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**STRUCTURAL TESTING
OF
SM-2 FUEL ELEMENTS**

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ALCO PRODUCTS, INC.

NUCLEAR POWER ENGINEERING DEPARTMENT
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**STRUCTURAL TESTING
OF
SM-2 FUEL ELEMENTS**

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ABSTRACT

Ability of the originally designed SM-2 stainless steel fuel elements, of both tungsten inert gas (TIG) and electrical resistance welded construction, to withstand static transverse pressure gradients of normal reactor operation was investigated. Fourteen simulated original SM-2 type fuel elements made by these two welding processes were subjected to pressure gradients to 6 psi (12 in. Hg), measured for deflection during stress, and for distortion after stress. Tests provided a basis for selecting a reference SM-2 fuel element design, and established a method of predicting maximum plate deflections under anticipated SM-2 operating conditions.

Results showed that: (a.) TIG welded elements, slightly more prone to deflection, are preferred for SM-2 application because they are less susceptible to weld failure; (b.) fuel plate thickness is the most significant parameter in determining plate strength; (c.) equalizing the length of the outer and inner plates significantly reduces maximum plate deflection; and (d.) effects of weld spacing and side plate thickness were not significant within the pressure range of the tests.

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1.0 SUMMARY AND CONCLUSIONS

SM-2 fuel element structural tests performed as part of Task 6.0 consisted of subjecting 14 welded stainless steel fuel elements to transverse pressure gradients under simulated reactor operating conditions.

While results of constant pressure gradient deflection measurements on the outside plates favored resistance welded fuel elements because their ability to withstand pressure gradients equalled or slightly exceeded TIG welded elements, they were less reliable⁵, and removed from present consideration by the Task 5 program. It was felt that production of reliable, high quality elements by this technique would first require an extensive development program. Therefore, TIG welded fuel lattices containing 0.040-in. thick fuel plates, 0.030 to 0.040-in. side plates and 2 to 4-in. weld spacings are recommended as the best choice of those tested for SM-2 application.

Conclusions drawn from results of tests on TIG welded elements are:

1. Under uniform pressure gradient, fuel element thickness had the largest effect on fuel plate deflection characteristics. The 0.040-in. stainless steel plate produced roughly half the deflection of similar 0.030 in. plate. At 6 in. Hg. pressure loading, average deflections of 0.040-in. plates ranged from 0.007 to 0.010 in. Beyond 4 in. Hg., deflection of 0.030-in plate rapidly exceeded 0.010 in. Though stainless clad matrix fuel plates were not directly tested, a similar relationship is anticipated for these.
2. After application of 12 in. Hg pressure loading, permanent distortion noted for 0.040-in. elements exhibiting no weld failure ranged from 0.00065 in. to 0.0025 in. After an applied pressure of 10 in. Hg., the 0.030 in.plate exhibited abnormal distortion (0.018 in. at 12 in. Hg.).
3. Maximum deflection and distortion occurred at and near the ends of outside fuel plate lengths beyond the edges of the inner fuel plates.
4. Under equivalent conditions, stainless clad matrix elements deflected approximately 31% more than those of solid stainless steel (annealed).
5. Annealed stainless steel plates deflected approximately 18% more than 40% cold-rolled plate of the same dimensions.
6. Weld spacing and side plate thickness were not significant within the range tested.

7. An empirical expression was derived to approximate anticipated average deflection at the fuel plate centerline under the pressure gradient range of this evaluation. The expression was:

$$\zeta_c = \frac{3.32 w l^4}{384 EI}$$

where

- ζ_c = average deflection at plate centerline, in.
 w = uniformly applied load, lb/in.
 l = plate width, in.
 E = modulus of elasticity, lb/in.²
 I = moment of inertia, in.⁴

The value of E was established for:

Annealed stainless steel	28.4×10^6 psi
Stainless steel clad (0.005 in.) UO ₂ - stainless steel matrix (25-75 s/o) (0.030 in.)	24.2×10^6 psi

Below the yield point, the beam equation for two fixed ends correlated highly with data on brazed fuel elements from ORNL.⁷

8. The quantitative effect of a linear variation of pressure gradient along the length of the plate was not obtained, and attempts to simulate core conditions were not successful; however, the qualitative effect concurred with constant pressure gradient measurements.
9. Maximum deflections were noted in that portion of the longitudinal ends of the outer fuel plate that extends beyond the internal fuel plates. It is recommended that outer plates be reduced to the same length as internal plates, to equalize flow within the fuel element and flow in the lattice passages, and reduce expected deflection of the outside fuel plate. This has been adopted as reference design for the SM-2 fuel element. (See Fig. 1.)

Fig. 1 Reference SM-2 Fuel Element Design

2.0 INTRODUCTION

This report covers fuel element structural experiments conducted as part of the SM-2 Core Development Program, Task 6, which covers pressure drop, mechanical stress and deflection analysis of reactor fuel elements and associated structures. Experimental data concerning fuel plate deflection under lateral pressure gradients is presented and analyzed.

The furnace brazed SM-1 reference design fuel element (Fig. 2) was totally enclosed in a shroud; coolant flowed through the element in the shroud and the lattice area between the shrouds. Low flow rates (1/3 SM-2 element flow) did not present a problem in plate (0.030 in. thick) or shroud deflection.

The original SM-2 fuel element design abandoned the shroud, and exposed the outside plates of each element to lattice flow (Fig. 3). Coolant flows through both elements and lattice passages; since lattice flow differs from fuel element flow, significant pressure differentials across the outside fuel plate of the element are possible. In this design, the largest transverse pressure gradients can exist across the outside plates of each element, thus producing the largest deflections. Development studies indicated the desirability of fabricating stainless steel plate-type fuel elements by welding rather than by furnace brazing. Study of two welding methods for fuel element fabrication was proposed: (a) electrical resistance welding, and (b) inert gas tungsten arc welding (TIG).

Structural experiments were performed to aid development of a reliable fuel element made by either process. Deflection measurements were taken on the outside fuel plates while the plates were subjected to pressure gradients across the plate faces, and again after the loading was removed. In an effort to simulate reactor operating conditions, deflection was measured at various longitudinal points as the plates were stressed along their length by a linearly varying pressure gradient.

An empirical expression, derived from the test data to approximate the deflection of outside plates under a given pressure gradient, was correlated with ORNL test data.⁶

Fig. 3 Original SM-2 Fuel Element Design

3.0 DESIGN OF EXPERIMENTAL FUEL ELEMENTS

Fourteen fuel elements, representing 11 different designs, were chosen for the study. Twelve elements were of solid stainless steel, the remainder depleted UO_2 (25% matrix weight) stainless steel plates, clad in 0.005-in. stainless.

In addition to welding methods and fuel plate composition, other variables included in the design of the experiment were:

1. Weld Spacing

TIG - 1/2 in. long welds on 2, 3, and 4 in. pitches (Fig. 4).
Welds on the sides are alternated along the plate length.
Resistance - Spot Welds 3/4 and 1 in. apart (Fig. 3).

2. Heat Treatment

Before annealing, each fuel plate was cold-rolled. Only one of the test specimens was not stress relieved before the welding process.

3. Side plate thickness

All side plates to be resistance welded were 0.025 in. thick, a dimension dictated by requirements of the process. TIG welded side plates varied in thickness from 0.025 in. to 0.040 in.

4. Fuel plate thickness

One element had a fuel plate thickness of 0.030 in., and a 11 others were 0.040 in. Matrix elements had a meat thickness of 0.030 in. with 0.005 in. clad on each face.

The 14 elements chosen for this study, each consisting of 16 inside plates 23 in. long and 2 outside plates 27 in. long, bound together by 2 side plates, are presented in detail in Table 1.

Fig. 4 Weld Orientation on Element Side Plates

TABLE 1
SUMMARY OF TEST FUEL ELEMENT CHARACTERISTICS

Element Identity	Weld Process	Plate Material	Heat Treatment	Side Plate Thick (in.)	Fuel Plate Thick (in.)	Weld Length (in.)	Weld Spacing (in.)
1	TIG	SS**	Ann. ¹	0.030	0.030	1/2	3
2-2	TIG	SS	Ann.	0.030	0.040	1/2	3
4	TIG	SS	Ann.	0.030	0.040	1/2	3
5	RES	SS	Ann.	0.025	0.040	---	3/4
5R	RES	SS	Ann.	0.025	0.040	---	3/4
C	RES	SS	Ann.	0.025	0.040	---	3/4
6	TIG	UO ₂ -SS***	Ann.	0.030	0.040	1/2	3
10	TIG	SS	Ann.	0.025	0.040	1/2	3
11	TIG	SS	Ann.	0.040	0.040	1/2	3
11R	TIG	SS	Ann.	0.040	0.040	1/2	3
12	TIG	SS	Ann.	0.030	0.040	1/2	2
13	TIG	SS	Ann.	0.030	0.040	1/2	4
17	RES	SS	Ann.	0.025	0.040	---	1
26	TIG	UO ₂ -SS***	C.R. ²	0.040	0.040	1/2	3

** Stainless Steel

*** Depleted UO₂ Stainless steel meat clad with stainless steel

1. Annealed fuel plates

2. Cold rolled fuel plates (40% reduction in cross-sectional area)

4.0 EXPERIMENTAL PROCEDURES

4.1 DEFLECTION MEASUREMENTS WITH CONSTANT PRESSURE GRADIENTS

4.1.1 Whole Plate Measurements

Deflection measurements of the outside fuel plates of each test element were taken for nine different pressure gradients across the plate face. At 3 of the 9 differential pressures applied, 33 points in 17 locations along the outside surface of the fuel plate were measured. At the other differential pressures, only 15 points in 5 locations were measured. A schedule of the procedure was:

<u>Pressure Differential</u> <u>(in. Hg.)</u>	<u>15 Measurements</u>	<u>33 Measurements</u>
0.5	x	
1.0	x	
1.5	x	
2.0		x
4.0	x	
6.0		x
8.0	x	
10.0	x	
12.0		x

Location of the 33 measurements is indicated in Fig. 5. The 15 points at 5 different locations were taken at plate center, 5 in. from plate center, and 10.5 in. from plate center. A description of the test apparatus is given in Fig. 6.

Fig. 5 Outside Fuel Plate Measurement Locations

Fig. 6 Static Deflection Test

The fuel elements were tested in a horizontal position with extremities clamped to prevent lateral restraint of the ends of the outside fuel plates. To simulate anticipated SM-2 design, dial micrometer measurements were taken before, during, and after each pressure differential was applied, and loading was reduced to zero before proceeding on to the next pressure. The outside plates of each fuel element were given the full series of tests consecutively, and air under constant pressure was continuously bled through the test fuel element.

4.1.2 Small Interval Measurements

Deflection measurements were taken at intervals along a portion of the plate to observe deflection change as a result of weld position, and determine the probable position of maximum deflection. Seventeen measurements of element 11 R, at 6 in. Hg. pressure, were taken with a dial micrometer at 0.5 in. intervals over a total length of 2 inches. Location of test points is indicated in Fig. 7.

4.1.3 Whole Plate Measurements with One End Restrained

Elements 4, 5 and 6 were subjected to 6 in. Hg. with one end restrained, and measured along the centerline at intervals of 1.5 in.

4.2 DEFLECTION MEASUREMENTS WITH LINEARLY VARYING PRESSURE GRADIENTS

As the reactor core fuel element, unrestrained at both ends, will experience a linearly varying pressure gradient along the length of the outside fuel plates, a test (Fig. 8) was designed to measure fuel plate deflection in this condition. The varying pressure gradient was simulated by mounting elements 4, 5 and 6 vertically, sealing the bottom, and filling the element with a liquid. To obtain different pressure gradients, two liquids were used; water (density 1.0 gm/cc) and tetrabromoethane (density 3.0 gm/cc). Deflection measurements before and after the element was filled with liquid were taken at 1.5 in. intervals along the centerline length of the outside fuel plates. Measurements taken with tetrabromethane as the contained liquid were obtained simultaneously on both outside plates.

However, sealing the bottom and the four corners on the side with a hard-setting cement restrained the element. In an attempt to evaluate the results of these tests, the same test elements were examined under a constant pressure gradient with one end laterally restrained, as described in Section 4.1.3. The results were then compared with the results of the same test element having unrestrained ends.

Fig. 7 Deflection Readings for 1/4 in. Increments Across Weld Positions at Plate Centerline Element 11-R

Fig. 8 Linear Pressure Gradient Rig

4.3 EVALUATION OF MODULUS OF ELASTICITY

Tests were made to establish an effective modulus of elasticity for fuel plate types, and to obtain an empirical expression for deflection under pressure gradient stress.

The fuel plate was supported by two knife edges spaced 22 in. apart along the length of the plate. Loading was applied in 4 oz. increments at the center of the plate between the knife edges, and deflection measurements taken at each load, including zero. When total deflection reached 1 in., the load was reduced to zero by 4 oz increments.

5.0 EXPERIMENTAL RESULTS

5.1 DEFLECTION MEASUREMENTS WITH CONSTANT PRESSURE GRADIENTS

5.1.1 Whole Plate Measurements

Deflection data obtained over the length of each element was averaged to give a mean deflection for each pressure loading; results are presented in Table 2. A graph of front, back, and average deflections of a typical element (Number 2-2) is presented in Fig. 9. To obtain a smooth curve through these data points, a least square analysis² was made, using a cubic equation to describe fuel plate deflection along the plate length. Fig. 10 indicates the results of this analysis on element No. 2-2 at 2 in., 6 in., and 12 in. Hg. pressure. Deflection curves at other pressures were plotted through the average of front and back plate deflections. Except for initial low pressure gradient measurements, graphs of the data generally indicate direct proportionality of deflections to load. Imperfections in plate flatness and increased dial gage error existing at low pressure gradients did not permit the extended straight line portion of each plot to pass through the origin. This was compensated for by parallel transposition (See Fig. 11); also, higher loads smoothed out the curves.

TABLE 2. - AVERAGE OUTSIDE FUEL PLATE DEFLECTION vs. PRESSURE LOADING

(Deflection given in thousandths of an inch)

OUTSIDE FUEL PLATE ELEMENT IDENTITY

PRESSURE LOADING (in Hg.)	1	2-2	4*	5	5R	C	6	10	11	11R	12	13	17**	26
0.5	1.24	0.67	0.74	0.55	0.60	0.29	0.25	0.74	2.47	0.32	0.28	0.69	1.78	0.58
1	2.16	1.01	1.65	0.79	0.73	0.52	0.70	1.40	2.94	0.69	0.74	1.43	2.02	1.45
1.5	3.47	1.46	1.78	1.43	1.39	0.89	2.11	2.14	3.67	1.67	1.32	2.08	3.86	2.01
2	3.93	2.07	2.83	2.74	1.85	1.16	4.33	2.78	4.15	3.38	2.39	2.72	1.05	2.39
4	9.75	4.82	5.20	5.74	3.87	7.68	6.57	5.39	6.90	7.65	5.16	5.93	7.54	5.49
6	17.96	7.17	8.36	8.04	5.89	9.00	10.33	8.06	9.46	9.83	7.88	8.40	7.09	8.02
8	24.06	10.04	- -	9.48	8.60	9.02	11.09	10.61	11.68	13.37	10.10	11.65	11.83	10.92
10	29.84	12.23	- -	12.03	10.86	11.95	16.74	13.44	14.08	15.44	12.40	15.66	17.93	13.60
12	35.41	14.83	- -	14.56	12.97	13.07	22.45	16.56	16.68	18.59	14.83	17.49	- -	16.48

* No Data was taken above 6 in Hg.

** Back plate data given only. Front plate failed as pressure loading approached 12 in. Hg.

Fig. 9 Average Outside Fuel Plate Deflection Vs. Length for Three Pressure Loadings, Element 2-2

Fig. 10 Least Square Cubic Polynomial Approximation Plate Deflections Vs. Length

Fig. 11 Least Square Linear Approximation of Load Deflection Characteristics for all Elements

To obtain linear plots which best fit the data, the method of least squares was used.³ According to this method, the linear plot had the form

$$\zeta = mP + b$$

where

$$P = \text{pressure in Hg.}$$

$$m = \frac{N_b}{D} = \text{Slope}$$

$$b = \frac{N_a}{D} = \text{Ordinate Intercept}$$

and

$$D = \begin{vmatrix} n & \sum P \\ \sum P & \sum P^2 \end{vmatrix} \quad n = \text{number of values of } P$$

$$N_b = \begin{vmatrix} n & \sum \zeta \\ \sum P & \sum P\zeta \end{vmatrix}$$

$$N_a = \begin{vmatrix} \sum \zeta & \sum P \\ \sum P\zeta & \sum P^2 \end{vmatrix}$$

Consider this data from measurements on elements 10:

<u>P (in. Hg.)</u>	<u>ζ (inches)</u>	<u>P²</u>	<u>P ζ</u>
<u>(Data taken from Table 2)</u>		<u>(Calculated values)</u>	
0.5	0.00074	0.25	0.00037
1	0.00140	1.00	0.00140
1.5	0.00214	2.25	0.00321
2	0.00278	4.0	0.00556
4	0.00539	16.0	0.02156
6	0.00806	36.0	0.04836
8	0.01061	64.0	0.08488
10	0.01344	100.0	0.13440
12	0.01665	144.0	0.19980

$$\sum P = 45.0 \quad \sum \zeta = 0.06121 \quad \sum P^2 = 367.5 \quad \sum P\zeta = 0.49954$$

$$D = \begin{vmatrix} 9 & 45 \\ 45 & 367.5 \end{vmatrix} = 1282.5$$

$$N_b = \begin{vmatrix} 9 & 0.06121 \\ 45 & 0.49954 \end{vmatrix} = 1.74141$$

$$N_a = \begin{vmatrix} 0.06121 & 45 \\ 0.49954 & 367.5 \end{vmatrix} = 0.015375$$

$$\text{and } m = \frac{1.74141}{1282.5} = 0.0013578$$

$$b = \frac{0.015375}{1282.5} = 0.000011988$$

The least square fit for element 10 was:

$$\zeta = 0.0013578 P + 0.000011988$$

This analysis was used to establish all 14 graphs in Fig. 11.

Typical load curves (as element 2-2, Figs. 9 and 10) show greater deflection at and near the ends of the test element than at the center, because, in the 2 in. outside plate extension, the side plates are prone to bend laterally in response to bending moment at the edges of the outside plates. Higher pressure gradients result in increased deflection near the extremities.

The amount of permanent distortion in each fuel plate was obtained by using the averaged data presented in Table 2. For each pressure loading on each test sample, the average distortion was computed. This information is presented in Table 3.

TABLE 3 - AVERAGE OUTSIDE FUEL PLATE PERMANENT DISTORTION VS. PRESSURE LOADING

(Permanent Distortion Given in Thousandths of an Inch)

Outside Fuel Plate Element Identity

Pressure Loading (in. Hg.)	1	2-2	4*	5	5R	C	6	10	11	11R	12	13	17**	26
0.5	0.15	0.07	0.28	-0.48	-0.24	0.09	0.05	0.03	1.87	0.09	-0.34	-0.09	1.18	0.08
1	0.17	-0.31	0.28	-0.10	-0.25	0.21	0.09	0.19	1.43	0.37	-0.16	-0.07	-1.38	0.13
1.5	0.40	-0.37	-0.12	-0.33	-0.23	0.35	0.39	0.25	1.50	1.09	-0.09	-0.13	-0.44	0.15
2	0.95	-0.05	-0.31	1.43	-0.17	0.68	1.41	-0.14	2.06	2.13	0.78	0.27	-1.45	-0.34
4	2.10	0.12	0.04	1.40	-0.24	3.80	1.85	0.08	2.18	2.70	0.10	-0.01	2.82	0.93
6	4.05	0.03	----	1.31	0.44	1.65	2.79	-5.72	1.98	3.52	0.88	0.38	3.51	0.16
8	5.19	0.30	----	1.52	0.66	2.56	4.58	0.20	2.16	6.56	0.64	0.62	6.38	0.54
10	9.80	0.56	----	2.58	0.84	4.20	6.09	1.43	2.31	8.40	0.87	0.68	6.90	0.60
12	18.55	1.13	----	1.68	1.36	10.27	8.80	2.40	3.56	9.56	1.64	0.99	----	0.65

* No data was taken above 6 in. Hg.

** Back plate data given only. Front plate failed as pressure loading approached 12 in. Hg.

Examination of Fig. 12, showing the retained deflection of seven fuel element outside plates after removal of load in the range of 0-2 in Hg., shows erratic data points due to imperfections in initial flatness of the plates. Depending on the direction of these irregularities, certain plates subject to local buckling under pressure did not return to original conformation on relaxation of load. However, a definite deflection pattern was noted at higher load pressures (2 in. Hg.) and influence of irregularities became unimportant as the plate was stressed by higher pressures. Fig. 12 indicates a gradually increasing permanent distortion with increasing applied pressure gradients.

Table 3 shows that elements 1, C, 6, 11R, and 17 retained abnormally large deflections after pressure gradients were relaxed. The following information was noted for the elements showing this poor strength property: element 1 consisted of 0.030 in. fuel plates; element 6 was an annealed, stainless steel-clad matrix element; elements C, 11R and 17 contained faulty welds. The remainder exhibited no abnormal stress distortion, which indicates that welded elements can effectively resist distortion at pressure loadings up to 12 in. Hg.

5.1.2 Small Interval Measurements

Fig. 7 shows the portion of 11R where data was taken at 0.5 in. intervals with respect to welds. Local deflections pictured above the test locations are measured at 6 in. Hg. pressure gradient and graphically compared with the curve of average deflections measured over the entire element length as described in Section 5.1.1. Weld location had no apparent effect on deflection.

The discrepancy between local and overall pressure measurement (~ 0.03 inch) was due to the pressure of permanent deformation after tests over the length of the plate. Deflection measurements using new zero loading data did not show this difference.

5.2 DEFLECTION MEASUREMENTS WITH LINEARLY VARYING PRESSURE GRADIENTS

Fixed element 4 was used to establish the effect of a linearly varying pressure gradient along the length of the fuel plate. Average of front and back plate deflections versus element length were plotted (Fig. 13). Pressure gradients applied were 0 to 0.92 psi for contained water and 0 to 2.70 psi for contained tetrabromoethane. Data on element 6 was included for comparison. Fig. 14 contains deflection data for Elements 4 and 6 with one end restrained when a constant pressure gradient (6 in. Hg. or 3 psi) was applied. Fig. 15 and 16 contain information of Figs. 13 and 14 plotted as the best cubic fit to data of element 4.

Fig. 12 Average Outside Plate Permanent Distortion Vs. Pressure Loading

Fig. 13 Linear Pressure Gradient Variance Across Plate, Plate Deflection Vs. Height above Base of Liquid-Filled Elements

Fig. 14 Comparison of Deflection Vs. Length Measurements for One End Restrained Vs. Unrestrained Ends, Elements 4 and 6

Fig. 15 Least Square Cubic Approximation to Deflection Vs. Length Curves, Element 4, for Linearly Varying Pressure Gradient

Fig. 16 Least Square Cubic Approximation to Deflection Vs. Length Curves, Element 4, for One End Restrained Constant Pressure Gradient Vs. Unrestrained Ends

Since the final design of the SM-2 element (Fig. 1) is not restrained at the ends, a correction from the restrained to the unrestrained condition was computed from the least square cubic fit curves of Fig. 16. New curves were made of the computed unrestrained deflection of the elements (Fig. 17). Unrestrained deflection could not be computed for Fig. 14 due to extreme difficulties in achieving effective sealing compound control; however, the qualitative result of increasing deflection as a function of increasing pressure gradient (expressed as a function of liquid height and density) was noted.

5.3 EVALUATION OF MODULUS OF ELASTICITY

The modulus of elasticity was determined for a solid plate and a plate containing depleted UO_2 by solving the basic equation for the deflection of a simply supported beam with a concentrated load at the center.

$$\zeta = \frac{PL^3}{48 EI}$$

where

- E = modulus of elasticity, lbs/in.²
 I = moment of inertia of the plate about its axis, in.⁴
 P = concentrated load weight, lb
 L = distance between knife edges, in.
 ζ = deflection of beam under load, in.

Deflection measurements were obtained and applied to the above equation:

$$\begin{aligned} L &= 22 \text{ in.} & L^3 &= 10.63 \times 10^3 \text{ in.}^3 \\ I &= \frac{2.80 \times (0.040)^3}{12} & &= 14.95 \times 10^{-6} \text{ in.}^4 \end{aligned}$$

Solving E for the solid stainless steel plate (annealed):

$$\begin{aligned} P &= 2.00 - 0.264 \text{ (gage resistance)} = 1.736 \text{ lbs} \\ \zeta &= 0.906 \text{ in. (measured)} \\ E &= \frac{1.736 \times 10.63 \times 10^3}{48 \times 0.906 \times 14.95 \times 10^{-6}} = 28.4 \times 10^6 \text{ psi} \end{aligned}$$

Fig. 17 Outside Plate Deflection Vs. Height Above Element 4,
Base Connected to Unrestrained End

This compared with a published value of 28.5×10^6 psi for 347 stainless steel.
For the plate containing depleted UO_2 :

$$P = 1.5 - 0.26 = 1.24 \text{ lbs}$$

$$\zeta = 0.869 - 0.109 \text{ (retained deflection)} = 0.760 \text{ in.}$$

$$E = \frac{1.24 \times 10.63 \times 10^3}{48 \times 0.760 \times 14.95 \times 10^{-6}} = 24.2 \times 10^6 \text{ psi}$$

As no values were found in the literature for elements of this type, direct comparison was not possible.

6.0 ANALYSIS OF DATA

6.1 RESISTANCE VERSUS TIG WELDED ELEMENTS

Four resistance welded fuel elements, numbers C, 5, 5R, and 17, were compared with a TIG welded element, number 10. These elements were chosen because they varied only in method of welding. Figure 18 indicates the deflection versus load characteristics of each as described by the linear least square fit equation (Section 5.1.1).

It is noted that the resistance welded elements (5, 5R and C) having 3/4-in. spacing between welds exhibited less outside plate deflection under pressure than the TIG welded element; however, when the designs were compared as self-sufficient units without reference, the other variables showed that within the accuracy of the measurements and analyses, the two methods exhibited comparable deflection patterns. As the metallurgical group indicated that an extensive development program would be essential to produce a consistently reliable resistance welded element, this method was dropped from present consideration, and testing was concentrated on TIG welded elements.

6.2 EFFECT OF PLATE MATERIAL

The effects of stainless steel and stainless clad UO₂ plates were analyzed by comparing the linear load deflection characteristics of TIG welded elements 4 and 6, which are identical in all respects except plate material. Element 4 was solid stainless steel and element 6 contained the UO₂ stainless steel matrix.

Since the plots are linear, the ratio of the slopes of the two curves (Fig. 19) will indicate relative strength. The ratio of the slopes:

$$\frac{\text{Element 6 Slope}}{\text{Element 4 Slope}} = \frac{0.00178}{0.00136} = 1.31$$

indicated that, under constant pressure differential, matrix type plate deflects 31% more than annealed stainless steel plate.

Fig. 18 Comparison of Least Square Linear Deflection Vs. Load Characteristics of Resistance Welded Elements and a TIG-Welded Element

Fig. 19 Load Deflection Characteristics Showing Effects of Plate Material and Heat Treatment

6.3 EFFECT OF HEAT TREATMENT

The influence of fuel plate heat treatment on deflection characteristics of outside fuel plates was established by studying derived load deflection characteristics of elements 11 and 26, and making use of the expression derived for the effect of plate material. Element 26 resembled element 11 except in heat treatment and plate material. The points of difference are indicated below:

<u>Element</u>	<u>Plate Material</u>	<u>Heat Treatment</u>
11	SS	Annealed
26	SS-UO ₂	40% Cold Rolled
x	SS-UO ₂	Annealed

Element X was hypothetically derived from element 11 characteristics by methods described in Section 6.2.

$$\frac{\text{Element X Slope}}{\text{Element 11 Slope}} = 1.31 = \frac{X}{0.001239}$$

$$X = 0.001623$$

The ratio of X to element 26 provides a comparison between elements differing only in heat treatment.

$$\frac{\text{Element X Slope}}{\text{Element 26 Slope}} = \frac{0.001623}{0.001376} = 1.18$$

Under identical loading annealed plates deflected 218% more than 40% cold-rolled plates (Fig. 19).

6.4 EFFECT OF WELD SPACING

The directly comparable elements chosen for a study of the weld spacing effect were:

Element 4	3 inch weld spacing
Element 12	2 inch weld spacing
Element 13	4 inch weld spacing

Figure 20 shows that the three elements behaved as expected, as elements with the closest weld spacing exhibited the least deflection. The choice of thickness for SM-2 application is not important with respect to meeting structural testing requirements.

6.5 EFFECT OF SIDE PLATE THICKNESS

TIG test specimens 4, 10, and 11, differing only in side plate thickness, were chosen for this study.

Element 4	0.030 inch side plate thickness
Element 10	0.025 inch side plate thickness
Element 11	0.040 inch side plate thickness

The effect of side plate thickness was evaluated by reference to Fig. 20, which shows that deflection resistance strength of the fuel element was slightly improved by increasing side plate thickness.

6.6 EFFECT OF FUEL PLATE THICKNESS

TIG fuel plate elements 1 and 4 used for this comparison differed only in fuel plate thickness.

Element 4	0.040 inch fuel plate thickness
Element 1	0.030 inch fuel plate thickness

Analysis of Fig. 20 showed that the slope of the load deflection curves was more than doubled by reducing the fuel plate thickness from 0.040 in. to 0.030 in. When the fuel plate was analyzed as a beam under stress, this ratio was predicted by the analysis.

No direct comparison was available for stainless steel-clad UO_2 - SS matrix elements of various thicknesses. Since the clad in each case would be 0.005 in. thick, some question existed concerning application of analysis on solid stainless steel plates to the actual fuel plates. It was established in section 6.2 that the 0.040 in. thick matrix element deflected 31% more than the solid element. As the ratio of matrix element clad thickness to total thickness of the solid element is 1 to 4, it is seen that the UO_2 - stainless steel meat contributed significantly to element strength. A similar comparison of 0.030 in. plate should indicate that the matrix element performs 69% (100-31) as well as solid plate.

Fig. 20 Least Square Linear Deflection Load Characteristics Showing Effects of Weld Spacing, Side Plate Thickness and Fuel Plate Thickness

6.7 EMPIRICAL RELATION FOR FUEL PLATE DEFLECTION

A fuel plate may be regarded as a beam across its width, with the welded portions acting as supports and internal pressure acting as a uniformly applied load. An analysis made on the TIG welded elements established an analytical approach describing deflection of the outside fuel plates.

Welds were arranged so the middle of an interweld span on one side of the plate occurred directly opposite a weld on the other side. Fuel plates were fitted into slots milled in the side plates; the slots provided support, but no restraint except at the welds. This construction suggested two basic alternating types of supports along the length of the fuel element:

1. Simply supported beam at both ends
2. A beam simply supported at one end and rigid at the other.

The deflection equations describing these cases⁴ for a uniformly distributed load are:

1. Simply supported beam:

$$\zeta = \frac{wl^4 a}{24EI} (1 - 2a^2 + a^3)$$

2. One fixed end and one simply supported end beam:

$$\zeta = \frac{wl^4 a}{48EI} (1 - 3a^2 + 2a^3)$$

where

ζ	=	beam deflection at point of interest, in.
l	=	length of beam (width of plate), in.
a	=	location of point of interest, fraction of distance along l
w	=	beam loading, lb/in.
E	=	modulus of elasticity, lb/in. ²
I	=	moment of inertia, in. ⁴

When these equations are applied to a solid stainless steel fuel plate, the following values result for deflection at plate centerline as a function of pressure gradient (β).

<u>Location</u>	<u>Plate Thickness</u>	
	<u>0.030 in.</u>	<u>0.040 in.</u>
At weld location	$\zeta_c = 0.00225\beta$	$\zeta_c = 0.00095\beta$
Not at weld location	$\zeta_c = 0.00563\beta$	$\zeta_c = 0.00273\beta$

where

ζ_c = deflection in inches at plate centerline.

β = load on plate in lbs/in.² = $\frac{w}{\text{plate width}}$

Figure 21 presents the graph of these relations for 0.040 in. thick plates. It was found that load-deflection curves for all 0.040 in. fuel plates tested fell between the plots of these two expressions, thus indicating the expected result. A similar result was found when element 1 was compared with the expressions for the 0.030 in. thick plates (Fig. 22.) Using the graphs of the 0.030 in. thick plates, and approximate expression was derived to indicate fuel plate deflection at centerline as a function of basic properties. For a simply supported beam at the center:

$$\zeta_c = \frac{5w1^4}{384 EI} ; a = 1/2$$

For a beam fixed at one end and simply supported at the other:

$$\zeta_c = \frac{2 w 1^4}{384 EI} ; a = 1/2$$

An approximate expression for deflection of a fuel plate was derived by interpolating between these curves:

$$\zeta_c = \frac{3.32 w 1^4}{384 EI}$$

By substituting appropriate values of the modulus of elasticity, this expression may be extended to cold rolled stainless steel plates, and to stainless steel clad matrix fuel plates.

Analysis of the 0.040 in. plates showed a variation of 2.63 to 3.33 in the numerator constant; therefore, the above equation will predict deflection conservatively.

Fig. 21 Comparison of Deflection - Load Characteristics of Element 1 (0.040 In. Plate) with Characteristics of Standard Beams

Fig. 22 Comparison of Deflection - Load Characteristics of Element 1 (0.030 In. Plate) with Standard Beam

6.8 EVALUATION OF ORNL TEST DATA

ORNL⁷ had presented deflection data on brazed fuel plate assemblies. This test data was analyzed using the beam equation method described in Section 6.7.

Since the brazed element may be considered a beam with fixed ends along the total length of the fuel plate, the deflection equation for a beam with fixed ends⁴ was applied.

$$\zeta_c = \frac{wl^4}{384 EI}$$

The ORNL plates were 0.030 in. thick and 2.74 in. wide. The modulus of elasticity used was that of stainless steel (28.5×10^6), the material of the test specimens.

The data plotted directly up to the yield point, ~ 9 psi, on the line described by the above equation, which indicated that the model predicted plate deflection very well.

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7.0 REFERENCES

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