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THERMAL STRESS TESTING OF SM-2 FUEL ELEMENTS
INTERIM TECHNICAL REPORT

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By:

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ABSTRACT

To determine thermal stability of SM-2 plate type fuel elements, test specimens were subjected to reactor operating temperature differences. Thermal stresses produced by the relatively cool side plates restraining the axial expansion of the fuel region were investigated. An analysis is presented which predicts the maximum possible value of these stresses, and the test apparatus and procedure are described. Test results were inconclusive due to distortion of welded and brazed plate specimens occurring when specimens were cut from full elements. During testing, as the region averaged temperature difference was increased from 0° to 90°F, the amplitude of distortion increased from 0.015 in. to 0.030 in. At the latter condition maximum measured side plate tensile stress was 10,000 psi.

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TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT - - - - -	vii
1.0 SUMMARY - - - - -	1
2.0 INTRODUCTION - - - - -	3
2.1 General - - - - -	3
2.2 Approach - - - - -	3
2.3 Description of Fuel Elements - - - - -	4
3.0 THERMAL STRESS ANALYSIS - - - - -	9
3.1 Temperature Profile - - - - -	9
3.2 Stress Analysis - - - - -	9
4.0 DESCRIPTION OF TEST RIG - - - - -	19
4.1 Components - - - - -	19
4.2 Design Features - - - - -	27
4.3 Instrumentation - - - - -	27
5.0 TEST PROCEDURE - - - - -	35
6.0 TEST RESULTS - - - - -	37
6.1 Initial Flatness of Test Specimens - - - - -	37
6.2 Temperature Profile - - - - -	37
6.3 Plate Deflections - - - - -	43
6.4 Side Plate Stress - - - - -	57
7.0 CONCLUSIONS - - - - -	69
8.0 APPENDIX - - - - -	71
8.1 Test Log and Data Sheets for Tests Performed on Braze Fuel Plate - - - - -	73
8.2 Data Sheets for Tests Performed on TIG Welded Fuel Plate - - - - -	85

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LIST OF ILLUSTRATIONS

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
2-1	Photograph; TIG Welded Fuel Element - - - - -	7
3-1	Isotherm Plot, One Quarter Fuel Plate - - - - -	11
3-2	Division of One Quarter Fuel Plate for Thermal Analysis - - - - -	12
3-3	Area Average Temperatures at Hottest Spot in SM-2 Core - - - - -	13
4-1	Assembly Drawing; Thermal Stress Rig - - - - -	21
4-2	Photograph; Thermal Stress Rig - - - - -	22
4-3	Photograph; Thermal Stress Test, Complete Assembly - - - - -	23
4-4	Photograph; Thermal Stress Test, Front Heater Plate Removed - - - - -	24
4-5	Photograph ; Rear Heater Plate and Rear Side of Test Plate - - - - -	25
4-6	Thermocouple Locations on Test Plate - - - - -	29
4-7	Strain Gage Locations on Test Plate - - - - -	33
4-8	Deflection Measurement Locations - - - - -	34
6-1	Comparison of Test Plate Flatness with Fuel Element Plate Flatness - - - - -	39
6-2	Effect of Rig Water Seals on Test Plate Flatness - - -	40
6-3	A Comparison of Test Temperature Distribution with the Calculated Reactor Temperature Distri- bution Across the Width of the Fuel Plate - - - - -	41
6-4 thru 6-9	Test Temperature Distribution Across Width of Test Plate - - - - -	45 thru 50

LIST OF ILLUSTRATIONS (CONT'D)

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
6-10	Fuel Plate Distortion Resulting from Thermal Stresses - Brazed Test Plate - - - - -	51
6-11	Fuel Plate Distortion Resulting from Thermal Stresses - Welded Test Plate - - - - -	52
6-12	Test Plate Distortion as a Function of Temperature Difference - - - - -	53
6-13	Test Plate Distortion as a Function of Ripple Length - - - - -	54
6-14	Effect of Weld Location on Initial Plate Distortion. - - - - -	55
6-15	Total Test Plate Distortion as a Function of Initial Distortion - - - - -	56
6-16 thru 6-19	Side Plate Strain vs. Temperature Difference - Brazed Test Plate - - - - -	59 thru 62
6-20 thru 6-23	Side Plate Strain vs. Temperature Difference - Welded Test Plate - - - - -	63 thru 66

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
2-1	Dimensions of Fuel Elements - - - - -	5
8-1	Data Sheets - Brazed Test Plate - - - - -	81
8-2	Data Sheets - Welded Test Plate - - - - -	87

1.0 SUMMARY

Thermal stress testing is being performed on portions of reactor fuel elements, as part of the SM-2 Fuel Element Structural Test Program. Test specimens consist of a single fuel plate and its proportionate share of the element side plates, the specimens being cut from standard, full-size fuel elements. Two plates have been tested to date, one cut from a brazed SM-1 dummy fuel element and the other cut from a TIG (Tungsten electrode, Inert Gas shield) welded SM-2 reference element. The TIG welded plate contained a core of depleted UO_2 .

The test procedure has consisted of subjecting the test specimens to transverse temperature differences (fuel plate centerline to side plate) of up to 200°F , and while at temperature, to measure distortion and strain at various locations.

Results of testing completed to date are considered inconclusive, due to unrepresentative initial plate distortion. This distortion, in the form of transverse ripples approximately 0.015 in. in amplitude, occurred as the test specimens were cut from the fuel element. Despite this initial distortion, several useful observations can be made regarding the welded plate specimens, from tests performed:

1. The effect of thermal stress was to increase the amplitude of original distortions, the original wave length remaining unchanged.
2. With an initial ripple in the test plate of 0.015 in., the distortion approximately doubled at the maximum reactor temperature differential.
3. The additional distortion due to thermal stress was found to be proportional to temperature differential and to ripple length.
4. Tensile stresses in the side plate sections were measured as approximately 10,000 psi at maximum reactor temperature difference. This figure should increase as initial plate distortion is reduced.
5. Individual weld loadings in shear were measured as 38 lbs. per weld. This load will also increase with a reduced initial distortion.

Future work in this program will be directed toward obtaining a test specimen which has a representative initial flatness.

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2.0 INTRODUCTION

2.1 General

As part of the SM-2 Fuel Element Structural Test Program being conducted in the ALCO General Engineering Laboratory, thermal stress testing is being performed on plate-type reactor fuel elements. Actual fabricating of the test equipment and conducting the test work were done by or under the supervision of General Engineering Laboratory personnel. When a multi-plate fuel element assembly is producing power within a reactor, thermal stresses are produced within the element which tend to distort the element structurally and can, in extreme cases, lead to fuel element failure. In the SM-2 element, the major thermal stresses are produced by the temperature difference between the heated portion of the fuel plate and the inert edges of the plate and the side plates. The relatively cool inert sections restrain the normal thermal expansion of the fuel portion. The purpose of this test program was to demonstrate the ability of welded fuel elements to withstand representative thermal stresses without severe fuel plate distortion or failure of the welds which bond the fuel plates to the side plates.

2.2 Approach

As the first step in designing a facility to evaluate thermal stresses in the SM-2 fuel elements, a literature search was conducted. The report, ORNL-113, "Thermal Stability of Multiplate Assemblies"* contained the only useful information found in the survey. In the test work reported, which was an evaluation of MTR fuel elements, a comparison was made between single fuel plate and full fuel element testing. Test results of the single plate model reportedly agreed quite well with the results from a full fuel element. This report in conjunction with the following are the reasons for selecting a single plate test specimen:

1. Control of plate temperatures and temperature differentials is simpler and more reliable for a single plate.
2. Instrumenting test samples is much easier for a single plate.
3. Deflection measurement is easier for a single plate.
4. A multi-plate assembly having uniform side plate temperatures and the same temperature profile on every fuel plate has no

* ORNL-113 - "Thermal Stability of Multiplate Assemblies," W. B. Allred, G. Ascoli, H. C. Savage, July, 1948.

stresses or restraints which are not produced in a single plate test. Controlled variations of individual plate temperatures in a multiplate assembly are extremely difficult to produce. Uncontrolled variations (which would certainly exist in any experimental work) are undesirable.

The schedule of testing, as originally conceived, proposed the testing of several variations of welded fuel elements plus the original SM-1 brazed element design. The brazed design was included mainly as a comparison of the two methods of manufacture. For this reason, the main emphasis of this report is placed on the results of the welded fuel plate test, with sufficient data on the brazed plate test included for comparison. Due to the delays experienced in making the test rig operational, thermal stress testing was started late in the fuel element development program, and all other proposed designs and fabrication techniques had been eliminated except for the element tested. Reasons for eliminating the other designs were either structural or metallurgical.

2.3 Description of Fuel Elements

The fuel element proposed for use in the SM-2 core is a multiplate assembly featuring the use of a tungsten electrode, inert gas shielded (TIG) welding process. The welds, 16 to each fuel plate, are each 1/2 in. in length and spaced 3 in. apart. The weld pattern is staggered, a weld on one edge of a fuel plate occurring at the midpoint between welds on the opposite edge (see Figure 6-14). The same staggered pattern is used between adjacent fuel plates.

Dimensional data on the welded and the brazed type fuel elements is given in Table 2-1. A photograph of a welded element is given in Figure 2-1.

TABLE 2-1
DIMENSIONS OF FUEL ELEMENTS

	<u>SM-2 Welded</u>	<u>SM-1 Brazed</u>
Overall Length (incl. end fixture)	26-1/2 in.	33-5/8 in.
Fuel Plate Length	23 in. *	23 in.
Fuel Plate Width	2.87 in.	2.84 in.
Side Plate Width	2.86 in.	2.86 in.
Fuel Plate Thickness	0.040 in.	0.030 in.
Side Plate Thickness	0.040 in.	0.050 in.
Fuel Length	22 in.	22 in.
Fuel Width	2.50 in. **	2.50 in.
Number of Fuel Plates	18	18
Fuel Plate Spacing	0.163 in.	0.163 in.
Coolant Channel Width	0.123 in.	0.133 in.

Notes: * Fuel plate length recently increased to 23-1/2 in. to include 1/2 in. of absorber section.

** Fuel width recently increased to 2.67 in. Plate width remains unchanged.

Prior to the start of rig design, an analysis was made of the temperature pattern which will exist across the width of the fuel plate and the magnitude of the stresses these temperature differences will produce.

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FIG. 2-1 - TIG WELDED FUEL ELEMENT-END FIXTURES REMOVED FOR CLARITY

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3.0 THERMAL STRESS ANALYSIS - I. Beretsky*

3.1 Temperature Profile

Preliminary results of the temperature profile and thermal stress in the SM-2 fuel element were obtained using a two dimensional heat transfer code on the IBM 704.

In Figure 3-1, the temperature profile of the hottest spot in the SM-2 element located at the most adverse position in the core is shown for one fourth of the whole element since there is symmetry. The details of the boundary conditions are shown in Figure 3-2.

The resulting temperature distribution is shown pictorially in Figure 3-3 in terms of region averaged temperature

The region averaged temperature of region j, T_j is given by the equation:

$$\bar{T}_j = \frac{\sum_{L=1}^{L=n} T_i A_i}{\sum_{L=1}^{L=n} A_i}$$

where A_i = area of region i at a temperature of T_i

As mentioned above, this calculated temperature profile represents the maximum temperature difference which occurs at any point in the core. It does not continue along the entire length of any one fuel plate as it was produced on the test plate. If the calculated temperature difference is averaged along the entire length of the fuel plate, its magnitude is reduced by a factor of approximately 2. Thus the test condition is somewhat conservative.

* APAE Memo 197, "SM-2 Reactor Core and Vessel Review Report."
J. G. Gallagher, Task 2.10, June 5, 1959

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FIG. 3-1 - SM-2 ISOTHERM PLOT ONE QUARTER FUEL PLATE PLAN VIEW

Film coefficients, $\text{BTU/hr-ft}^2\text{-}^\circ\text{F}$

$$h_1 = 7600$$

$$h_2 = 4560$$

$$h_3 = 5320$$

$$h_4 = 7600$$

Thermal conductivity of water gap = $0.035 \text{ BTU/hr-ft-}^\circ\text{F}$

Regions 2-13 are meat, divided into smaller regions to account for the effect of variable heat generation.

**FIG. 3-2 - DIVISION OF ONE QUARTER FUEL PLATE
FOR THERMAL ANALYSIS**

(a)

611	611	620	623	631	650	DEAD EDGE	SIDE PLATE 520
596	603	604	607	614	635	523	
585	588	590	592	596	625		

(b)

623	523	520
607		
594		

(c)

612	523	520
-----	-----	-----

FIG. 3-3 - AREA AVERAGE TEMPERATURES AT
HOTTEST SPOT IN SM-2 CORE

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3.2 Stress Analysis

Before proceeding to obtain values of thermal stress a theoretical model of the stress problem is developed below showing the necessary assumptions.

Body (1) is heated up to a higher temperature than body (2) due to the differences in temperatures in the bodies, respectively T_1 and T_2 . This causes body (1) to expand δ_t due to thermal expansion. However body (2), which is not a rigid body but elastic causes a restraining force on body (1) thus preventing the latter from expanding as much as δ_t . The net expansion of body (1) is therefore equal to

$$\delta_t - \delta_r = \alpha(T_1 - T_0) L - \frac{P_1 L}{A_1 E}$$

This total deformation must also equal the deformation of body (2) since they both are of equal length. The deformation on body (2) however is equal to

$$\alpha(T_2 - T_0) L + \frac{P_2 L}{A_2 E}$$

Equating the deformations, and noting that the loads P_1 and P_2 are equal we have

$$E \alpha(T_1 - T_2) = \left(\frac{A_2}{A_1} - \frac{A_1}{A_2} \right) P$$

However since the stress is equal to P/A , we have

$$S_1 = \frac{P}{A_1} = \left(\frac{A_2}{A_1} - \frac{A_1}{A_2} \right) \alpha(T_1 - T_2) E, \text{ Compression}$$

$$S_2 = \frac{P}{A_2} = \left(\frac{A_1}{A_1} - \frac{A_1}{A_2} \right) \alpha(T_1 - T_2) E, \text{ Tension}$$

The above equations for S_1 and S_2 should be modified to account for two

degrees of restraint by dividing by $1 - \nu$, where ν is Poisson's ratio and is numerically equal to 0.3.

Finally we have

$$S_1 = \frac{E \alpha (T_1 - T_2)}{1 - \nu} \left(\frac{A_2}{A_1 + A_2} \right)$$

$$S_2 = \frac{E \alpha (T_1 - T_2)}{1 - \nu} \left(\frac{A_1}{A_1 + A_2} \right)$$

If we consider $T_1 > T_2$ as shown above, we can define an average temperature of both bodies as being equal to

$$T_{avg} = \frac{T_1 A_1 + T_2 A_2}{A_1 + A_2} = \frac{A_1 T_1}{A_1 + A_2} + \frac{A_2 T_2}{A_1 + A_2}$$

Using this definition we can redefine the stress as being equal

$$S_1 = \frac{E \alpha (T_{avg} - T_1)}{1 - \nu} = \frac{E (T_2 - T_1)}{1 - \nu} \left(\frac{A_2}{A_1 + A_2} \right)$$

and

$$S_2 = \frac{E \alpha (T_{avg} - T_2)}{1 - \nu} = \frac{E \alpha (T_1 - T_2)}{1 - \nu} \left(\frac{A_1}{A_1 + A_2} \right)$$

where $T_1 = T_{max}$ of the body, and $T_2 = T_{min}$ of the body

Since $T_2 - T_1 < 0$, S_1 which is negative is viewed as compressive stress.

Referring to Figure 3-3C, body 1 can be considered to be at a temperature of 612°F, while the dead edge and side plate can be considered to be body 2 at a temperature of 522°F.

$$A_1 = 228 \times 10^{-4} \text{ in.}^2$$

$$A_{\text{dead edge}} + A_{\text{side plate}} = A_2 = 28.2 \times 10^{-4} + 20.4 \times 10^{-4} = 48.6 \times 10^{-4} \text{ in.}^2$$

Since $E \propto T \approx 245$, using the previous equations derived, we have

$$S_1 = S_{\text{meat}} = 5570 \text{ psi, Compression}$$

$$S_2 = S_{\text{dead edge \& side plate}} = S_{\text{sp}} = 26,050 \text{ psi, Tension}$$

Using a more conservative approach, consider the edge of the meat adjacent to the dead edge. As shown in Figure 3-3, the temperature varies from 650°F to 625°F , the average temperature (locally) being 640°F .

Using 640°F being equal to T_1 instead of 612°F , we find the stress in the meat and attached portion (side plate and dead edge) to be equal to:

$$S_1 = 7320 \text{ psi, Compression}$$

$$S_2 = 34,200 \text{ psi, Tension}$$

Since this local average temperature varies from 650°F to 625°F , the compressive stress in the meat may vary from 7930 psi to 6370 psi and the tensile stress in the outer portion will vary from 37,100 psi to 29,800 psi.

Load on Weld

The total load on the side plate portion is equal to the local stress multiplied by the cross sectional area of the side plate.

$$P_{\text{sp}} = 34,200 \times 20.4 \times 10^{-4} = 65.8 \text{ lbs}$$

However, this load is only for $1/2$ the total side plate; therefore, the total load to be carried by the weld is

$$2 \times 65.8 \text{ lbs} = 132 \text{ lbs./weld}$$

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4.0 DESCRIPTION OF TEST RIG

An assembly drawing of the thermal stress rig is given in Figure 4-1. Photographs of the rig and its various components are given in Figures 4-2, 4-3, 4-4, and 4-5.

4.1 Components

4.1.1 Heaters

Radiant heaters were used to provide an easily controlled heat source which would not disturb the test specimen. The original heater design, as shown on Figure 4-1, Section C-C, consisted of four parallel nichrome wires connected in series. Thermal expansion of the wire resulted in short-circuiting and grounding. This situation was remedied by substituting coils of wire for the four parallel straight wires. Coils are visible in Figures 4-4 and 4-5. A summary of the laboratory development program for the design of these heaters is presented in Appendix A, with a summary of the performance of other components of the rig.

4.1.2 Spray Cooling

To provide the necessary cooling of the side plates and edges of the fuel plate, spray pipes were located parallel to the test specimen. In the original design, spray holes were provided along the entire length of the plate, but experience proved that most were unnecessary and they were subsequently plugged. Several spray holes located near the top of the plate were adequate; runoff from these providing cooling at the bottom.

4.1.3 Water Seal

The water seal between the cooled and heated portions of the test plate was accomplished by using 0.003 in. thick stainless steel strip bent to form cantilever springs 24 in. wide by 1/2 in. long. The ends of these springs contacted the test plate along the fuel edge, providing the necessary seal with a minimum of restraint to the test plate.

4.1.4 Air Cooling

To provide the necessary temperature depression at the plate centerline, air supply tubes were mounted to the heater plate. These tubes have a row of holes spaced every 1/2 in. to provide jets of air which impinge on the test plate centerline. Tubes are visible in Figures 4-2 and 4-5.

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FIG. 4-2 - SM-2 - THERMAL STRESS RIG

FIG. 4-3 - SM-2 TASK 6. 2 THERMAL STRESS TEST
COMPLETE ASSEMBLY

FIG. 4-4 - SM-2 TASK 6.2 THERMAL STRESS TEST
FRONT HEATER PLATE REMOVED SHOWING TEST PLATE IN PLACE

FIG. 4-5 - SM-2 TASK 6.2 THERMAL STRESS TEST
REAR HEATER PLATE AND REAR SIDE OF TEST PLATE

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4.1.5 Dial Gage Support

Test plate deflections were measured with a dial indicator mounted to steel bars running parallel to the test plate. The gage moved axially along the test plate on these rods and could be moved transversely across the plate on a traversing bar. Slots in the front heater plate provided gage access to the test plate.

4.2 Design Features

To adequately perform its function, an apparatus for thermal stress testing of reactor fuel plates must have certain design features.

1. It must impose the required temperature patterns on the test specimen.
2. It must not impose extraneous restraint to normal thermal expansion.
3. The test plate must be accessible for instrumentation.

The temperature patterns were produced by heaters, water sprays and air jets previously described. Each of these was controlled manually by suitable autotransformers and valves. The test plate was painted a flat black along the edges of the fuel section to concentrate the heat absorption in this area.

A technique of axial temperature control, considered but never used, was to vary the width of the painted area along the plate length to concentrate the heating effect in certain areas.

A minimum of rig restraint was transmitted to the test plate since the test plate was touched only by the spring seals in a line contact. It was free to expand axially and transversely.

The design provides minimum space for instrumentation, in order to reduce heat loss and deflection probe lengths. Keeping the rig small caused some difficulties in heater design and instrumentation that might have been avoided with a slightly larger rig.

4.3 Instrumentation

4.3.1 Temperature

To determine the temperature profiles existing on the test plate, thermocouples were installed at the locations shown on Figure 4-6. Thermocouples were made of 0.005 inch diameter iron-constantan wire electri-

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LOCATION IDENTICAL FOR BRAZED AND WELDED PLATE
NUMBERING SYSTEM USED ON DATA SHEETS,
APPENDIX 8.1 AND 8.2

FIG. 4-6 - THERMOCOUPLE LOCATIONS ON TEST PLATE

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cally insulated with 2 hole 0.050 diameter ceramic sleeving. They were attached to the test plate by capacitance discharge welding. Accuracy of temperature measurements was $\pm 2^{\circ}\text{F}$.

4.3.2 Stress

Tensile stresses in the unheated side plate sections were measured by SR-4 strain gages cemented to the outer surface of the side plates and coated with a waterproofing compound. Trouble was experienced in obtaining a bond which would withstand the severe water conditions of the rig. During testing of the brazed fuel plate, visible bond failure was experienced on several gages. When testing the depleted core welded plate, a different waterproof coating was used and no visible evidence of bond failure was noted. However, test results seem to indicate gage slippage might have occurred. Gage locations for the two test plates are shown on Figure 4-7.

4.3.3 Deflection

Deflection measurements were taken with a dial indicator, as mentioned previously. The gage had a range of 0.25 in. and was graduated in 0.0001 in. increments. No attempt was made to provide absolute parallelism between the gage support. Rather, the deflection readings were corrected for this effect before plotting. Location of deflection measuring points are given in Figure 4-8. Accuracy of deflection measurements was ± 0.002 in.

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FIG. 4-7 - STRAIN GAGE LOCATIONS ON TEST PLATES

NUMBERING SYSTEM USED ON DATA SHEETS,
APPENDIX 8.1 AND 8.2

FIG. 4-8 - DEFLECTION MEASUREMENT LOCATIONS

5.0 TEST PROCEDURE

Conducting tests with a complex rig required definite test procedures, especially for installing the test specimen in the rig.

After installation of the instrumentation on the test plate, the plate was set into the rig and the instrument leads connected. At this time the seal springs barely touched the plate. The water sprays were turned on and the spring adjusting screws tightened until water leakage stopped. This provided maximum sealing with a minimum of restraint to the test plate.

Once this adjustment had been made the heaters were installed and the temperature of the rig allowed to stabilize. A zero temperature difference reading of all instruments was taken.

In testing the brazed fuel plate the temperature of the heated portion of the plate was raised until the average temperature of the five thermocouples located in the heated portion of mid-height was approximately 70°F above the temperature of the side plates. A complete reading of all instrumentation was again taken. The temperature was then raised to an average differential of 110°F and data recorded. The plate was then allowed to cool and the above procedure repeated for a total of three tests. This completed the testing of the brazed plate.

In testing the welded, depleted core plate, the same procedure as above was followed except that the temperature was raised in six 20° increments. This provided data on the temperature dependence of deflections and stresses.

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6.0 TEST RESULTS

Test results to date have been significant in some areas but inconclusive in others. The main difficulty has been the attempt to obtain a test specimen which duplicates the flatness of the fuel plates in a welded assembly. If assumed that a flat plate would behave as a slender column in compressive loading, the eccentricity of loading (initial distortion or rippling in the case of the flat plate) is an important parameter in the strength of the column. For this reason it is imperative that the initial flatness of the test specimen be representative of the plates in an element.

6.1 Initial Flatness of Test Specimens

The specimen used for testing brazed plates, which was cut from a dummy SM-1 fuel element, duplicated quite closely the flatness of plates in an element. This measurement is based on flatness measurements of the outer plates of the elements recently fabricated for SM-1 Core II. A comparison of measurements is given in Figure 6-1.

The flatness of the plates in a welded fuel element was not duplicated by the second test specimen. Flatness measurements of the outer fuel plates of several of these elements (when channel spacer plates were used during welding) showed variations of only 0.002-0.003 in. The test plate, although cut from one of these elements, showed initial variations up to 0.020 in. A comparison of welded plate measurements is also shown in Figure 6-1. Reasons for this initial rippling are thought to be minor locked-in welding stresses and/or machining stresses induced when the plate was cut from the assembly.

When the initial distortion of the test plate was discovered, a check was made to determine if distortion was caused by the water seals in the rig. The adjusting screws on the water seals were loosened until the seals barely touched the test plate. Dial-gage readings were taken. Results, plotted in Figure 6-2, show good agreement between the test and relaxed conditions. At least part of the variation shown was caused by a shifting of the plate in the rig as the adjusting screws were loosened.

6.2 Temperature Profile

A comparison of the calculated temperature profile across a reactor fuel plate with a typical profile imposed upon a plate during thermal stress testing is shown in Figure 6-3. The important fact in comparing the two curves is that the average temperature difference, heated to unheated portion, is the same, 89°F. The fact that temperature peaks occur in the

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FIG. 6-1 - COMPARISONS OF TEST PLATE FLATNESS WITH FUEL ELEMENT PLATE FLATNESS

FIG. 6-2 - EFFECT OF RIG WATER SEALS ON TEST PLATE FLATNESS

THE CALCULATED DISTRIBUTION PREDICTS THE HIGHEST
TEMPERATURE DIFFERENCES WHICH WILL EXIST IN THE
SM-2 CORE

FIG. 6-3 - A COMPARISON OF TEST TEMPERATURE DISTRIBUTION
WITH THE CALCULATED REACTOR TEMPERATURE
DISTRIBUTION ACROSS THE WIDTH OF THE FUEL PLATE

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reactor plate means only that localized thermal stresses are produced in these areas, which contribute to the overall deflection and stress results. However, these results depend mainly upon the average temperature differences, which are duplicated. (See section 3.0, Thermal Stress Analysis.) Since the thermocouple locations were equally spaced in the heated region, they were at the centers of equal areas. Therefore, the area average temperature is simply the arithmetic average of the thermocouple readings. This is not true in the unheated portion since the thermocouples there were located in the coldest area of the plate. Location of these thermocouples was dictated by space requirements.

Plots of test temperature profiles for brazed and welded fuel plates are given in Figures 6-4 through 6-9.

6.3 Plate Deflections

The effect of temperature differentials on plate deflections is presented graphically in Figures 6-10, 6-11, and 6-12.

Figures 6-10 and 6-11 show the deflection of the test plate centerline at various temperature differences, Figure 6-10 showing the brazed plate and Figure 6-11 showing the welded plate. Since major emphasis of this test program has been placed on the welded fuel element, most of the analysis of test results has been done on that test plate.

Figure 6-12 is a plot which shows the variation in plate deflection as a function of temperature difference. The points plotted are the maximum and minimum which occur on each side of the plate mid-height (see Figure 6-11, the 10 and 14 in. axial locations). The dependence of plate deflection on temperature difference is obvious, although not a straight-line function. A possible explanation for the non-linearity of the curves is that the plate may be exhibiting column strength up to 50 and 80 mils deflection for the top and bottom curves, respectively.

Figure 6-13 shows the effect of ripple length (half period) on plate deflection. The results appear reasonable if one considers each ripple to be a bent plate fixed at both ends. For small deflections, the deflection is proportional to the change in length, and for the same temperature change, the change in length is proportional to the original length ($\Delta L = L_0 \alpha \Delta t$).

The reason for the variation in ripple length cannot be fully explained. A plot of plate distortion showing weld locations is shown in Figure 6-14. This plot shows that the ripples span several welds, apparently a random number, although the peak of each ripple occurs between welds.

Figure 6-15 shows the relationship between initial distortion and thermal deflection. There is an apparent linear relationship although no logical

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AXIAL LOCATION: 10" ABOVE PLATE CENTERLINE
BRAZED TEST PLATE

FIG. 6-4 - TEST TEMPERATURE DISTRIBUTION ACROSS
WIDTH OF TEST PLATE

AXIAL LOCATION: CENTERLINE

BRAZED TEST PLATE

FIG. 6-5 - TEST TEMPERATURE DISTRIBUTION ACROSS WIDTH OF TEST PLATE

AXIAL LOCATION: 10 INCHES BELOW PLATE CENTERLINE

BRAZED TEST PLATE

FIG. 6-6 - TEST TEMPERATURE DISTRIBUTION ACROSS WIDTH OF TEST PLATE

Axial location: 10 inches above plate centerline

Welded Test Plate

FIG. 6-7 - TEMPERATURE DISTRIBUTION ACROSS WIDTH OF TEST PLATE

Axial location: Centerline

Welded Test Plate

FIG. 6-8 - TEMPERATURE DISTRIBUTION ACROSS WIDTH OF TEST PLATE

AXIAL LOCATION: 10 INCHES BELOW PLATE CENTERLINE

WELDED TEST PLATE

FIG. 6-9 - TEMPERATURE DISTRIBUTION ACROSS
WIDTH OF TEST PLATE

FIG. 6-10 - FUEL PLATE DISTORTION RESULTING FROM THERMAL STRESSES

FIG. 6-11 - FUEL PLATE DISTORTION RESULTING FROM THERMAL STRESSES

WELDED TEST PLATE
UPPER CURVE: RIPPLE
 IMMEDIATELY ABOVE PLATE
 MID-HEIGHT. SEE FIG. 6-11
LOWER CURVE: RIPPLE
 IMMEDIATELY BELOW PLATE
 MID-HEIGHT. SEE FIG. 6-11

FIG. 6-12 - TEST PLATE DISTORTION AS A FUNCTION OF TEMPERATURE DIFFERENCE

100-10-102-1-100, 190

TEMPERATURE DIFFERENCE 89°F

WELDED TEST PLATE

FIG. 6-13 - TEST PLATE DISTORTION AS A
FUNCTION OF RIPPLE LENGTH

FIG. 6-14 - EFFECT OF WELD LOCATION ON INITIAL PLATE DISTORTION

TEMPERATURE DIFFERENCE: 89°
WELDED TEST PLATE

FIG. 6-15 - TOTAL TEST PLATE DISTORTION AS A FUNCTION OF INITIAL DISTORTION

reason for the relationship is evident. A possible explanation is that the magnitude of the initial distortion is a function of ripple length, and hence a function of thermal deflection.

6.4 Side Plate Stress

Strain gages were bonded to the side plate sections of the test specimen to measure the tensile stresses produced in these members. These stresses are maximum at mid-height of the side plate and fall off toward the ends. As stated in section 4.3, Instrumentation, test results seem to indicate a failure of the bond between the gage and the test plate during the test.

Plots of side plate strain vs. temperature difference for the brazed test specimen are presented in Figures 6-16 through 6-19 and for the welded specimen in Figures 6-20 through 6-23. (See Figure 4-7 for gage locations.)

6.4.1 Brazed Plate

The gage locations for the brazed specimen were selected before the stress pattern in the side plates was fully understood; therefore no gages were located at the maximum stress point, mid-height.

Gages 1 and 2 (Figures 6-16 and 6-17) gave somewhat logical results for test 1 but apparently failed during test 2. The results of test 1, gages 3 and 4 (Figures 6-18 and 6-19), are not so logical but are in excellent agreement. The measured strain at 110° temperature difference also agrees well with that indicated by gage 3. These gages also apparently failed during test 2.

If it is assumed that strain gages 2, 3, and 4 were correct during test 1 at 110° , an average of these readings is 750 microinches per in. Side plate stress is then equal to this strain times the modulus of elasticity or $S = E \epsilon = 750 \times 10^{-6} \times 29 \times 10^6 = 21,800$ psi. The cross-sectional area of the side plate section is $0.050 \times 0.163 = 0.0082$ sq. in. The load required to produce a 21,800 psi stress is therefore $21,800 \times 0.0082 = 179$ lbs. This is the load which was transmitted across the brazed joint in the form of a shear stress. A calculation of theoretical side plate stress by the same method used for the welded element in section 3.0 yields 29,300 psi for the brazed element at the 110° test ΔT . The difference in stress values in the two elements is due to differences in areas of heated and unheated regions. The fact that measured stress is not as high as theoretical stress is understandable. The analysis does not take into account any bending in the heated region, which reduces stress. Also the analysis predicts the theoretical maximum stress, which, as mentioned previously, occurs at the mid-height of the plate and not at the ends where the gages were located.

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Strain Gage No. 1

Brazed Test Plate

FIG. 6-16 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

Strain Gage No. 2

Brazed Test Plate

FIG. 6-17 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

Strain Gage No. 3

Brazed Test Plate

FIG. 6-18 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

STRAIN GAGE NO. 4
BRAZED TEST PLATE

FIG. 6-19 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

Strain Gage No. 1

Welded Test Plate

FIG. 6-20 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

Strain Gage No. 2

Welded Test Plate

FIG. 6-21 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

Strain Gage No. 3

Welded Test Plate

FIG. 6-22 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

Strain Gage No. 4

Welded Test Plate

FIG. 6-23 - SIDE PLATE STRAIN VS. TEMPERATURE DIFFERENCE

6.4.2 Welded Plate

A review of the plotted strain gage readings for the welded plate (Figures 6-20 through 6-23) shows better agreement for the several tests performed than was obtained in the results of the brazed plate tests, although the readings for the welded plate are still far from satisfactory.

Gages 1 and 2 were located between the first and second weld at the top of each side plate. Although the two gages are at different distances from the plate mid-height, their readings show close agreement. This agrees with the analysis, which predicts that the stress is independent of specimen length. The strain indicated by these gages at the 90° operating temperature difference of SM-2 was approximately 200 microinches per in. This is equivalent to $200 \times 10^{-6} \times 29 \times 10^6 = 5800$ psi stress, and indicates a shear loading on these end welds of 38 lb. Strength tests performed on individual welds revealed that the minimum tensile load resulting in weld failure was 1270 lbs. * Weld strength of the SM-2 TIG welded elements appears to be fully adequate.

Gages 3 and 4, located near mid-height of the plate, should indicate the maximum stress in the side plates. This stress, as indicated by gage 3, was approximately $350 \times 10^{-6} \times 29 \times 10^6 = 10,000$ psi at 90° temperature differential. This stress seems reasonable since the buckled plate would not develop full theoretical stress. (Theoretical stress is 26,000 psi.) Gage 4 does not agree with gage 3 in the value of the maximum stress. There is, however, some agreement in the slopes of the curves which can be seen between 20° and 80° temperature difference. Possibly some variation in initial conditions can account for the difference between gage readings.

* APAE Memo No. 223, "SM-2 Reactor Core and Vessel Review Report," by J. G. Gallagher, Task 5.1, September 8, 1959.

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7.0 CONCLUSIONS

Due to the non-representative ripples present in the welded test specimen, no conclusions as to the acceptability of the welded fuel elements can be made at this stage of the test program. However, several observations can be made, referring to the welded plate:

1. The effect of thermal stress was, generally, to increase the magnitude of existing distortions, following directly the original wave pattern.
2. With an initial ripple in the test plate of 0.015 in., the distortion approximately doubled at the maximum reactor temperature differential.
3. The additional distortion due to thermal stress was found proportional to temperature differential and to ripple length.
4. Tensile stresses in the side plate sections, were approximately 10,000 psi at the maximum reactor temperature differential. This value should increase as initial plate distortion is reduced.
5. Individual weld loadings in shear were 38 lbs. per weld. This load will also increase with a reduced initial distortion.

To obtain valid data from thermal stress testing, future work will be directed toward obtaining a representative test specimen. Several different approaches can be used:

1. Force the side plate sections to remain straight by placing them in grooves cut in heavy bars. Normal longitudinal expansion would not be restrained nor would normal thermal distortion of the fuel plate.
2. Reduce or eliminate stresses induced in the test plate while cutting it from the element by using a different cutting technique.
3. Remove machining and welding stresses from the test plate by a high temperature anneal.
4. Test a flat plate having additional width to simulate the restraint to expansion provided by the side plate sections of the welded test specimen (plate width would be $2.874 + (2 \times .123) = 3.120$ in. This method is undesirable since it does not include the effects of the welds on thermal distortion. Also the moment of inertia of the welded test specimen would have to be duplicated in some manner.

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8.0 APPENDIX

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8.1 TEST LOG AND DATA SHEETS FOR TESTS PERFORMED ON ON BRAZED FUEL PLATE

SM-2 FUEL ELEMENT STRUCTURAL TEST PROGRAM THERMAL STRESS TESTING (TASK 6.2) - E. S. HARAWAY

Abstract - The initial runs (brazed fuel plate) were completed October 8, 1959, in accordance with the test procedure dated October 5, 1959, to the satisfaction of N. P. E. D. This will present a historical review of activities leading up to the first successful runs.

Review - The information presented below has been grouped in readily identifiable categories for simplification. Each category within itself is chronological.

I. Heater Plates

The heater plates have been revised from the original design as follows:

- A. Heater Coils.** Initial runs on the original designs failed due to excessive growth of the heater wires resulting in electrical shorts, hot spots and burn outs. Since no simple scheme of insulation or restraint of the straight heater wires was resolved, tests were started with coiled heater wires.

Virtually all of the expansion in the coiled heater wires was expended radially about the coil center line resulting in no lateral distortion. It was decided that further heater development would be based on coiled heaters.

Additional testing established a "burn out length" for the available power and the following coil specifications were resolved. Using No. 24 Nichrome wire rated at 1.710 ohms per foot, coils were formed on a 0.285 O. D., 24 threads per inch stud. These coils were stretched to 9 turns per inch for the rear heater plate and 10 turns per inch for the front heater plate, resulting in approximately 5 inches of heater wire per inch of heater plate.

- B. Tie-Downs.** In conjunction with the coiled heater tests tie-down spacing was investigated. No bucking or sagging was experienced with spacings up to 5 in. centers. However, it was found that any

discontinuities in the coils, such as sharp bends, were exaggerated during heating. It was decided that a 3 in. tie-down spacing was practical from an installation point of view and would tend to circumvent any difficulty arising from inadvertent discontinuities.

C. **Insulation.** Thermal insulation was of no concern while electrical insulation was obtained by the use of ceramics and asbestos.

1. Ceramic insulators were used as tie-down insulators and feed thru insulators. Double bore insulators were cemented into the steel heater plates such that 1/16" of the insulator extended beyond the surface of the heater side of the plate. The cement used was four parts by weight of Emerson and Cummings Stycast #2662 well blended with one part by weight of E & C Catalyst #14. The cemented insulators were cured in accordance with the following schedule:
 - a. 24 hours at 130°F.
 - b. 2 hours at 212°F.
 - c. 3 hours at 302°F.
 - d. 1 hour at 500°F.
2. Asbestos paper, 1/16" thick, was used to insulate the heater coils from the steel heater plates. The asbestos was punched to clear the ceramic insulators and cemented to the steel heater plates in accordance with the procedure described for the ceramic insulators. Curing for both ceramic and asbestos insulation was accomplished at the same time.

II. Test Plate

The first runs were made on a brazed, 0.030" thick dummy plate which had been instrumented previously with 18 gage, chromel-alumel thermocouples resistance welded in place. The juxtaposition of these oversized thermocouples at the knife edge water seal made it practically impossible to obtain a seal or a temperature differential across the seal. The size and location of the thermocouples had further detrimental effects including fin effect, shadow and physical interference with deflection measurement.

To relieve the above conditions, several changes were carried out and are described below.

- A. **Thermocouples.** To reduce so-called fin effect and shadow, it was decided to miniturize the thermocouples to a degree that any error

attributable to the thermocouple itself was negligible relative to the indicating instrument error.

1. **Preparation.** Chrome-alumel thermocouple wire, 0.005" O. D. was obtained along with 0.050" O. D., 2 bore, ceramic insulators. The insulators were threaded on to the wire, exercising extreme care to prevent cross shorting the thermocouples, in appropriate lengths for the ultimate application. A new brazed, 0.030" thick, test plate was obtained and strenuously cleaned with acetone and wiped down with a lint free cloth.
 2. **Fabrication and Application.** The thermocouples were fabricated from 0.005" O. D. chromel-alumel wire crossed and welded by the stored energy resistance welding method. The welded junction was sectioned and attached to the test plate by the same method. During this procedure extreme care was exercised to eliminate any cross shorting conditions. The application of the thermocouples was such that fin effect is negligible and well within the accuracy of the indicating instrument.
 3. **Arrangement.** The thermocouples were located in accordance with Figure 4-6 to present temperature profiles across the test plate at three positions. Adequate space was provided for the knife edge seal eliminating previous difficulties due to physical interference. All thermocouples that may have interfered with deflection readings were placed on the rear side. Edge thermocouples were attached to the front side of the plate to simplify access since no spray area penetrations exist at the rear side.
- B. **Strain Gages.** Five 60 ohm strain gages were incorporated in the system to determine strain imparted to the cold side plates by the hot fuel plate.
1. **Preparation.** The areas selected for strain gage application were roughed with abrasive paper to facilitate cementing and cleaned with acetone until the areas could be wiped with a white cloth without discoloration. The strain gage cover paper was trimmed to fit the edge; care being taken to always handle the gage by the wires preventing contact with the gage by the fingers.
 2. **Application.** Duco cement was applied lightly to the metal surface and to the long side of the gage cover and the two

were carefully pressed together. Once in contact with the metal surface care must be exercised to prevent movement of the gage. Excess cement must be forced out carefully from beneath the gage when the cement becomes tacky. The cement was allowed to set for 18 hours.

When the cement had set the strain gage connecting wires were insulated from the test plate with plastic tape and the area sealed with Duco cement. In detail the stepwise procedure for wiring the strain gages follows:

- a. Place a narrow strip of plastic under the connecting wires and adjacent to the gage cover paper.
 - b. Make a twisted connection between the connector wire and an insulated lead wire and just touch with solder. The lead wire must have an "S" curve bent into it near the joint to relieve the connecting wire of any mechanical load.
 - c. Cover this connection with a narrow strip of plastic tape and repeat the procedure for joining the second lead wire.
 - d. Cover with a narrow strip of plastic tape and render the entire area (gage, connection and leads) water tight with Duco cement.
3. Arrangement. One strain gage was applied to each of the four corners of the test plate. The gages were mounted on the outside edges of the side plate at the termination of the braze area. A fifth, or dummy, gage was applied to a stainless steel sheet sample and the sample was mounted in the spray area. The latter gage compensates for temperature induced errors in strain gage meter reading.

C. Miscellaneous Preparations

1. Prior to application of thermocouples and strain gages the test plate was painted flat black with the exception of a strip 1-1/2" wide on both sides of the plate on the longitudinal center line. This was in accordance with N. P. E. requirement.
2. After the test plate was cut from the fuel element the ends of the side plates extend beyond the end of the fuel plate. These ends were not trimmed off at the bottom of the test plate but were utilized to raise the test plate off the base plate. This separation interrupts the heat sink created by a water seal between the test plate resting on the base plate.

III. Rig Assembly

Various revisions were made to the original rig design to improve reliability. These are itemized below.

- A. **Spray Pipes.** The position of the holes in the spray pipes was changed from 27° to 45° . This eliminated direct impingement of the water on the knife edge seal and instead directed the water across the seal.

To reduce flooding and excessive chilling at the bottom of the test plate, all holes in the spray pipes were plugged except for No. 15, 26, 31, 36, 39, 42, 43, 44 and 45. Spray pipe holes were numbered from the bottom.

- B. **Spring.** The original springs were made from 0.010" shim stock and proved to be too rigid imparting considerable restraint to the test plate at the knife edge seal. These springs were replaced with springs made from 0.0035" shim stock. Although the latter springs are adequate they are more subject to deformation and it is recommended that for future spring requirements 0.005" shim stock be used.
- C. **Wiring.** To remain compatible with the miniaturizing of the thermocouples, a terminal block was arranged at the top of the rig to relieve the 0.005" thermocouple wires of any structural load imparted by the 18 gage thermocouple leads. Each thermocouple wire was wound around the fixed thermocouple lead, soldered, and sealed with Duco cement. The latter doubled as electrical insulation and waterproofing.

An additional selector was employed for the strain gage reading. Again the connections at the rig were sealed with Duco cement.
- D. **Mechanical Closure.** The closure remained essentially unchanged except for notching the hinged doors to permit thermocouple and strain gage penetration. Additional holes were drilled in the base plate directly beneath the test plate to improve water run-off.
- E. **Heater Plates.** Careful centering of the heater plates during installation is essential to uniform temperature profile and, in the case of the front plate, accurate deflection reading.
- F. **Deflection Gage Support.** The deflection gage support had to be tailored to the rig at assembly in order to facilitate the desired

locations. It was found that squaring the support structure distorted the test rig to a degree that deflection readings could not be taken. Therefore the support was adjusted to the rig without distortion to the latter and all set screws made up to retain the acceptable condition.

IV. Testing

The test on the first (brazed) test plate was performed in accordance with the test procedure by Nuclear Power Engineering dated October 5, 1959.

A. Initial Reading. Table 8-1

1. Zero deflection readings were taken in the cold (room temperature) condition and recorded. Ultimately it was found that the travel of the deflection gage probe was not adequate as set and the run had to be shut down. The gage was shimmed to permit freedom of travel in both directions and the run was started again.
2. The cold strain gage readings were taken and recorded. There appeared to be excessive outside influence on two of the readings. It was found that two connections were loose and these were repaired. Although the readings were less erratic there remained some doubt as to the validity of the strain gage readings due to unidentified external influence on the meter.

B. Raised Temperature Readings, Table 8-1.

Deflection and strain readings were recorded, after each of the temperature profiles were established, as required by the procedure. The profiles were established by setting water flow and heat input and varying the air flow until by forced convection the profile is broadened to its maximum with minimum cooling (profile shortening).

It was found that a minimum of 1/2 hour was required for the strain gage to stabilize after the temperature had become uniform.

C. Final Reading. Table 8-1.

Subsequent to the high temperature reading, the unit was allowed to cool and final readings recorded. It was found that approximately

one hour was required after room temperature was reached for the strain gage to stabilize. A corrective multiplier of 1.21 must be applied to the difference between cold and hot or initial and final strain gage meter readings.

D. Re-tests. Table 8-1.

Tests 2 and 3 repeated IV A, B, and C on the brazed plate and the results were recorded.

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TABLE 8-1
DATA SHEET-BRAZED PLATE, TEST 1

Temperature			Deflection				
Thermo- couple	Variac 60 G. P. N. 7 Air F & B	Variac 80 .7 G. P. N. Air F & B	Pos. No.	Initial; Room Temp.	70° + 10° Temp. Diff.	110° + 10° Temp. Diff.	Final; Room Temp.
1	75	75	1	(0.0979	(0.0989	(0.1016	(0.0982
2	110	110	2	(0.1020	(0.1123	(0.1026	(0.100
3	160	200	3	(0.1071	(0.1055	(0.1076	(0.1061
4	170	210	4	(0.1120	(0.1116	(0.1122	(0.1099
5	185	210	5	(0.1159	(0.1151	(0.1154	(0.1144
6	130	160	6	0.1049	0.1019	0.0992	0.1040
7	80	90	7	0.1090	0.1084	0.0985	0.1081
8	75	80	8	0.1203	0.1268	0.1345	0.1192
9	115	140	9	(0.1072	(0.1078	(0.1094	(0.1048
10	160	200	10	(0.1069	(0.1087	(0.1119	(0.1087
11	170	220	11	(0.1131	(0.1146	(0.1163	(0.1118
12	170	220	12	(0.1174	(0.1200	(0.1213	(0.1178
13	125	160	13	(0.1217	(0.1241	(0.1253	(0.1202
14	80	80	14	0.1052	0.1015	0.0969	0.1056
15	80	80	15	0.1151	0.1184	0.1204	0.1166
16	130	160	16	0.1283	0.1400	0.1497	0.1289
17	155	200	17	(0.1107	(0.1106	(0.1126	(0.1092
18	165	210	18	(0.1138	(0.1137	(0.1129	(0.1117
19	120	150	19	(0.1183	(0.1176	(0.1177	(0.1161
20	80	80	20	(0.1218	(0.1211	(0.1224	(0.1193
			21	(0.1245	(0.1242	(0.1248	(0.1227
			22	0.1102	0.1068	0.1010	0.1111
			23	0.1219	0.1258	0.1274	0.1233
			24	0.1315	0.1399	0.1441	0.1333
			25	(0.1282	(0.1270	(0.1255	(0.1266
			26	(0.1266	(0.1266	(0.1257	(0.1263
			27	(0.1268	(0.1297	(0.1274	(0.1276
			28	(0.1325	(0.1336	(0.1331	(0.1323
			29	(0.1358	(0.1372	(0.1368	(0.1356
			30	0.1326	0.1354	0.1381	0.1335
			31	0.1292	0.1276	0.1373	0.1270
			32	0.1252	0.1284	0.1247	0.1264

Strain Gage Readings				
Gage No.	Initial; Room Temp.	70° + 10° Temp. Diff.	110° + 10° Temp. Diff.	Final; Room Temp.
1	0-10 1660	0-12 0000	0-12 0160	0-12 0650
2	0-4 1200	0-4 1820	0-6 0025	0-6 0170
3	0-10 1360	0-10 1360	0-12 0100	0-12 0060
4	0-16 0180	0-16 0180	0-16 0870	0-16 0670

TABLE 8-1

DATA SHEET-BRAZED PLATE, TEST 2

Temperature			Deflection				
Thermo-couple	Variac 60 G. P. N. .7 Air F & B	Variac 80 .7 G. P. N. Air F & B	Pos. No.	Initial; Room Temp.	70°+10° Temp. Diff.	110°+10° Temp. Diff.	Final; Room Temp.
1	75	75	1		0.1004	0.0994	0.0993
2	110	130	2		0.1025	0.1030	0.1016
3	160	210	3		0.1067	0.1062	0.1085
4	170	220	4		0.1115	0.1120	0.1132
5	170	220	5		0.1172	0.1150	0.1165
6	130	170	6		0.1016	0.1001	0.1059
7	80	65	7		0.1098	0.1094	0.1099
8	80	60	8		0.1276	0.1358	0.1208
9			9		0.1071	0.1071	0.1053
10	160	205	10		0.1098	0.1125	0.1091
11	170	220	11		0.1144	0.1173	0.1141
12	170	220	12		0.1187	0.1218	0.1192
13	130	165	13		0.1237	0.1256	0.1222
14			14		0.1012	0.0959	0.1064
15	80	80	15		0.1179	0.1196	0.1167
16	125	170	16		0.1392	0.1491	0.1291
17	155	205	17		0.1098	0.1120	0.1078
18	160	220	18		0.1141	0.1140	0.1130
19	120	160	19		0.1174	0.1172	0.1170
20	80	80	20		0.1208	0.1202	0.1202
			21		0.1245	0.1258	0.1245
			22		0.1055	0.0991	0.1110
			23		0.1053	0.1053	0.1229
			24		0.1373	0.1451	0.1324
			25		0.1277	0.1256	0.1258
			26		0.1269	0.1261	0.1298
			27		0.1299	0.1274	0.1313
			28		0.1333	0.1322	0.1340
			29		0.1386	0.1401	0.1396
			30		0.1360	0.1434	0.1343
			31		0.1302	0.1387	0.1375
			32		0.1273	0.1271	0.1264

Strain Gage Readings				
Gage No.	Initial; Room Temp.	70°+10° Temp. Diff.	110°+10° Temp. Diff.	Final; Room Temp.
1		0-12 700	0-12 570	0-12 830
2		0-6 40	0-6 500	0-4 1910
3		0-10 1710	0-10 1750	0-10 1780
4		0-16 570	0-16 550	0-16 490

TABLE 8-1
DATA SHEET-BRAZED PLATE, TEST 3

Temperature

Deflection

Thermo- couple	70° + 10° Temp. Diff.	110° + 10° Temp. Diff.
1	75	75
2	110	125
3	165	190
4	180	200
5	175	200
6	130	150
7	75	80
8	75	80
9		
10	170	200
11	180	210
12	175	205
13	130	150
14		
15	80	80
16	130	160
17	170	200
18	170	210
19	130	155
20	80	80

Strain Gage Readings

Gage No.	Initial; Room Temp.	70° + 10° Temp. Diff.	110° + 10° Temp. Diff.	Final; Room Temp.
1	0-12 300	0-12 730	0-12 740	0-12 410
2	0-6- 650	0-6- 1030	0-6 900	0-6 170
3	0-10- 1850	0-10- 1830	0-10 1750	0-10 1770
4	0-16- 620	0-16- 450	0-16 390	0-16 280

Pos. No.	Initial; Room Temp.	70° + 10° Temp. Diff.	110° + 10° Temp. Diff.	Final; Room Temp.
1	0.0989	0.1016	0.1009	0.0975
2	0.1015	0.1033	0.1017	0.1023
3	0.1088	0.1068	0.1083	0.1057
4	0.1115	0.1156	0.1113	0.1108
5	0.1183	0.1151	0.1171	0.1171
6	0.1059	0.1031	0.1013	0.1060
7	0.1103	0.1105	0.1112	0.1108
8	0.1211	0.1298	0.1354	0.1220
9	0.1072	0.1095	0.1103	0.1062
10	0.1082	0.1128	0.1410	0.1098
11	0.1130	0.1173	0.1163	0.1130
12	0.1194	0.1191	0.1205	0.1175
13	0.1233	0.1222	0.1243	0.1226
14	0.1068	0.1004	0.1075	0.1076
15	0.1167	0.1195	0.1200	0.1183
16	0.1294	0.1421	0.1480	0.1314
17	0.1093	0.1103	0.1115	0.1102
18	0.1126	0.1247	0.1135	0.1145
19	0.1178	0.1166	0.1172	0.1163
20	0.1232	0.1197	0.1204	0.1192
21	0.1230	0.1244	0.1240	0.1217
22	0.1115	0.1037	0.1014	0.1120
23	0.1236	0.1251	0.1274	0.1243
24	0.1329	0.1400	0.1454	0.1341
25	0.1251	0.1283	0.1276	0.1259
26	0.1278	0.1293	0.1265	0.1263
27	0.1307	0.1301	0.1274	0.1278
28	0.1359	0.1350	0.1320	0.1327
29	0.1382	0.1403	0.1381	0.1374
30	0.1370	0.1397	0.1414	0.1350
31	0.1287	0.1284	0.1282	0.1295
32	0.1273	0.1266	0.1281	0.1279

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WAS INTENTIONALLY
LEFT BLANK

**8.2 DATA SHEETS FOR TESTS PERFORMED ON
TIG WELDED FUEL PLATE**

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

TABLE 8-2

WELDED PLATE, TEST 1

TEMPERATURE

Thermo-couple	20	40	60	80	100	120
1	65	70	70	75	80	80
2	80	90	110	130	145	160
3	90	110	140	175	200	220
4	100	115	145	185	210	230
5	95	110	140	180	200	220
6	80	95	120	140	165	185
7	65	65	70	70	70	70
8	65	65	70	70	70	70
9	80	80	95	100	105	105
10*	80	90	110	120	130	150
11	100	125	170	210	245	260
12	100	120	160	190	230	250
13	80	80	110	130	145	160
14	65	65	70	70	70	70
15	65	65	70	70	70	70
16	85	100	130	165	180	200
17	100	120	165	205	240	265
18	100	120	165	205	240	265
19	85	100	130	155	175	190
20	65	70	70	70	70	70

STRAIN GAGE

Gage No.	0°	20°	40°	60°	80°	100°	120°	0°
1	0-8-0920	0-8-1030	0-8-1050	0-8-1120	0-8-1190	0-8-1240	0-8-1180	0-8-0870
2	0-10-0870	0-10-0920	0-10-0960	0-10-1050	0-10-0860**	0-10-0860**	0-10-0530**	0-10-0250
3	0-12-0890	0-12-0970	0-12-1050	0-12-1250	0-12-1290	0-12-1310	0-12-1270	0-14-0080
4	0-12-0290	0-12-0270	0-12-0320	0-12-0410	0-12-0470	0-12-0520	0-12-0420	0-10-1820

* Inaccurate thermocouple

** Possible failure of gage

DEFLECTION

Position	0°	20°	40°	60°	80°	100°	120°	0°
1	0.1011	0.1023	0.1005	0.1010	0.1000	0.1022	0.1074	0.1049
2	0.1043	0.1064	0.1050	0.1044	0.1028	0.1052	0.1105	0.1087
3	0.1088	0.1102	0.1092	0.1094	0.1078	0.1095	0.1146	0.1146
4	0.1125	0.1140	0.1152	0.1132	0.1139	0.1140	0.1233	0.1189
5	0.1152	0.1187	0.1185	0.1163	0.1154	0.1189	0.1278	0.1243
6	0.1039	0.1000	0.1008	0.1088	0.0959	0.0957	0.0959	0.0966
7	0.1058	0.1016	0.1027	0.1094	0.0958	0.0958	0.0958	0.0947*
8	0.1111	0.1079	0.1087	0.1076	0.1074	0.1041	0.1010	0.1024
9	0.1100	0.1078	0.1094	0.1100	0.1142	0.1215	0.1344	0.1125
10	0.1111	0.1092	0.1111	0.1139	0.1168	0.1252	0.1396	0.1160
11	0.1136	0.1127	0.1129	0.1146	0.1204	0.1330	0.1453	0.1192
12	0.1180	0.1155	0.1158	0.1167	0.1216	0.1325	0.1450	0.1198
13	0.1187	0.1176	0.1185	0.1179	0.1221	0.1290	0.1369	0.1219
14	0.1169	0.1158	0.1172	0.1182	0.1214	0.1303	0.1400	0.1183
15	0.1176	0.1153	0.1165	0.1148	0.1112	0.1057	0.0959	0.1055
16	0.1205	0.1193	0.1189	0.1161	0.1110	0.0990	0.0959	0.1054
17	0.1208	0.1210	0.1206	0.1201	0.1239	0.1275	0.1298	0.1230
18	0.1232	0.1240	0.1250	0.1228	0.1245	0.1270	0.1336	0.1233
19	0.1261	0.1256	0.1247	0.1252	0.1260	0.1286	0.1319	0.1250
20	0.1300	0.1292	0.1275	0.1286	0.1279	0.1297	0.1320	0.1262
21	0.1336	0.1319	0.1297	0.1311	0.1308	0.1319	0.1305	0.1264
22	0.1338	0.1352	0.1360	0.1372	0.1442	0.1632	0.1718	0.1452
23	0.1387	0.1403	0.1415	0.1424	0.1473	0.1556	0.1583	0.1458
24	0.1391	0.1403	0.1410	0.1400	0.1361	0.1307	0.1102	0.1303
25	0.1324	0.1341	0.1353	0.1332	0.1348	0.1379	0.1335	0.1320
26	0.1355	0.1363	0.1361	0.1363	0.1365	0.1341	0.1338	0.1331
27	0.1384	0.1378	0.1376	0.1382	0.1391	0.1325	0.1330	0.1352
28	0.1400	0.1405	0.1401	0.1393	0.1414	0.1367	0.1364	0.1379
29	0.1417	0.1445	0.1418	0.1408	0.1435	0.1406	0.1369	0.1414
30	0.1400	0.1398	0.1398	0.1410	0.1470	0.1597	0.1707	0.1502
31	0.1348	0.1350	0.1338	0.1355	0.1335	0.1348	0.1357	0.1339
32	0.1316	0.1305	0.1292	0.1273	0.1232	0.1158	0.1086	0.1236

TABLE 8-2
WELDED PLATE, TEST 2

TEMPERATURE

Thermo- couple	20	40	60	80	100	120
1	65	65	70	75	75	80
2	80	90	115	135	150	165
3	90	120	155	180	210	235
4	90	125	160	185	215	245
5	90	120	155	180	210	235
6	80	95	120	140	155	170
7	65	65	70	70	70	70
8	65	65	70	70	70	75
9	75	85	100	105	110	115
10*	75	90	110	130	145	160
11	95	135	180	195	230	270
12	95	130	170	185	220	255
13	80	90	110	125	140	155
14	65	65	65	70	70	70
15	65	65	65	70	70	70
16	80	100	130	155	170	190
17	95	125	165	190	215	245
18*	95	125	170	?	280*	?
19	80	100	120	145	160	180
20	65	70	70	70	70	70

STRAIN GAGE

Gage No.	0°	20°	40°	60°	80°	100°	120°	0°
1	0-8- 0870	0-8- 0860	0-8- 0980	0-8- 0930	0-8- 0980	0-8- 0910	0-8- 0910	0-8- 0810
2	0-10- 0250	0-10- 0310	0-10- 0410	0-10- 0390	0-10- 0460	0-10- 0490	0-10- 0500	0-10- 0150
3	0-14- 0080	0-14- 0150	0-14- 0260	0-14- 0320	0-14- 0320	0-14- 0450	0-14- 0530	0-14- 0520
4	0-10- 1820	0-10- 1790	0-10- 1870	0-10- 1900	0-10- 1910	0-10- 1940	0-10- 1970	0-10- 1690

* Inaccurate thermocouple

DEFLECTION

Posi- tion	0°	20°	40°	60°	80°	100°	120°	0°
1	0.1309	0.1302	0.1302	0.1318	0.1319	0.1325	0.1359	0.1346
2	0.1329	0.1321	0.1314	0.1328	0.1329	0.1334	0.1384	0.1373
3	0.1386	0.1373	0.1364	0.1376	0.1389	0.1375	0.1397	0.1421
4	0.1426	0.1415	0.1410	0.1424	0.1419	0.1425	0.1446	0.1456
5	0.1451	0.1448	0.1444	0.1480	0.1487	0.1463	0.1494	0.1484
6	0.1193	0.1179	0.1156	0.1142	0.1123	0.1092	0.1020	0.1216
7	0.1141	0.1120	0.1088	0.1067	0.1023	0.0980	*0.0959	0.1140
8	0.1257	0.1251	0.1247	0.1259	0.1259	0.1263	0.1259	0.1256
9	0.1373	0.1376	0.1400	0.1426	0.1477	0.1500	0.1607	0.1378
10	0.1391	0.1392	0.1420	0.1459	0.1511	0.1558	0.1658	0.1390
11	0.1425	0.1426	0.1453	0.1509	0.1560	0.1611	0.1712	0.1410
12	0.1426	0.1433	0.1458	0.1503	0.1550	0.1595	0.1695	0.1433
13	0.1430	0.1437	0.1433	0.1473	0.1514	0.1547	0.1614	0.1412
14	0.1416	0.1426	0.1443	0.1473	0.1506	0.1540	0.1624	0.1407
15	0.1294	0.1282	0.1255	0.1229	0.1204	0.1170	0.1105	0.1275
16	0.1320	0.1290	0.1261	0.1217	0.1178	0.1140	0.1049	0.1290
17	0.1480	0.1471	0.1476	0.1492	0.1500	0.1503	0.1515	0.1473
18	0.1470	0.1465	0.1474	0.1493	0.1520	0.1523	0.1537	0.1467
19	0.1491	0.1480	0.1482	0.1502	0.1506	0.1529	0.1557	0.1473
20	0.1499	0.1490	0.1497	0.1507	0.1529	0.1538	0.1551	0.1486
21	0.1505	0.1510	0.1500	0.1527	0.1509	0.1533	0.1543	0.1486
22	0.1686	0.1693	0.1722	0.1770	0.1823	0.1880	0.1984	0.1686
23	0.1679	0.1673	0.1684	0.1705	0.1738	0.1740	0.1785	0.1662
24	0.1522	0.1500	0.1475	0.1441	0.1434	0.1393	0.1314	0.1513
25	0.1569	0.1576	0.1580	0.1572	0.1600	0.1582	0.1600	0.1576
26	0.1584	0.1582	0.1575	0.1584	0.1591	0.1615	0.1582	0.1567
27	0.1605	0.1595	0.1598	0.1601	0.1612	0.1625	0.1617	0.1587
28	0.1629	0.1615	0.1614	0.1614	0.1624	0.1643	0.1636	0.1637
29	0.1642	0.1637	0.1657	0.1648	0.1637	0.1655	0.1650	0.1635
30	0.1723	0.1732	0.1766	0.1806	0.1830	0.1847	0.1965	0.1729
31	0.1551	0.1542	0.1557	0.1573	0.1555	0.1535	0.1560	0.1550
32	0.1450	0.1432	0.1428	0.1402	0.1435	0.1387	0.1307	0.1448

TABLE 8-2
WELDED PLATE, TEST 3

TEMPERATURE

Thermo- couple	20	40	60	80	100	120
1	70	70	70	75	75	75
2	80	90	110	135	150	160
3	95	120	150	185	210	230
4	95	120	160	190	220	235
5	95	115	150	180	210	230
6	80	95	115	140	150	165
7	85	85	70	70	70	70
8	85	85	70	70	70	70
9	80	85	100	105	110	125
10*	85	90	110	130	145	160
11	100	130	180	210	240	275
12	95	125	165	200	225	260
13	80	90	110	125	140	155
14	85	85	70	70	70	70
15	85	70	70	70	70	70
16	85	100	130	155	175	175
17	95	125	165	195	225	240
18*	100	125	?	?	?	?
19	80	100	125	150	160	165
20	70	70	70	70	70	70

STRAIN GAGE

Gage No.	0°	20°	40°	60°	80°	100°	120°	0°
1	0-8- 0810	0-8- 0740	0-8- 0920	0-8- 1000	0-8- 1040	0-8- 1050	0-8- 0780	0-8-
2	0-10- 0150	0-10- 0210	0-10- 0260	0-10- 0340	0-10- 0380	0-10- 0430	0-10- 0430	0-8- 1830
3	0-14- 0520	0-14- 0640	0-14- 0760	0-14- 0880	0-14- 0930	0-14- 1010	0-14- 1100	0-14- 0920
4	0-10- 1690	0-10- 1690	0-10- 1730	0-10- 1780	0-10- 1810	0-10- 1850	0-10- 1900	0-10- 1640

* Inaccurate thermocouple

DEFLECTION

Posi- tion	0°	20°	40°	60°	80°	100°	120°	0°
1		0.1349	0.1352	0.1353	0.1359	0.1368	0.1394	0.1346
2		0.1366	0.1366	0.1371	0.1361	0.1375	0.1413	0.1414
3		0.1418	0.1415	0.1421	0.1405	0.1413	0.1437	0.1430
4		0.1470	0.1459	0.1466	0.1482	0.1489	0.1484	0.1475
5		0.1526	0.1492	0.1491	0.1492	0.1505	0.1533	0.1505
6		0.1215	0.1179	0.1157	0.1119	0.1084	0.1041	0.1230
7		0.1116	0.1086	0.1050	0.1004	0.0959*	0.0959*	0.1149
8		0.1242	0.1240	0.1246	0.1246	0.1264	0.1274	0.1261
9		0.1392	0.1398	0.1434	0.1476	0.1510	0.1635	0.1380
10		0.1389	0.1418	0.1471	0.1529	0.1543	0.1688	0.1392
11		0.1424	0.1454	0.1522	0.1577	0.1583	0.1752	0.1415
12		0.1427	0.1450	0.1505	0.1588	0.1580	0.1015	0.1414
13		0.1444	0.1432	0.1467	0.1503	0.1506	0.1615	0.1405
14		0.1410	0.1425	0.1465	0.1503	0.1510	0.1640	0.1397
15		0.1250	0.1232	0.1207	0.1169	0.1195	0.1092	0.1357
16		0.1262	0.1237	0.1191	0.1142	0.1166	0.0998	0.1286
17		0.1463	0.1464	0.1468	0.1500	0.1514	0.1542	0.1484
18		0.1451	0.1463	0.1466	0.1492	0.1515	0.1540	0.1450
19		0.1475	0.1486	0.1493	0.1497	0.1540	0.1544	0.1467
20		0.1479	0.1483	0.1487	0.1497	0.1535	0.1538	0.1500
21		0.1486	0.1479	0.1505	0.1483	0.1528	0.1520	0.1484
22		0.1688	0.1711	0.1776	0.1825	0.1823	0.2002	0.1656
23		0.1871	0.1884	0.1707	0.1731	0.1732	0.1794	0.1660
24		0.1500	0.1483	0.1443	0.1409	0.1482	0.1337	0.1527
25		0.1571	0.1582	0.1581	0.1601	0.1611	0.1609	0.1584
26		0.1593	0.1581	0.1586	0.1598	0.1606	0.1601	0.1590
27		0.1586	0.1599	0.1585	0.1586	0.1617	0.1615	0.1612
28		0.1607	0.1634	0.1614	0.1620	0.1633	0.1622	0.1630
29		0.1625	0.1649	0.1616	0.1625	0.1667	0.1667	0.1660
30		0.1736	0.1785	0.1813	0.1852	0.1835	0.1907	0.1723
31		0.1548	0.1540	0.1557	0.1550	0.1588	0.1552	0.1559
32		0.1426	0.1413	0.1402	0.1354	0.1395	0.1320	0.1437