}$-hour cycles (sun and shade periods) during which the temperature of the transition joint is expected to vary by $\pm 50^{\circ}$ F (28° C) from its mean of 1500° F (816° C). Also, during testing and checkout of the power system, it will be subjected to a number of full temperature excursions from room temperature to 1500° F (816° C).

It was considered an essential development step in the Brayton program to assess the effect of such temperature variations on the integrity of the transition joint. Although a substantial background in smaller-diameter Cb-1Zr-to-316-stainless-steel joints was accumulated under the CANEL (Connecticut Aircraft Nuclear Engine Laboratory) program, experience with larger-diameter joints was limited. The maximum temperature to which the smaller-diameter joints had previously been evaluated was 1200° F (649° C), and the type of testing was not directly applicable to the Brayton situation.

Refractory metals offer the advantage of high strength at elevated temperatures for long duration, but suffer the disadvantage of requiring to be tested in a high-vacuum environment. Refractory metals also have a high unit cost both for raw material and for fabrication and processing. It will therefore always be desirable to make a transition from a refractory metal to another metal which is adequate at lower temperatures. The accumulated test experience will serve to broaden the experience for such applications.

DESCRIPTION OF BIMETAL JOINT TEST SPECIMEN

The test specimen consisted of a cylindrical tube having an outside diameter of 3.1875 inches (8.1 cm), an inside diameter of 3 inches (7.6 cm), and a length of 18.4375 inches (47 cm). Approximately one-half of its length was 316 stainless steel; the other half was Cb-1Zr. The transition zone was tapered and about 1.5 inches (3.8 cm) long. A cross section of the tube is shown in figure 1. The method of fabrication for such a joint is shown in figure 2. First, cylinders of stainless steel and Cb-1Zr are produced.

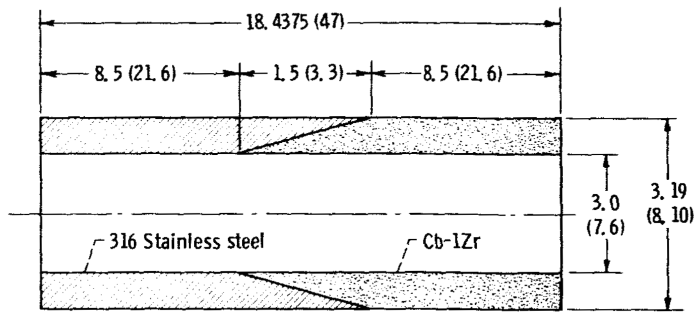


Figure 1. - Cross-sectional view of Cb-1Zr-to-316-stainless-steel joint. (Dimensions are in inches (cm).)

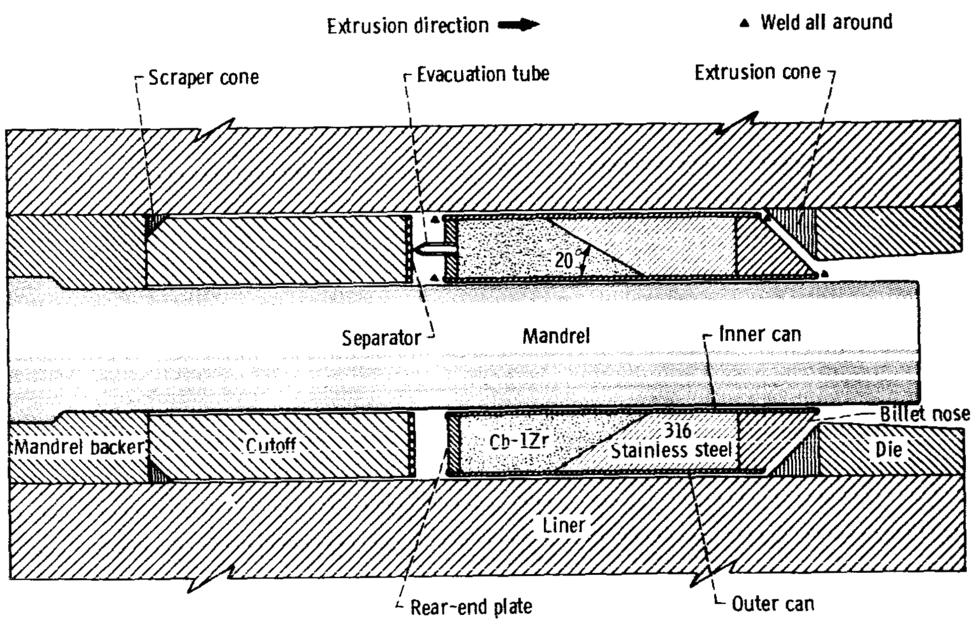
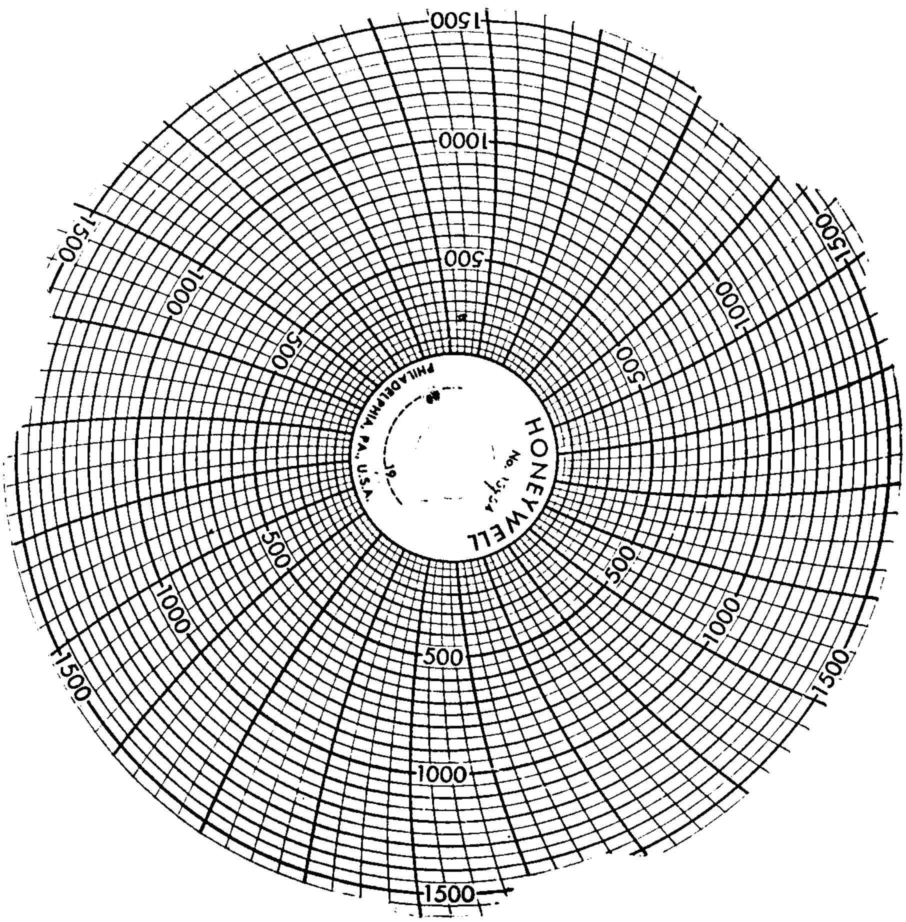


Figure 2. - Fabrication method for coextruded bimetal joint.

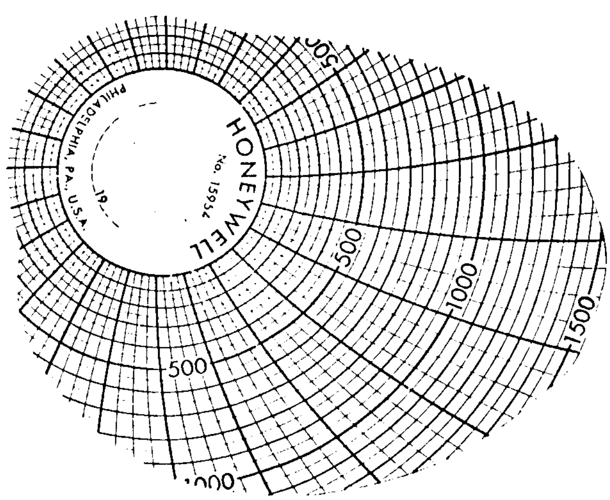
They are encapsulated, normally in low-carbon steel, to exclude oxygen during the heating and extrusion process. The billet is heated and extruded to rough dimensions. The carbon steel is removed by pickling and the tube is machined to print dimensions. (The exact details of the process are the property of the Nuclear Metals Division of the Whittaker Corporation.)

APPARATUS AND PROCEDURES

The tests of the coextruded joint were conducted in a Brew Model 922 furnace which has a test section 24 inches by 24 inches by 36 inches (60 cm by 60 cm by 91 cm). The



(a) Cam for test series 2.



(b) Cam for test series 3.

Figure 3. - Thermal cycling cams.

furnace is connected to a mechanical and an oil diffusion pump which permits its evacuation to pressures as low as 5×10^{-7} torr. The pump is equipped with a liquid-nitrogen cold baffle. The furnace temperature is controllable from a Barber Coleman MMP Control. This unit, through a slidewire, permits adjustment of the current input to the furnace heater strips whereby the rate of temperature rise can be controlled both manually and automatically. The initial heatup rate must be slow to maintain chamber pressure below 1×10^{-5} torr while outgassing is taking place. Thereafter, a heatup and cooldown rate of no greater than 50° F (28° C) per minute was permitted. The furnace temperature was recorded on a Brown strip-chart recorder.

The joint temperature was monitored by means of a platinum-rhodium thermocouple spotwelded on the stainless-steel section adjacent to the external Cb-1Zr - stainless-steel interface. Prior to insertion in the furnace, the bimetal joint was vapor degreased.

The thermal cycling tests were conducted with the tube standing upright on the stainless-steel end. No mechanical stresses were imposed. The incidental stress due to the weight of the upper half on the transition section was less than 3 psi (2.1 N/cm^2). Most of the thermal cycles were automatically controlled by a Honeywell-Brown Cam Controller. The two cams used for the two different types of test series are shown in figure 3.

TEST PROGRAM

The test program consisted of three test series:

(1) The first test series was designed for 20 cycles between ambient room temperature and 1540° F (838° C). Because of the long cooldown time to room temperature, the cycles were mostly terminated at 300° F (149° C) at the low-temperature end. In cycles 10, 12, 14, 16, 18, and 20, a total of 165 hours of soak time at 1540° F (838° C) were obtained. The other cycle periods were 3 hours with a 1-hour heatup and a 2-hour cooldown.

(2) The second test series consisted of 500 1-hour cycles in which the temperature was varied between 1450° and 1600° F (788° to 871° C). Each cycle included a soak time at 1550° F (843° C), and was constituted as follows:

- (a) 1450° to 1550° F (788° to 843° C) for 5 minutes
- (b) 1550° F (843° C) for 45 minutes
- (c) 1550° F to 1600° F (843° to 871° C) for 1 minute
- (d) 1600° F (871° C) for 4 minutes
- (e) 1600° F to 1450° F (871° to 788° C) for 5 minutes

(3) The third test series consisted of 58 cycles between 300° and 1550° F (149° to 843° C), each cycle consisting of a 1-hour heatup and a 2-hour cooldown period.

TEST RESULTS

After each test series, the bimetal joint was helium leak-checked, Zyglo inspected, ultrasonically inspected, and dimensionally examined in the transition region. To accomplish the latter, the specimen was mounted on a V-block. Indicator readings were then taken at 11 axial positions in each of the 0°, 90°, 180°, and 270° planes, both internally and externally. The inspection setup is shown in figure 4. The leak check, Zyglo inspection, and ultrasonic inspection always gave negative indications; that is, the joint remained sound. The dimensional inspection revealed a progressive necking down of the bimetallic region, which was apparent by visual inspection even after the first test series. Figure 5 shows the bimetal joint after the completion of the 578 cyclic tests.

The dial indicator readings, summarized in table I, showed a maximum radial deformation of 0.052 inch (0.13 cm) on the outside surface and of 0.055 inch (0.14 cm) on the inside surface. A thickening of the wall had occurred. The length of the joint had decreased by 0.012 inch (0.03 cm) after the first test. No further decrease in length occurred during subsequent tests.

After completion of the dimensional inspection, the transition area was sectioned.

TABLE I. - RADIAL CONTRACTION OF TRANSITION AREA AND JOINT LENGTH AFTER EACH OF THREE TEST SERIES[a]

[Shrinkage of length for all three tests, 0.012 in. (0.03 cm).]

Location from stainless-steel end		Test series 1		Test series 2		Test series 3	
		Inside diameter	Outside diameter	Inside diameter	Outside diameter	Inside diameter	Outside diameter
in.	cm	Cumulative radial contraction, in. (cm)					
8.50	21.6	0.009 (0.023)	0.003 (0.008)	0.012 (0.030)	0.008 (0.020)	0.029 (0.074)	0.020 (0.050)
9.00	22.9	0.015 (0.041)	0.008 (0.020)	0.020 (0.050)	0.015 (0.041)	0.055 (0.140)	0.052 (0.132)
9.25	23.5	0.026 (0.061)	0.018 (0.046)	0.031 (0.079)	0.025 (0.063)	0.055 (0.140)	0.045 (0.114)
9.50	24.1	0.025 (0.063)	0.015 (0.041)	0.027 (0.069)	0.023 (0.059)	0.027 (0.069)	0.017 (0.043)
9.75	24.8	0.011 (0.028)	0.003 (0.008)	0.011 (0.028)	0.010 (0.025)	0.015 (0.041)	0.010 (0.025)

[a]All figures are average of four readings on periphery.

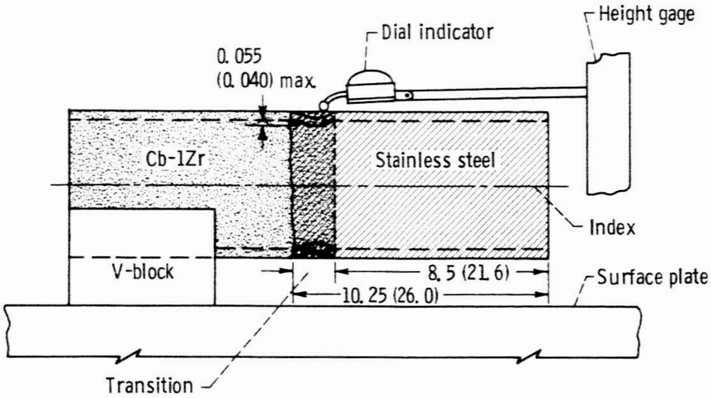


Figure 4. - Setup for dimensional inspection of Cb-1Zr - stainless-steel bimetal joint. (Dimensions are in inches (cm).)

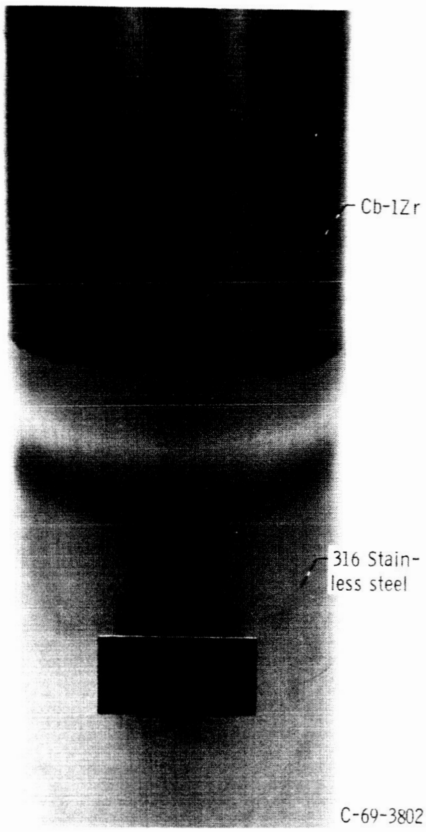


Figure 5. - Transition joint after completion of cycling test.

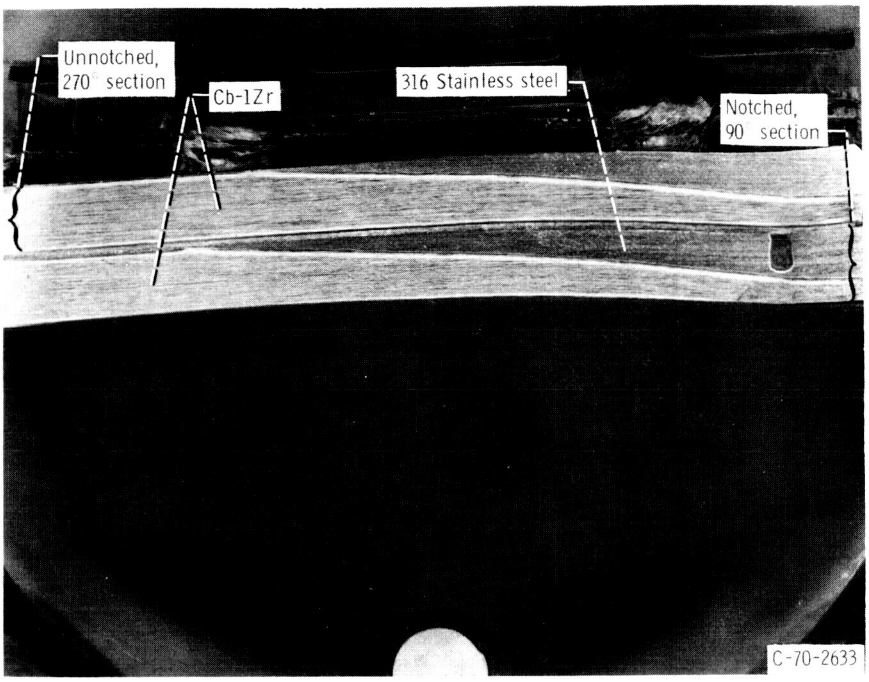


Figure 6. - Transition area in two planes. X3.5.

Figure 7. - Transition area. X250. (Etched to best show interface layer.)

Figures 6 and 7 show the bimetal joint interfaces at low and high magnification, respectively. Both show the section to be free of debonding - confirming ultrasonic test results. Figure 7 also shows the absence of significant diffusion.

DISCUSSION OF RESULTS AND CONCLUSIONS

Except for the diametral contraction, test results have shown no impairment of the usefulness of the transition joint. The reduction in flow area of about 6 percent will not materially affect the gas pressure drop.

The cause for the contraction can be sought in the difference of coefficient of thermal expansion between the two materials 10.5×10^{-6} inch per inch per $^{\circ}$F (19×10^{-6} cm/(cm)(K)) for 316 stainless steel and 4.5×10^{-6} inch per inch per $^{\circ}$F (8.1×10^{-6} cm/(cm)(K)) for Cb-1Zr. The stresses resulting from this difference during the thermal cycling create compression in the 316 stainless steel and tension in the Cb-1Zr, and the yield strength of the materials is exceeded. The stresses are first relieved by plastic flow, and subsequently by creep. Upon cooling, the inelastic deformation has to be accommodated. This occurs through radial inward displacement.

An exact analysis is complicated by the ratcheting action and by the change with temperature in relative strength of the two metals, and is beyond the scope of this report. For the purpose of preliminary evaluation, the test results have been extrapolated to assess the long-term deformation behavior of the bimetal joint for a period of 10 000 hours of service between 1450° and 1550° F (788° to 843° C). The creep component can be approximated from test series 2 since 85 percent of the test time was obtained at 1550° F (843° C). The effect of the cycles during the remaining 15 percent of the test time is believed to be very small. The cyclical deformation can be approximated from test series 3. A creep rate of 1.2×10^{-5} inch per hour (3×10^{-5} cm/hr) and a cyclical deformation of 6×10^{-4} inch per cycle (1.5×10^{-3} cm/cycle) were calculated.

For a 10 000-hour life, including 20 test cycles, the predicted radial deformation would be 0.132 inch (0.34 cm), causing about 18 percent flow area contraction. This is based on the conservative assumption of a constant creep rate. While this is still an acceptable reduction of area, definitive projection of joint integrity can, of course, not be made from a short-term test.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 20, 1970,
120-27.

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