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EXPERIMENTAL INVESTIGATION OF HFIR FUEL PLATE DEFLECTIONS INDUCED BY TEMPERATURE AND PRESSURE DIFFERENTIALS

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ABSTRACT

Fuel plate deflections in the High Flux Isotope Reactor fuel element have been investigated experimentally by subjecting a single plate to thermally induced displacements and to pressure differentials. Of particular interest were the plate's mechanical stability characteristics when subjected to longitudinal loading along the two edges of the plate, a condition that is encountered when a temperature difference exists between the fuel plate and side plate.

The results of the experiments indicate that under HFIR operating conditions the fuel plates will always deflect toward the convex side of the involute over the central portion of the plate and toward the concave side close to the ends. A plate was also subjected to a differential strain almost three times as great and a temperature 200°F higher than expected in HFIR; the same deflection characteristics were observed. In neither case was there any indication that the plate had buckled longitudinally, that is, that the critical load had been achieved.

Pressure deflections were found to be the same as predicted with calculations.

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INTRODUCTION

HFIR fuel plate deflections caused by differential thermal expansion are perhaps of greater concern than those in other research and testing reactors because of the unusually high power density in the HFIR. The deflection of greatest interest is that associated with the differential longitudinal thermal expansion, which results from a difference in fuel-plate and side-plate temperatures. When this temperature difference becomes large enough the fuel plate longitudinal stress will exceed a critical value, and the plate will buckle in the form of a complex sine wave. The critical stress value depends on the plate temperature (material properties), the initial geometry, the means of edge attachment and the temperature distributions in both the fuel plate and side plates. Also affected by these parameters is the wave length.

Evidence of the above type of buckling in a fuel element has been observed in some of the SPERT[1] destructive tests, and perhaps it was these observations more than anything else that prompted an investigation of steady-state conditions in the HFIR design.

Early in the HFIR program a rather simple calculation[2] was made in connection with fuel plate stability; results indicated that under HFIR operating conditions the plates would probably buckle, the deflection would be significant in terms of hydrodynamics, and the wave length would be about 2 in. To support this investigation experiments were

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[1]A. H. Spano and R.W. Miller, SPERT I Destructive Test Program Safety Analysis Report, IDO-16790, Phillips Petroleum Co., June 15, 1962.

[2]R. N. Lyon, Remarks on Thermal Buckling of Columns, Plates and Shells with Initial Sinusoidal Distortion (HFIR Fuel Plates), USAEC Report ORNL-TM-1482, Oak Ridge National Laboratory, April 7, 1966.

conducted which seemed to verify the calculational results, although there was some question concerning the accuracy of the data.

The results of the above calculations were incorporated in the overall heat transfer analysis[3] to the extent of assuming that two "bumps" appeared directly opposite each other (opposite sides of a coolant channel), but 180 deg out of phase, at the outlet end of the hot channel. It was further assumed that these "bumps" would have no effect on total flow rate through the channel even if several of them occurred along the length of the channel and remained 180 deg out of phase. The validity of this latter assumption depends upon the shape of the curve across the width of the plate. In a comparatively recent review[4] of the heat transfer analysis it was "discovered" that if the shape across the width were essentially square, and if the waves in the longitudinal direction were 180 deg out of phase, a rather drastic reduction in flow rate would occur in the particular channel. At about this same time fuel plate deflection experiments being conducted in connection with the ATR[5] indicated that the critical stress would not be achieved in the HFIR, although here again there was some doubt regarding the accuracy and applicability of the experimental results. These developments provided the necessary incentive for reinvestigating the stability problem and the part it plays in the HFIR heat transfer analysis.

METHOD OF ANALYSIS

An analysis of fuel plate buckling is complicated by the fact that temperatures in the fuel plate and the side plates are not uniform. This of course results from the variations in power distribution throughout the core, even though the distribution is essentially symmetrical. An isometric view of the assembled HFIR fuel elements is shown in Fig. 1, and typical longitudinal and radial (across the plate width) temperature

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[3]N. Hilvety and T. G. Chapman, HFIR Fuel Element Steady-State Heat Transfer Analysis, USAEC Report ORNL-TM-1903, Oak Ridge National Laboratory, December 1967.

[4]H. A. McLain, Letter to T. E. Cole, November 11, 1965, Effect of Sinusoidal Buckling of the HFIR Fuel Element Coolant Channels.

[5]R. E. Deville, Differential Thermal Expansion Tests on Advanced Test Reactor Fuel Plates, IDO-24461, National Reactor Testing Station, Phillips Petroleum Co., October 15, 1963.

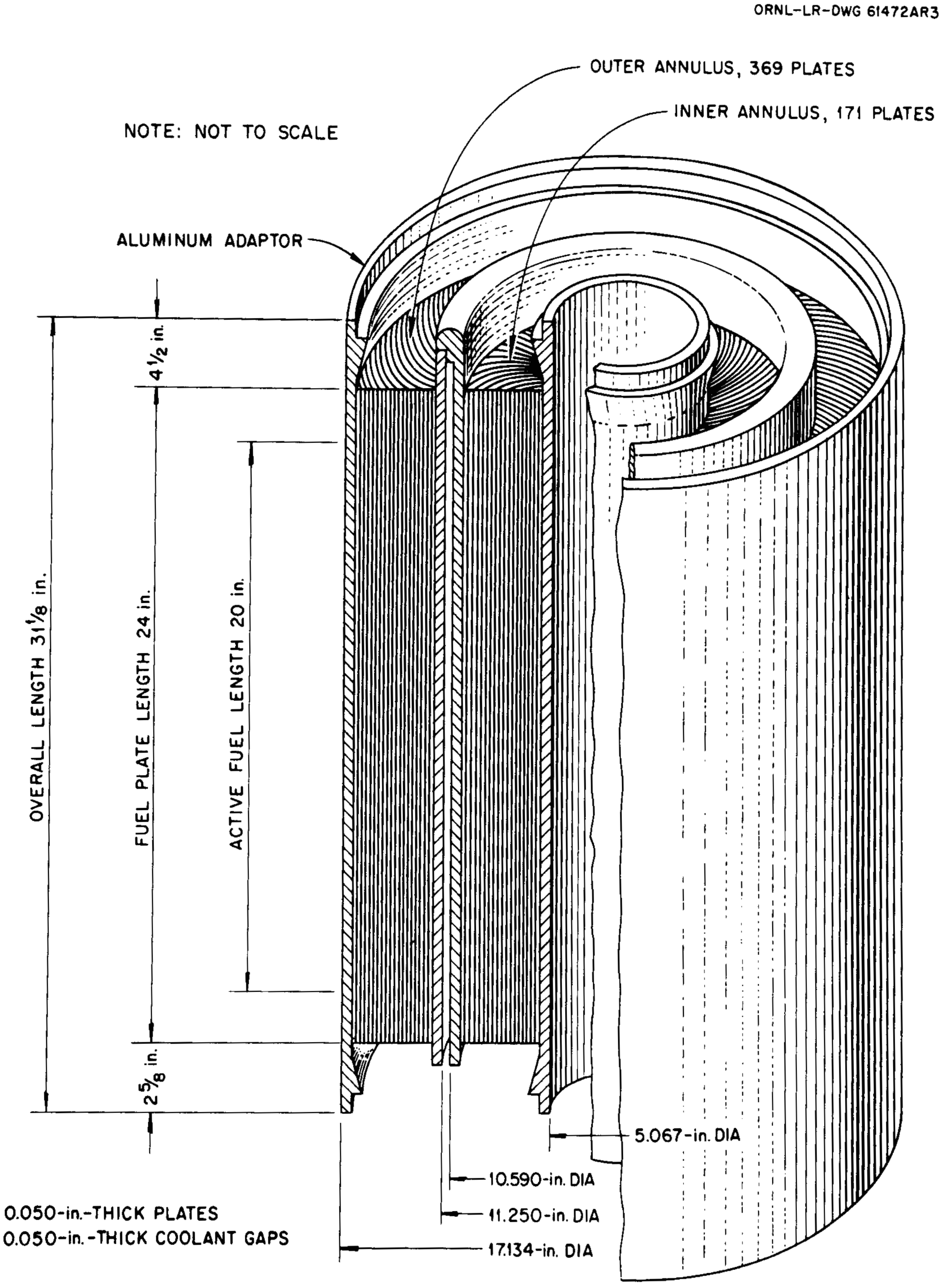

Fig. 1. HFIR Fuel Assembly.

distributions for the fuel plates are shown in Figs. 2 and 3. Not only do these distributions suggest complications in determining actual deflection curves, but the means by which such information could be used precisely in the heat transfer analysis is certainly equally complicated. Thus, before designing an experiment it was necessary to determine what type of information would be useful in the heat transfer analysis.

It appeared that about the most complicated data that could be handled in the heat transfer calculations was a rather general description of the axial and transverse deflection curves. This type of information could be obtained easily and conservatively, if it were assumed that the actual temperature distribution curve could be replaced with a step curve such as the upper curve shown in Fig. 3. Certainly, if this latter curve is drawn through the maximum of the actual curve in the fuel region and the minimum of the actual curve in the side plate region, the deflection assumed in the calculations would be conservative. However, the experiment referred to does not necessarily impose this restriction since the designer is at liberty to select his own "best" average step curve. In the axial direction the same type of averaging can be resorted to, or the length of the plate can be divided up into effectively infinite lengths, each at a different temperature.

The experiment alluded to above is one in which a fuel plate and an attached set of side plates, which has a coefficient of thermal expansion smaller than that of the aluminum fuel plate, are slowly brought to a uniform temperature, thus providing a differential expansion at some particular absolute temperature. By using different side plate materials (different coefficients) a family of curves can be obtained that will provide different combinations of differential expansion and fuel plate temperature. This feature can be important because in the heat transfer analysis fuel plate deflections provide feedback that changes plate temperatures and thus deflections. The appropriate combination of differential expansion and temperature are never known until the iterative procedure in the heat transfer analysis has converged.

Such a simple experiment as that mentioned above becomes somewhat more complicated when relative rotation of side plates, fuel plate "cold

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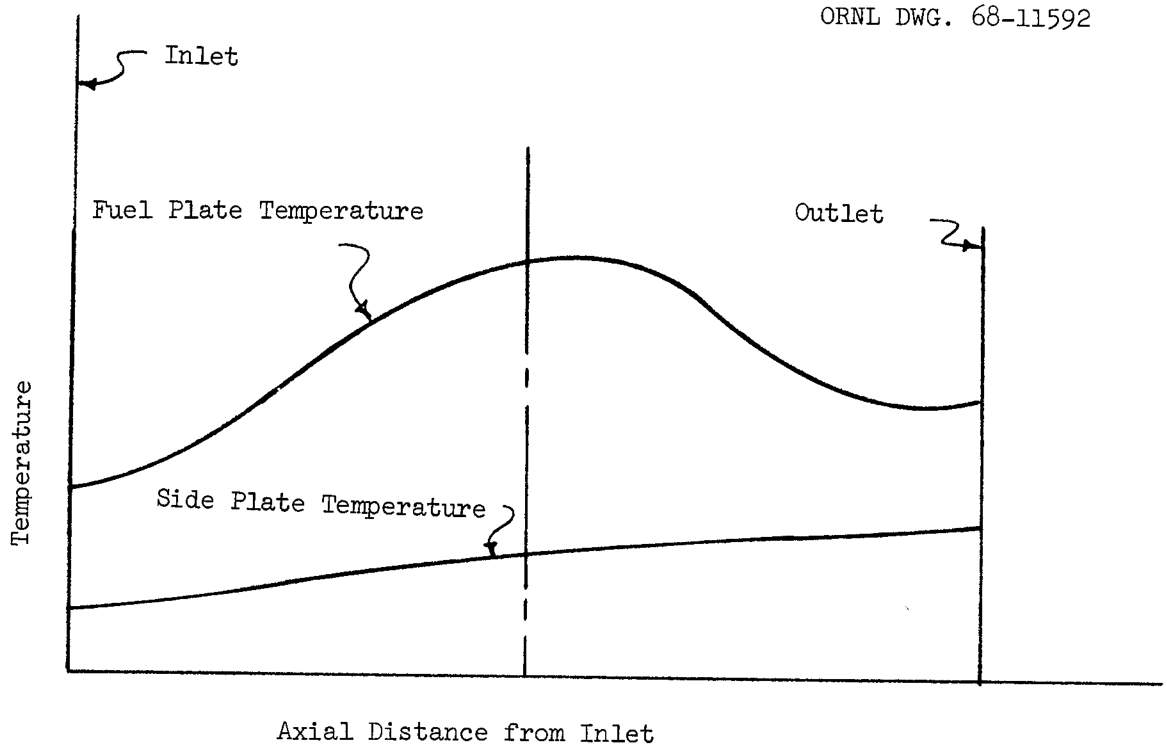

Fig. 2. HFIR Fuel Element Axial Temperature Profiles.

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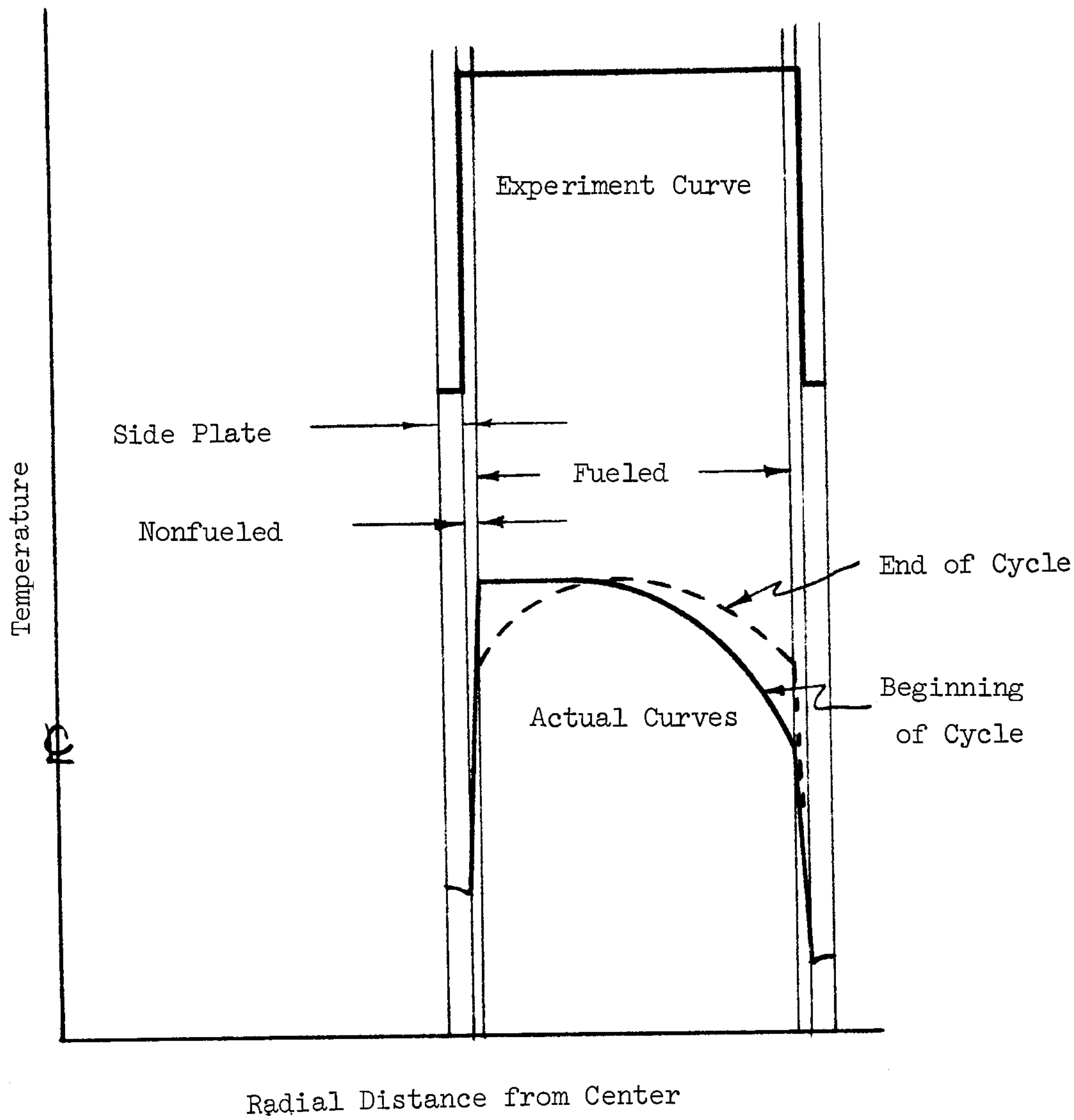

Fig. 3. HFIR Fuel Element Radial Temperature Profiles.

ends", edge attachments, side plate structural characteristics, differential pressure and initial shape effects are simulated.

The relative rotation of the side plates was designed into the HFIR fuel elements so as to minimize stresses resulting from the radial differential expansion between the fuel plates and side plates. As shown in Fig. 1, the inner side plate of the inner element and the outer side plate of the outer element support the elements, leaving their counterparts free to rotate as a difference in average temperatures between the fuel plates and side plates is generated. Of course this scheme does not completely eliminate "radial" stresses in the fuel plate because the axial temperature distribution is not uniform. Near the center of the core, where the plates are hottest, the plates will be subjected to a compressive edge load, and near the ends the load will be tensile, thus constituting a restrictive force to side plate movement.

A further restraint is applied to relative rotation of the side plates by the moments generated at the tab weld attachments. However, the resulting bending stresses are small compared to those eliminated by "free" rotation of the side plates.

The experiments discussed herein included both fixed and "free" side plates. However, the "free" side plate condition did not exactly reproduce the actual reactor condition because it was not possible to completely reproduce the variations in axial temperatures and temperature differences. Furthermore the small edge moments discussed above were not the same. This latter discrepancy is considered to be insignificant, but the lack of appropriate axial temperature distributions can introduce some difficulties in terms of application of test results. In an effort to at least partially simulate the actual case "cold ends" were added to some of the test plates.

The "cold end" effect in an actual fuel element is the result of having a significant nonfueled portion of the fuel plate at both ends of the fuel plate. Since the differential expansion between the side plates and "cold ends" is small, the cold ends act as restraints at the ends of the "hot" plate. Most of the experiments were conducted without this restraint; however, in a few cases an attempt was made to simulate the "cold ends" by attaching plate end extensions made of a material similar to that of the experimental side plate. Thus, the fuel plate effectively had a uniform temperature over the mid-20 in. of its length and a lower but uniform temperature over a 2-in. length at each end. This arrangement gave some indication of the axial restraint associated with "cold ends."

The degree of end fixation is also influenced by the existence or nonexistence of combs in the ends of the fuel element. In the original design of the HFIR element combs were included mainly as a safety precaution against possible inaccuracies in predicting inlet and outlet hydrodynamic effects on plate deflection and also against damage in handling. Because of the difficulties associated with installing combs it was intended that the need for combs would be investigated in greater detail at a later date. Thus, it was desirable to examine both cases during the deflection experiments. Actual combs were not included in the experiments, but the degree of end restraint was varied in such a way as to give some indication of the effect.

Fuel plate edge attachment is also an important parameter because in the process of transmitting the forces resulting from the differential expansion it can "absorb" some of the differential and thus reduce the buckling tendency. However, in the process the attachment might fail, or in the experiment the attachment might slip, resulting in erroneous data. In the present HFIR fuel element design the attachment is made by welding the fuel plate to the side plate at 1-in. intervals, the weld being ~0.12-in. long (see Fig. 4). This was simulated in the experiment by clamping edge tabs close to the effective edge of the plate. Since the restraint depended to a large extent upon frictional forces that might vary during the experiment it was necessary to prove that slippage would not occur, and this was done.

Longitudinal extension of the side plates resulting from the attachment forces provides some relief for the differential expansion. This condition was not simulated in the experiments because of mechanical complications. Had the results from the tests indicated excessive fuel plate deflections, a separate experiment was to be conducted to determine

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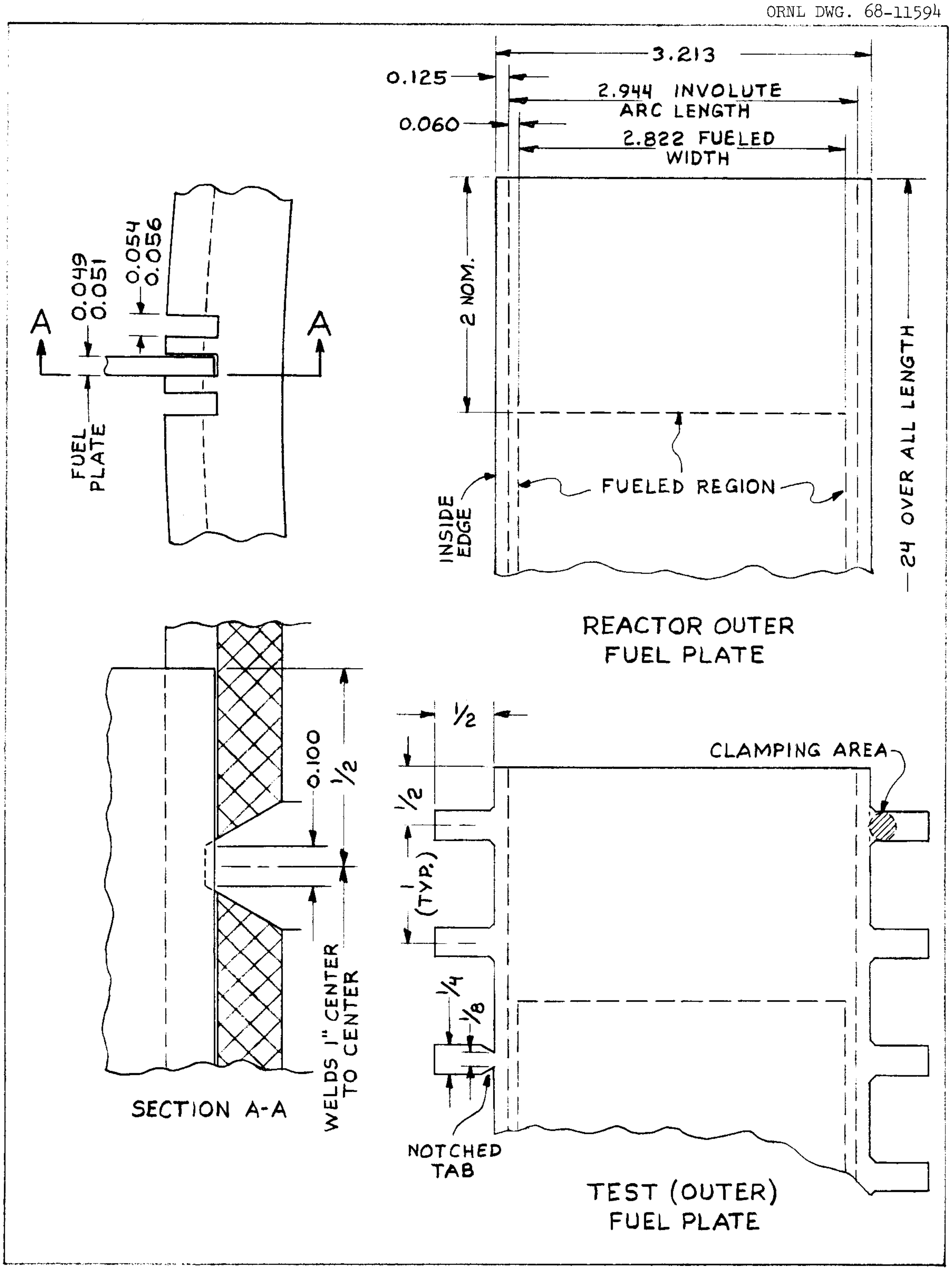

Fig. 4. Fuel Plate Groove and Weld Groove Detail.

appropriate equilibrium conditions between the side plates and fuel plates.

Coolant flowing through the core creates pressure differentials normal to the fuel plate surfaces because of nonuniformities in coolant channel thickness. These differentials are not uniform along the plate length, nor are they necessarily similar from channel to channel. Thus, a realistic simulation was not achieved. However, the effect of the differential pressure was investigated by uniformly pressurizing a fuel plate in the differential expansion apparatus while at the maximum temperature. In the process of achieving leak tightness around the edges of the plate, edge attachment conditions were probably altered to some extent. Thus, there is reason to question the validity of the data; nevertheless, it is believed that the trends were properly indicated.

Initial deviations from the perfect fuel plate shape were considered important, particularly if a true instability condition existed. Since it was not possible to install plates in the experimental side plates with the same degree of straightness as could be achieved in an actual fuel element the experiments were plagued with "excessive" initial deviations. In addition to somewhat random deviations over most of the plate surface, there was a regular sine-wave-type curve immediately adjacent to the edge of the plate that was induced by the attachment technique. (This same sort of condition with about the same amplitude (~0.001 in.) is produced in an actual fuel element as a result of welding.) There was also a way of purposely varying the longitudinal deviations. Thus, within reasonable limits the effects of shape deviations could be investigated.

As shown in Figs. 1 and 5, the HFIR has two different fuel plates; they are the same length and thickness, have approximately the same width, are both of involute geometry, but have different involute generating circles. The plates are located in two annular fuel elements, which make up a complete core loading, as shown in Fig. 1. Fuel plates in the outer element are flatter than those in the inner element because of the larger involute generating circle for the outer element. Thus, the outer element plates tend to be less stable against axial buckling. For this

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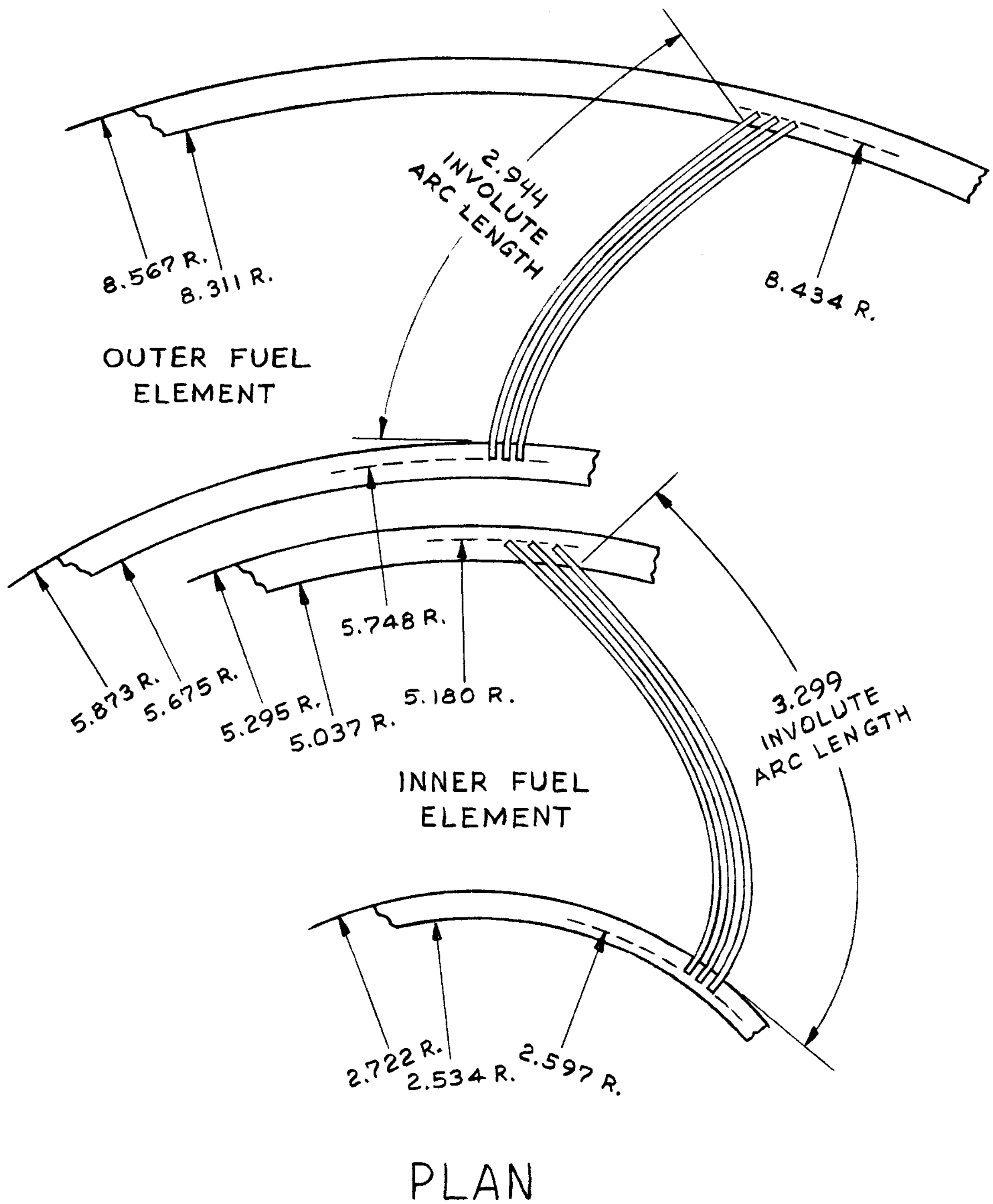

Fig. 5. HFIR Fuel Element Dimensions.

reason, and because the peak power density in the outer element was at least as great as that in the inner element, it appeared sufficient to investigate the deflection characteristics of the flatter plate only.

During the early part of the experimental program the effects of creep and thermal cycling on fuel plate deflections were investigated. The results indicated that all deflections were essentially instantaneous with changes in temperature, and that thermal cycling, consistent with normal reactor operation, had no significant effect on the results. Therefore, most of the experiments were of short duration and consisted of just one heating and cooling cycle.

DESCRIPTION OF APPARATUS AND PROCEDURES

The basic apparatus for investigating fuel plate deflections resulting from differential expansion between fuel plates and side plates and differential pressures consists of a base to clamp a fuel plate to, a device for measuring the relative deflection between fuel plate and base, and an oven in which to heat the assembly isothermally.

The fuel plates for these experiments were essentially identical in shape to actual HFIR outer fuel element plates. To simulate the intermittent weld attachment between the fuel plate and side plates, the fuel plates were provided with edge tabs, as shown in Figs. 4 and 6, which were clamped to the base. Various checks were made to insure no slippage of tabs during thermal cycling.

For most of the tests the tabs were spaced on 1-in. centers and were slightly over 1/4-in. in width. Since the actual effective width of the weld attachment now appears to be somewhat less than 1/4 in., more recent tests have been conducted with effective tab widths of 1/8 in.

Two basic types of "fuel" plates were used in the experiments. One was an actual fuel plate containing fuel, while the other was all aluminum (sheet stock). The length of the plates in all tests was 24 in., which is equal to the actual HFIR total plate length but which is 4-in. longer than the active (heated) length. In several cases the "cold end" effect was simulated by adding 2-in. steel ends to a 20-in. length of an all-

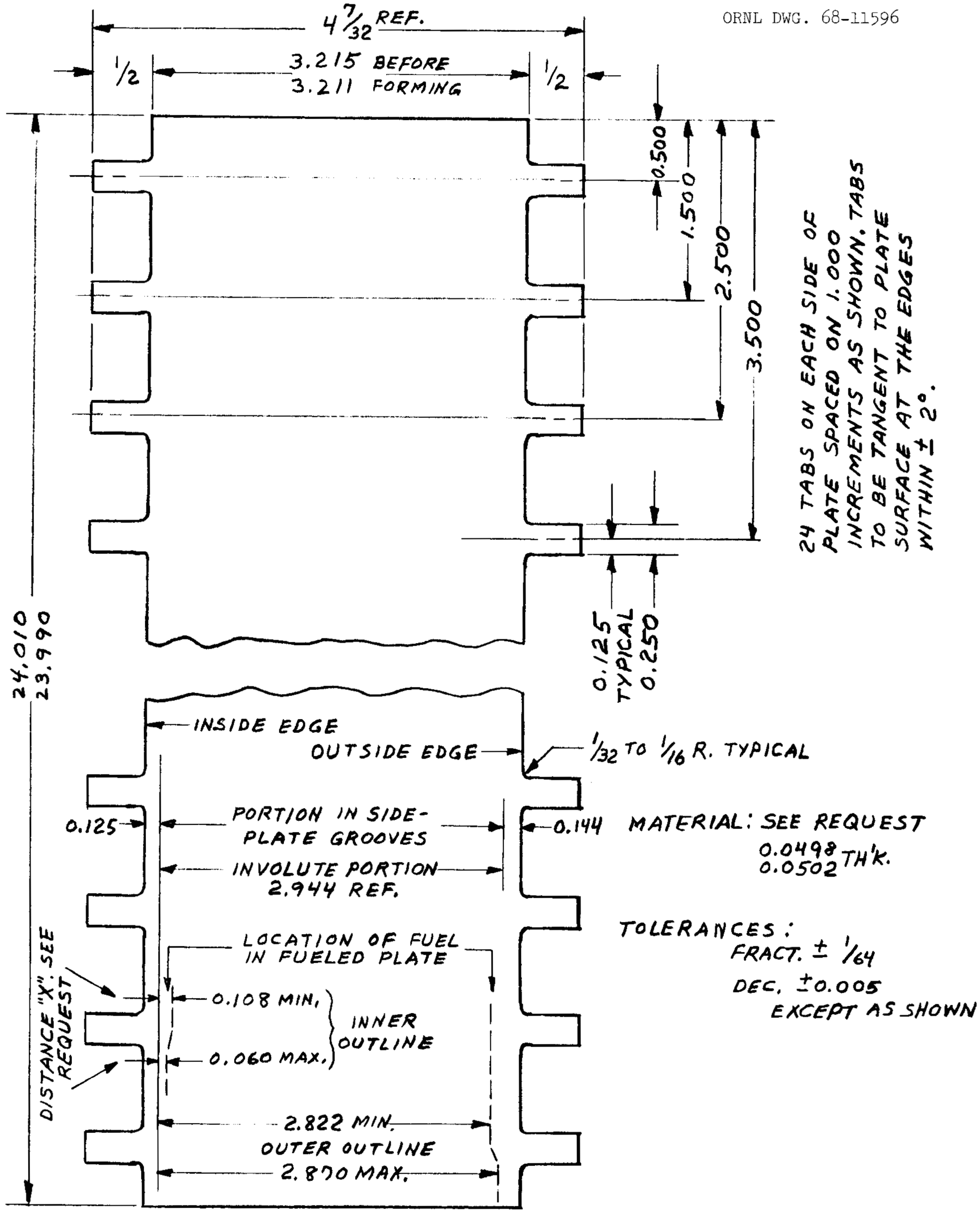

Fig. 6. HFIR Fuel Plate Test — Test Plate.

aluminum fuel plate. The joint between the aluminum and steel was achieved using a 1/4-in.-lap joint and epoxy cement.

In order to achieve the differential expansion between the aluminum fuel plate and the base with both at the same temperature, the base was made of a material having a lower coefficient of thermal expansion than that of the fuel plate. By changing base material the combination of differential strain and absolute temperature could be varied. In these experiments bases were made from carbon steel, Monel and Invar. The linear differential expansion between each of these bases and a fuel plate was determined by differential expansion measurements in the oven using a "loose" plate on the base. Differential expansion curves for the carbon steel and Invar bases are shown in Fig. 7. Difficulties in obtaining the desired Monel alloy resulted in the Monel and carbon steel curves being closer together than desired. Thus only a few experiments were conducted with the Monel base for the purpose of extending the range of achievable strain.

The complete experimental assembly is made up of several parts as shown in Fig. 8. The base, which has the proper involute edge angles machined on it, is shown positioned on the seprate track. Two bars, equipped with numerous adjustment screws, are used to secure the tabs on the edges of the fuel plate to the base. As shown in Fig. 9, the larger screws in the bars hold the bars in place while the smaller adjustment screws and inserts are used to actually apply pressure to the plate tabs. The inserts depress a portion of the tabs into a shallow spherical cavity in the base. Different inserts result in slightly different initial plate shapes after tightening. With a set of modified bars it is also possible to pull the bars down hard against the fuel plate, creating a fixed edge condition.

As indicated in Figs. 8, 9 and 10 the base is mounted on a track, which is used as a reference surface for making plate deflection measurements. The mounting was such that edge parallelism was maintained between the two, and yet the two were allowed to move freely with respect to each other so as to accommodate differential expansion without inducing significant stresses. Intimate contact between the base and track was achieved with spring loading.

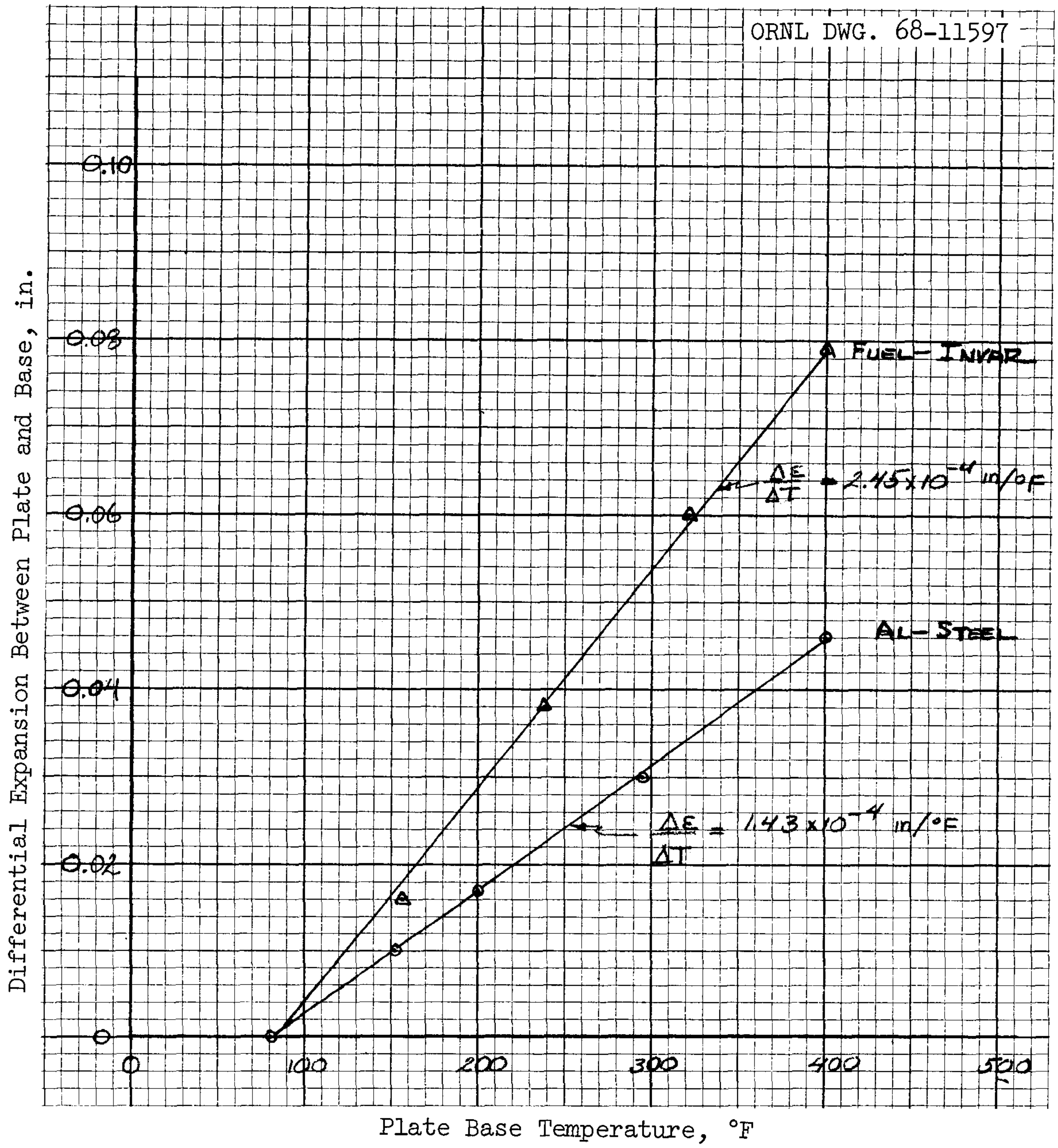

Fig. 7. Differential Expansion Between Plate and Base Plates.

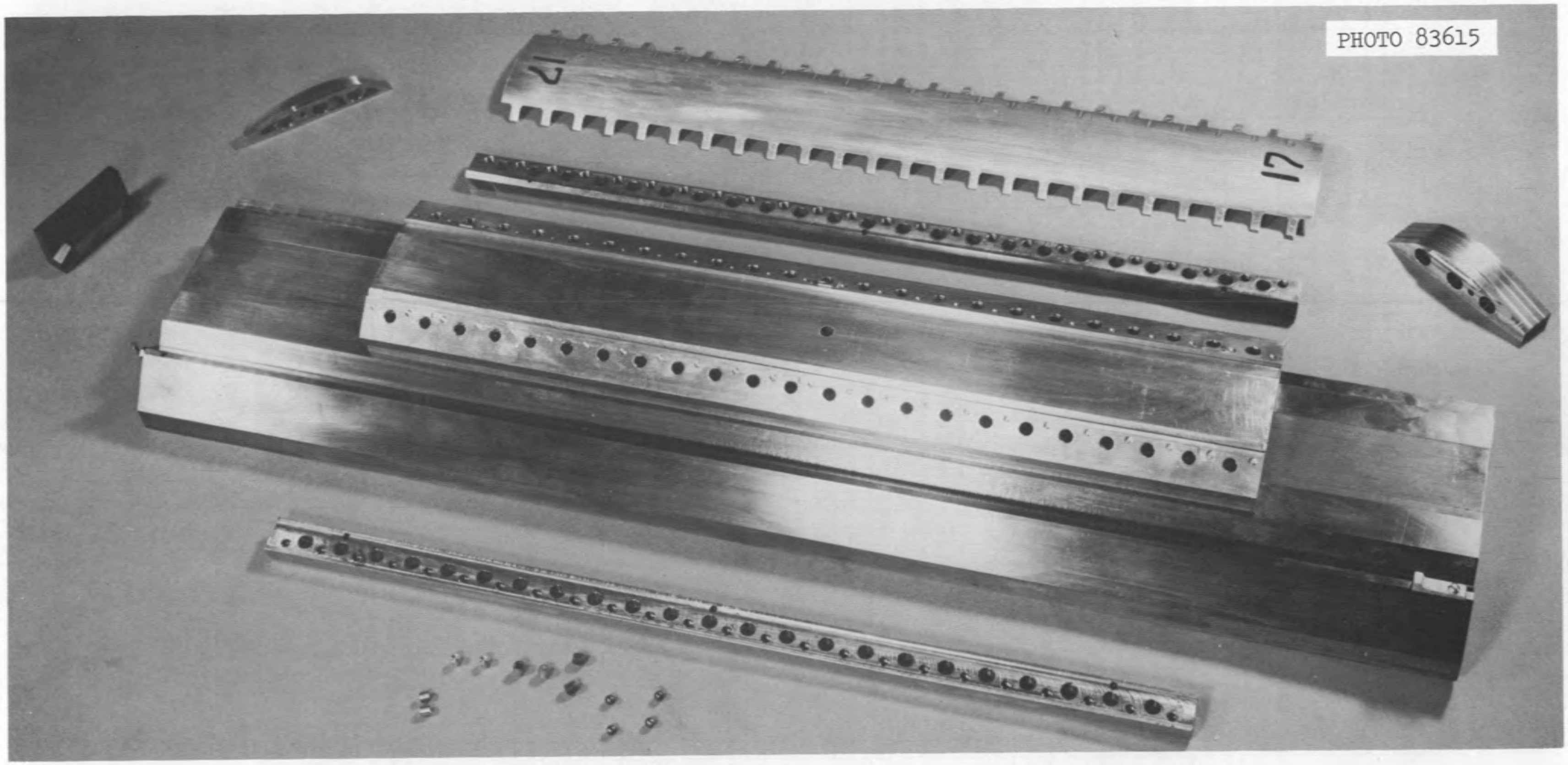

Fig. 8. HFIR Fuel Plate Deflection Apparatus Components.

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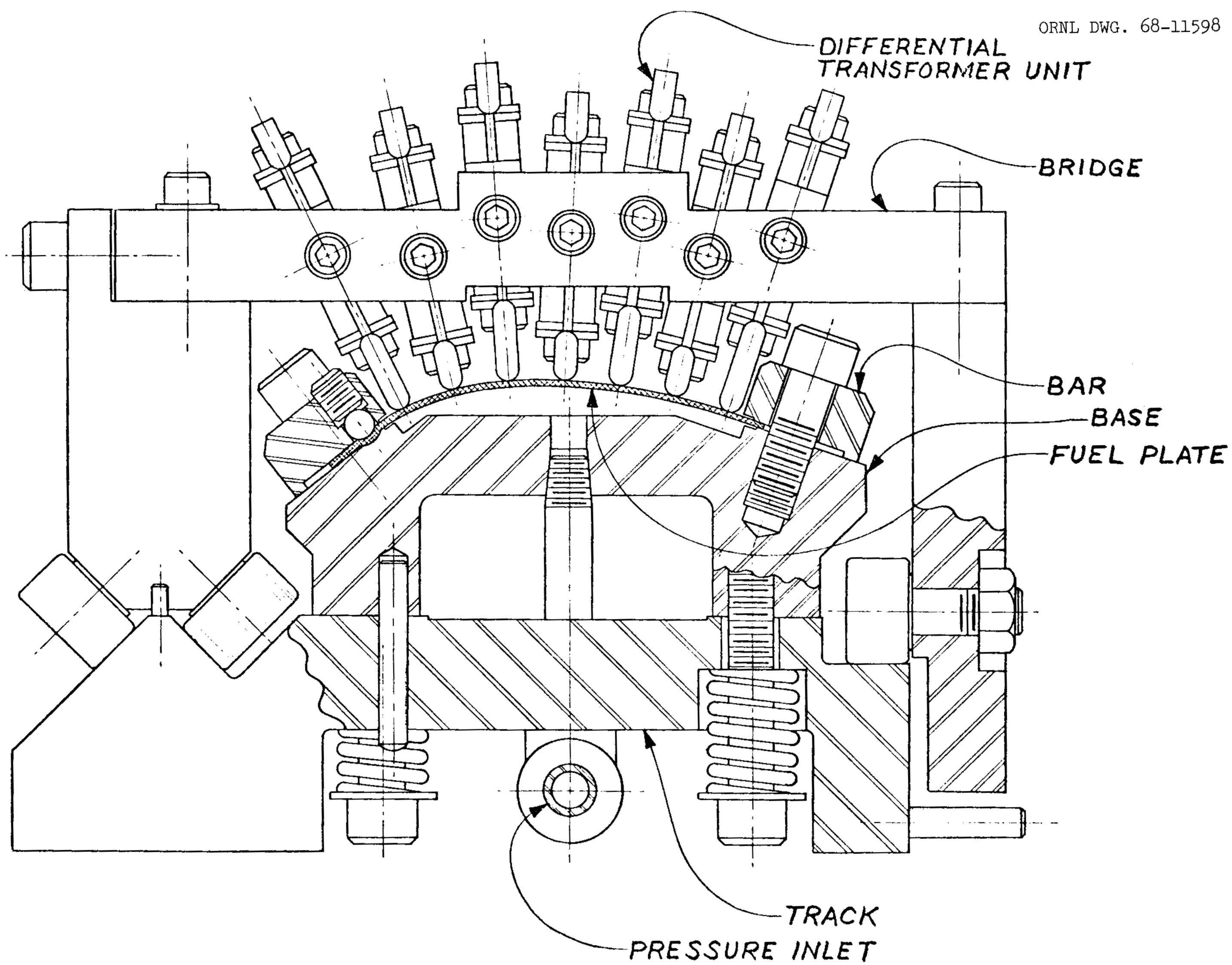

Fig. 9. Cross Section of HFIR Fuel Plate Deflection Experimental Apparatus.

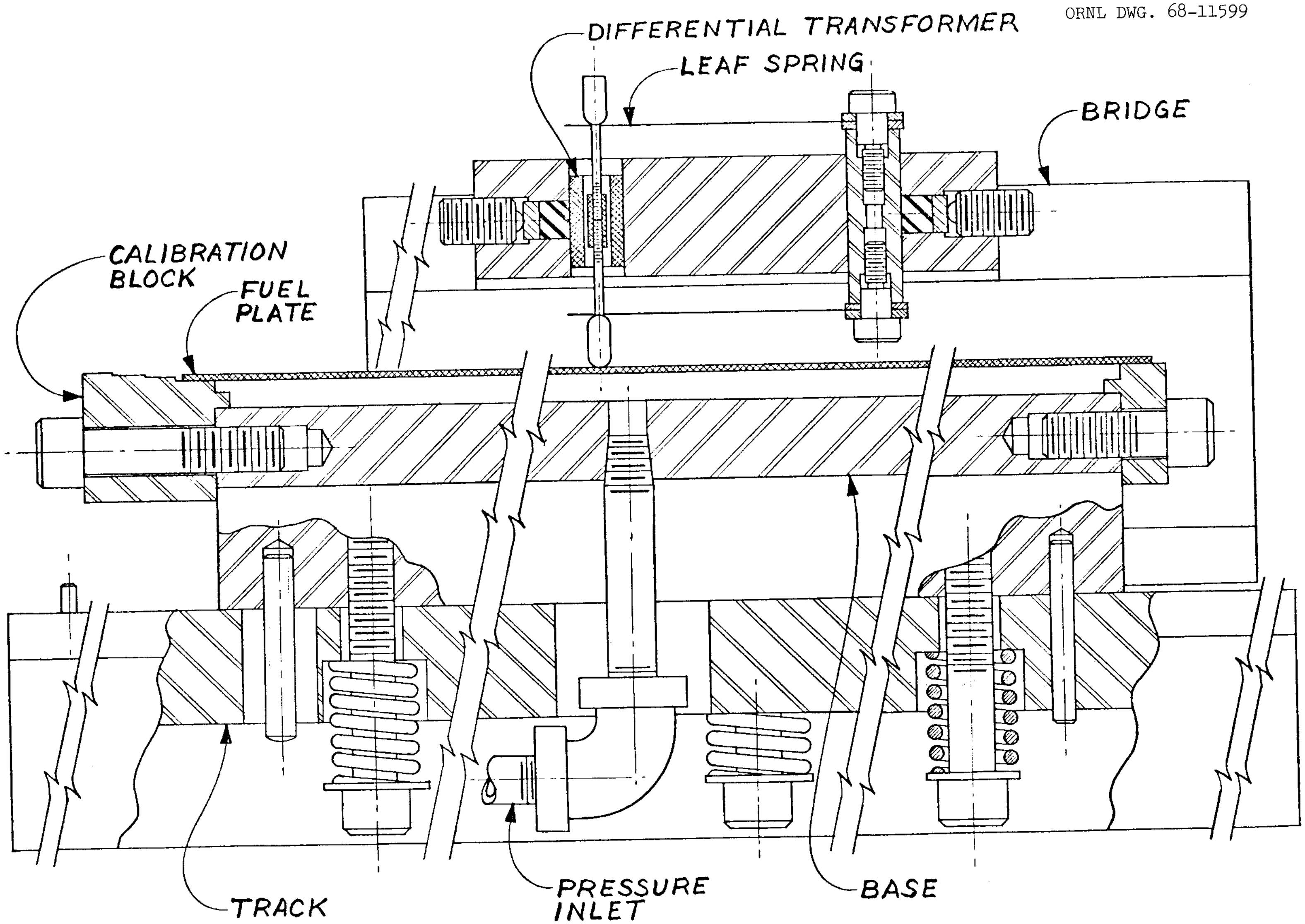

Fig. 10. Side View of HFIR Fuel Plate Deflection Experimental Apparatus.

Uncertainties regarding dimensional stability of the base and track during thermal cycling were minimized by carefully stress relieving the components during fabrication and by making relative measurements at temperature between the base and track and between the track and an outboarded precision straight edge. While at temperature the straight edge, which was supported at only two points on the track, was turned over so that measurements could be made from both sides, thus eliminating any dimensional instability in the straight edge from the measurement. After thermal cycling, all components were checked on a surface plate. In all cases straightness was within 0.001 in.

The base and track components were designed to be adequately rigid against the forces generated by the differential expansion between the fuel plate and base and the friction forces resulting from differential expansion between the base and track. An experimental check on the adequacy was obtained by making relative measurements between these components and the outboarded straight edge during typical thermal cycles.

Auxiliary base-track equipment included involute positioning end blocks, end stop-blocks, stepped involute standards and a modified micrometer for measuring "free plate" differential expansion.

The base was used both as a single piece and as two separate pieces. In the latter case the base was cut into two pieces,as shown in Fig. 11, and then held together in a precision manner with three aluminum bars. This "split" design allowed the aluminum fuel plate to expand transversely without restraint, thus simulating the rotating side plate condition discussed elsewhere in the text.

Plate deflection measuring instrumentation consisted of seven differential transformers and appropriate read-out equipment. As shown in Figs. 10, 11 and 12, the differential transformers were mounted on a bridge that traveled on the precision ways of the track. Styluses, which are extensions of the transformer cores, were supported and lightly spring loaded against a fuel plate by means of parallel leaf springs. Positioning of the transformers was such that the longitudinal axes of the styluses were normal to the true involute curve at the theoretical points of contact. Thus, for all practical purposes the measurements represented

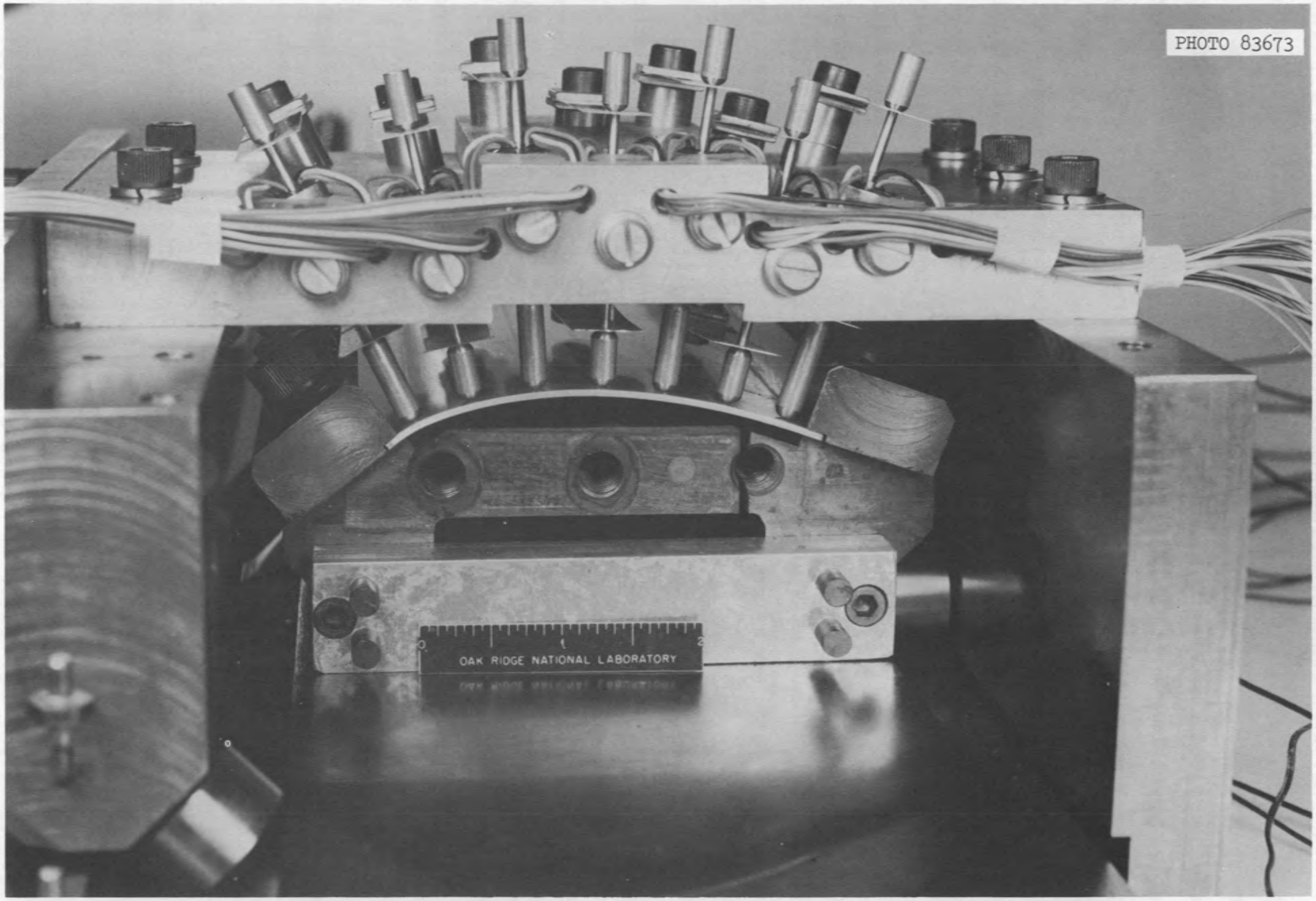

Fig. 11. End View of HFIR Fuel Plate Deflection Experimental Apparatus.

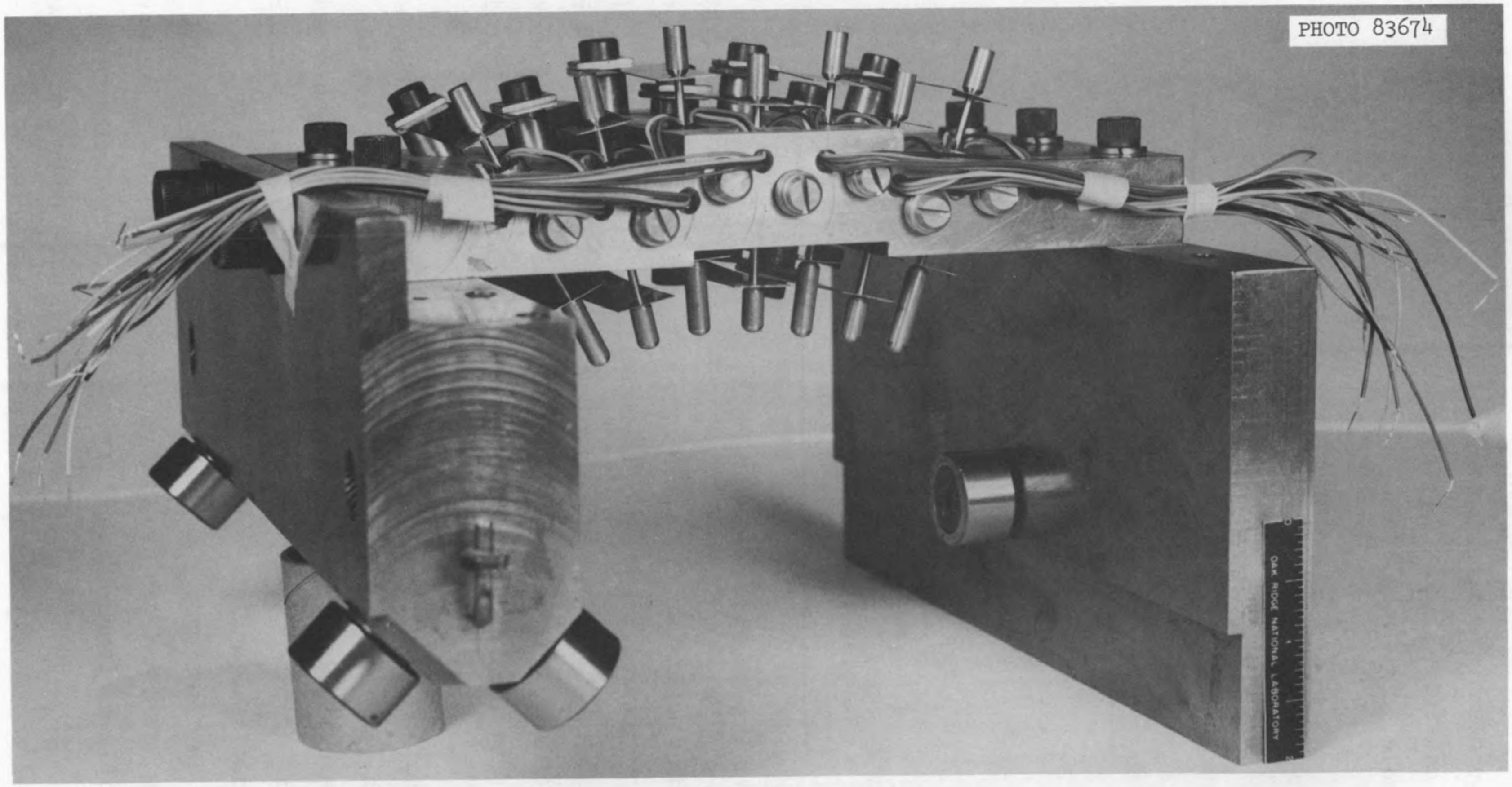

Fig. 12. Instrumented Bridge.

changes in coolant channel thickness. The theoretical positions of contact as measured in arc length from the involute generating circle are given in Table 1.

Table 1. Theoretical Positions of Contact for Differential Transformers (R = 5.873)

Transformer	Arc Length from Generating Circle
1	0.125
2	0.575
3	1.025
4	1.475
5	1.925
6	2.375
7	2.825
Complete involute arc length = 2.944	

Each differential transformer was calibrated at room temperature, at which time the amplifier gains and zero settings were adjusted, and at elevated temperatures by means of calibration blocks located at one end of the base (see Fig. 10). The accuracy with which the relative height of a calibration block point could be determined with the differential transformers was better than 0.0005 in.; for points on the plate it was better than 0.001 in.

The limiting temperature for sustained operation of these particular transformers was about 400°F. This limit was consistent with the maximum temperatures desired for the experiments, with the exception of a final run to 600°F. During this brief high temperature run the transformers functioned satisfactorily.

During an experiment the complete assembly, as shown in Fig. 13, was located in an oven and was brought to temperature slowly so as not to create significant temperature differences within the bulky parts and between the fuel plate and base assembly. A suitable number of appropriately located thermocouples was used to establish the correct heating and cooling rates.

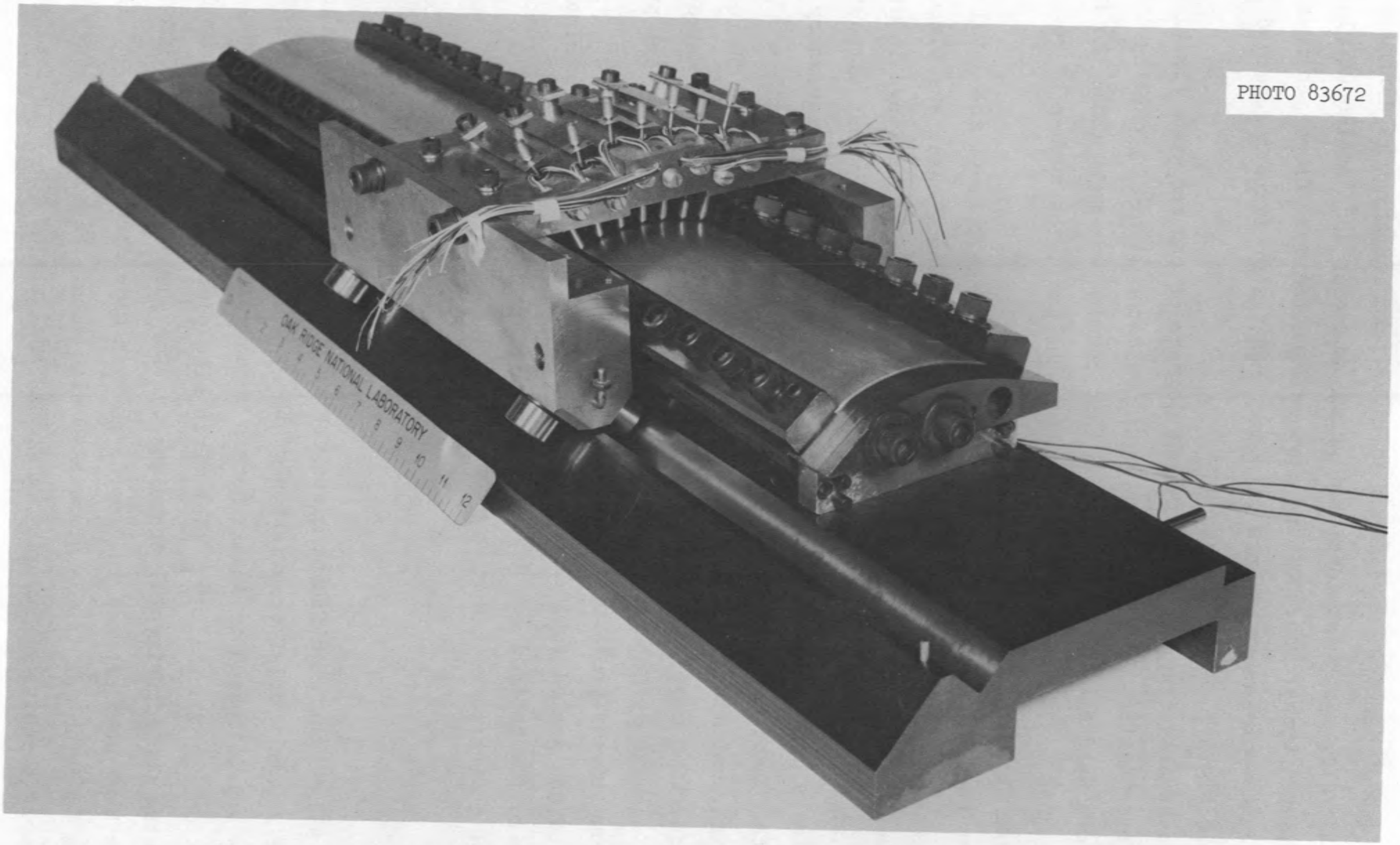

Fig. 13. HFIR Fuel Plate Deflection Experimental Apparatus Assembly.

A set of deflection readings could be taken at any time during a thermal cycle. Each set consisted of simultaneous and continuous plots of the seven transformer outputs plus calibration data from each transformer. A typical set of data with two transformer outputs recorded is shown in Fig. 14.

In several experiments different degrees of end and edge fixation were investigated. Edge clamping could be accomplished by pulling the bars down hard against the plate so that contact was made along the full length just inside the tabs. Using only the tabs, the number of restrained tabs could be varied.

At the ends of the plates the normal distance between the involute end blocks and the plate could be varied, and in some cases the plate ends were cemented to the blocks to provide complete fixation. In other cases stop blocks were used to restrain longitudinal movement without imposing a large end moment. During pressure tests it was necessary to seal the plate around the entire perimeter. This was done with a material that remained quite elastic at temperature. However, there is some question concerning the effect this material had on edge restraint.

Pressure differentials across the fuel plate were achieved by pumping a vacuum in, or pressurizing with bottled gas, the cavity between a mounted and sealed fuel plate and the base. Since some leakage always occurred the bottled gas was fed through a coiled tube in the furnace so as not to introduce temperature variations.

DISCUSSION OF RESULTS

All of the significant plate tests that were conducted are listed in Table 2 with a brief description of the test conditions. Not all of these tests are discussed in detail herein because several were used only as a check on reproducibility. (The first nine plates were used primarily for checking out experimental techniques.) For purposes of discussion the tests have been grouped in accordance with specific parameters of interest so as to establish trends associated with each. Finally an effort is made to apply the bits of information to the analysis of the HFIR fuel element.

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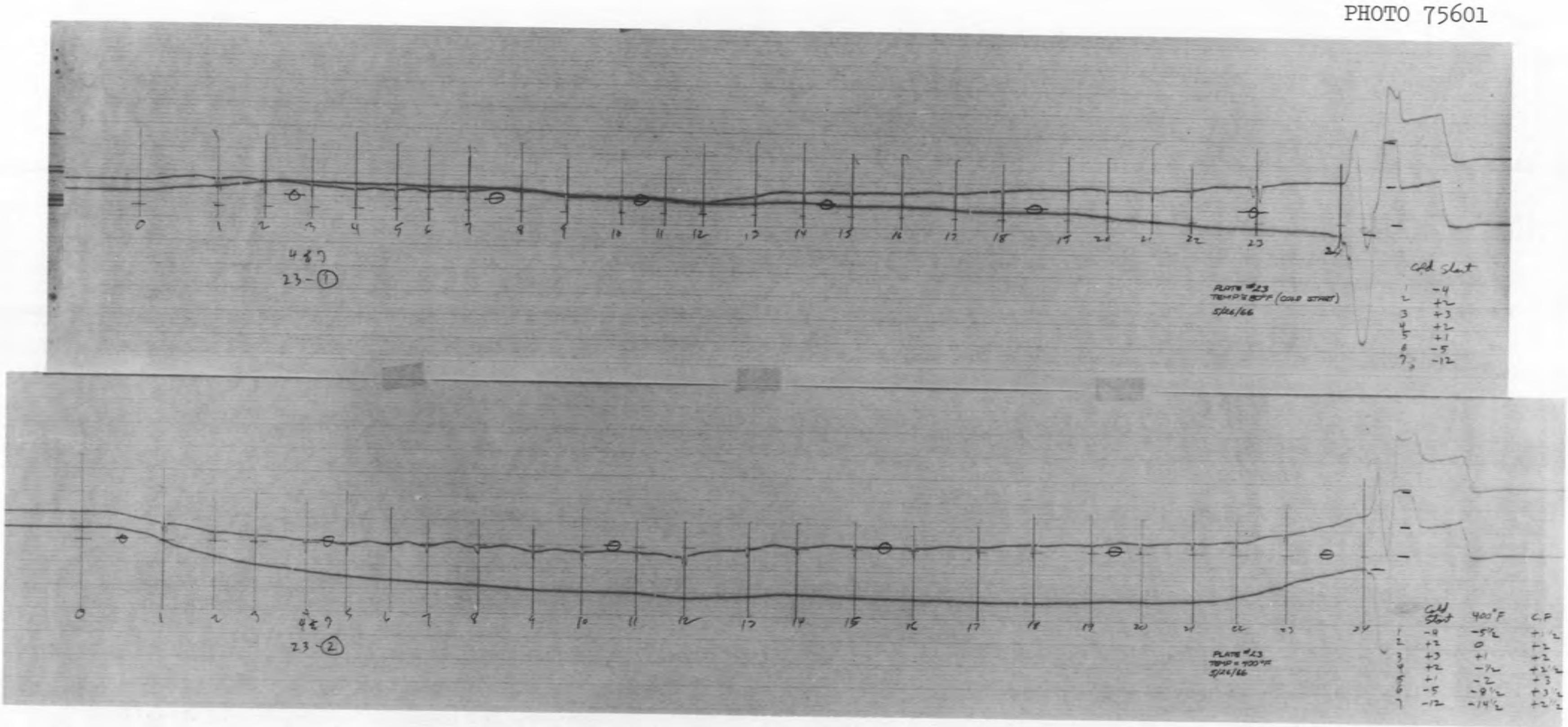

Fig. 14. Typical Data Recording for Two Transformers.

Table 2. Experimental Parameter Combinations

Test No.	Type Fuel Plate	Type Base Plate	End Attachment	End Attachment	Pressurized	Thermal Cycle	Creep Test	Date
10	A	E	L	O				3/23/66
12	A	E	N	O			3 days	3/25
13	A	E	N	O			15 days	4/5
14	C	E	N	O			3 days	4/21
15	C	F	N	O				5/2
16	A	F	N[a,b]	O				5/4
17	A	F	J	P				5/5
18	A	F	J[c]	O			3 days	5/6
19	A	F	N[b]	O		3 cycles	4 days	5/12
20	A	F	N[b]	O		2 cycles	2 days	5/18
21	A	F	J	O				5/23
22	A	F	K[d]	O				5/24
23	A	F	M	O				5/26
24	A	F	M	P				5/27
25	A	F	M	O[e]				5/31
26	A	F	K	O				6/6
27	C	F	K	O			3 days	6/8
29	C	I	M	U	Concave			7/15
30	C	I	M	U	Concave			7/19
31	C	F	N	P				7/21
32	C	I	M	T	Concave			7/22
33	C	I	M	T	Concave			7/26
34	C	I	M	T	Concave			7/27
35	C	F	N	P				7/29
36	C	G	J	O				8/18
37	C	G	J	O				8/19
38	C	F	N	O[e]				8/24
39	C	F	N	O[e]		2 cycles		8/25
40	B	F	N	O				9/1
41	B	F	N	O				9/2
42	C	H	N	O				9/7
43	C	H	M	O				9/9
44	B	F	N[b](0.010")	O				9/16
45	B	F	J	O				9/20
46	B	H	J	O				9/21
47	B	H	J	O				9/26
48	C	H	J	O				9/28
49	C	H	J	O				10/5
50	C	F	J	O				10/7
51	C	F	M	O				10/10
52	C	H	M	O				10/13
53	B	H	N(0.010")	O				10/17
54	C	F	J	O				10/24
55	C	H	J	O				10/26
56	C	F	J	P				10/31
57	C	F	J	O				11/3
58	C	F	J[a]	Q		4 cycles	2 days	11/7
59	C	F	J	R		4 cycles		11/16
60	C	I	M	U[f]	Concave 60 psi			12/7
61	C	I	M	Q[f]	Concave			12/21
62	C	I	M	O[f]	Concave			1/6/67
63	C	I	M	O[f]	Concave			1/11
64	C	I	M	P[f]	Concave			1/16
65	C	I	M	V[f]	Concave			1/18
66	C	H	J	O				2/1

[a]Plate corners cemented.

[b]Back involute block removed.

[c]Plate corners pinned.

[d]Filler between involute block and plate.

[e]Alternate cup and ball.

[f]Edges sealed with Scilastic.

Table 2 (contd.)

	Mounting and Plate Conditions
Fuel Plate Types	
A	Aluminum
B	Aluminum with steel ends
C	Fuel
D	Fuel with steel ends
Type Base Plate	
E	Steel, not split
F	Steel, split
G	Invar, not split
H	Invar, split
I	Monel, not split
End Attachment	
J	Free
K	Involute blocks snug
L	End stops snug, involute blocks free
M	Involute blocks snug and cemented
N	Involute blocks slightly below plate
Edge Attachment	
O	Every tab (1/4 in.)
P	Every other tab (1/4 in.)
Q	Every tab (1/8 in.)
R	Every other tab, special (1/8 in.)
S	Every tab (1/4 in.), corner dowels
T	Every tab (1/4 in.), bars tight against plate
U	Every tab (1/4 in.), bars tight against plate and cemented
V	Every other tab, special (1/4 in.)

Base Case

The base case is defined as an assembly consisting of an aluminum plate with 1/4-in. tabs, a carbon steel split base and all tabs secured with cups as opposed to balls. The degree of end fixation was a variable. When uniformly heated to 400°F, the plate took on the shape indicated in Fig. 15. Although the shape is not that of a multiple node sine wave as might have been expected for these particular conditions, the deflections are significant in analyzing fluid flow and heat transfer. For the purposes of such an analysis the deflection curves can be characterized by the deflection read-out at transformer No. 4 near the longitudinal center of the plate and at the plate ends. This sort of information is presented in Fig. 16 as a function of different degrees of end restraint. As indicated the deflection of the center of the plate tends to increase with increasing degree of end restraint while the deflection of the ends must of course decrease. The actual degree of partial end restraint achieved in each test is now known very accurately, and this situation probably accounts for some of the scatter in the data. However, initial shape of the plate before and after installation and uniformity of edge attachment have some small effect. It might also be that there is some difference between fueled plates, which are included in Fig. 16, and aluminum plates, although specific tests for comparing the two types of plates indicate that the difference is small (tests 26 and 27).

Some improvement in scatter can be achieved by using end deflection as an indicator of degree of end fixation rather than aligning cases by what was intended in the way of end restraint. However, in terms of application to fuel-element design the indicated scatter does not appear to be significant.

Cold Ends

A type of end restraint not included in the above group is that referred to as the "cold end" condition, a condition that exists in the reactor as a result of not having fuel in the last 2 in. of each end of the plate. This condition was simulated in the experiments by adding

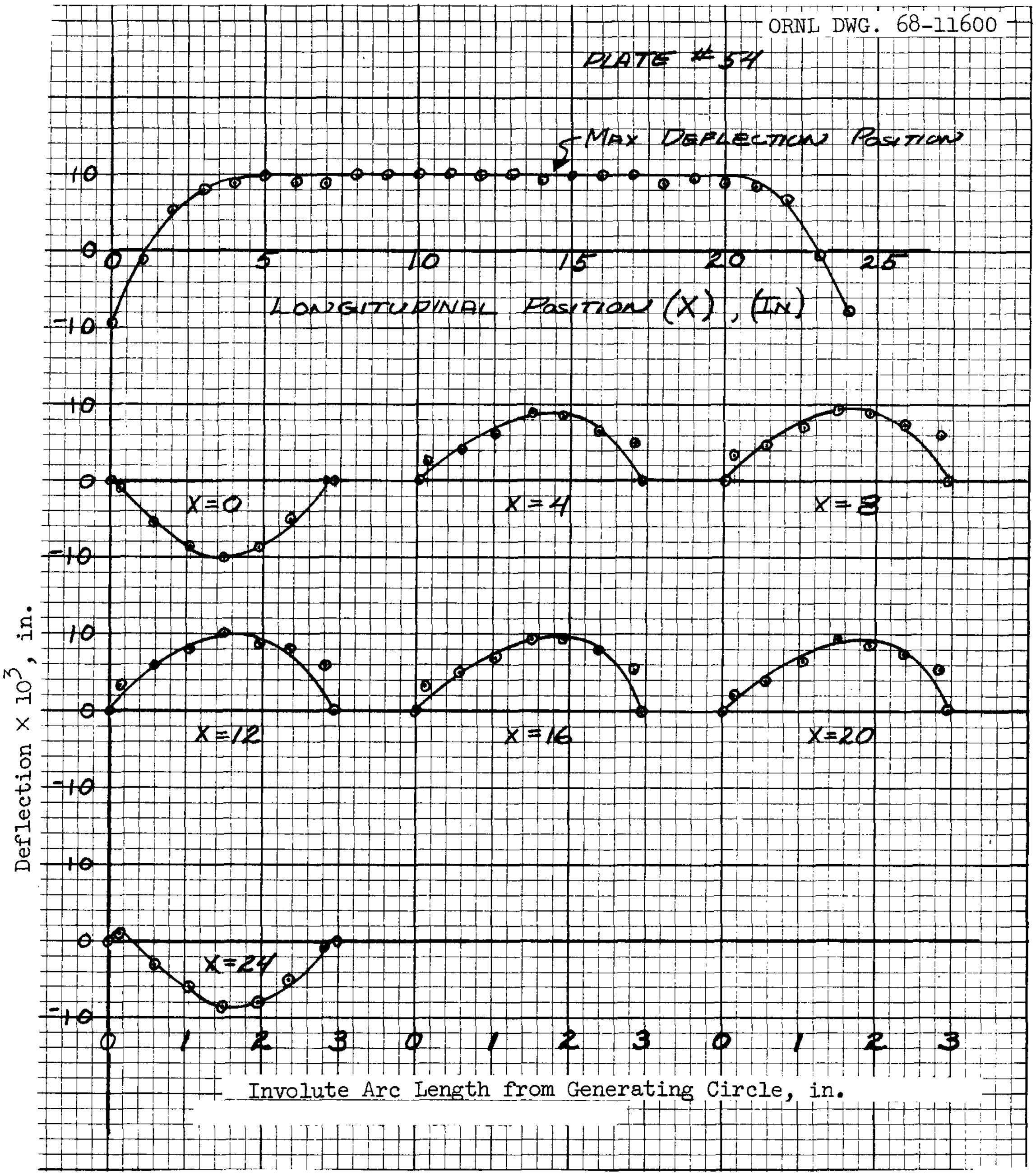

Fig. 15. Typical Plate Deflection Curves for Change in Temperature 80°F – 400°F.

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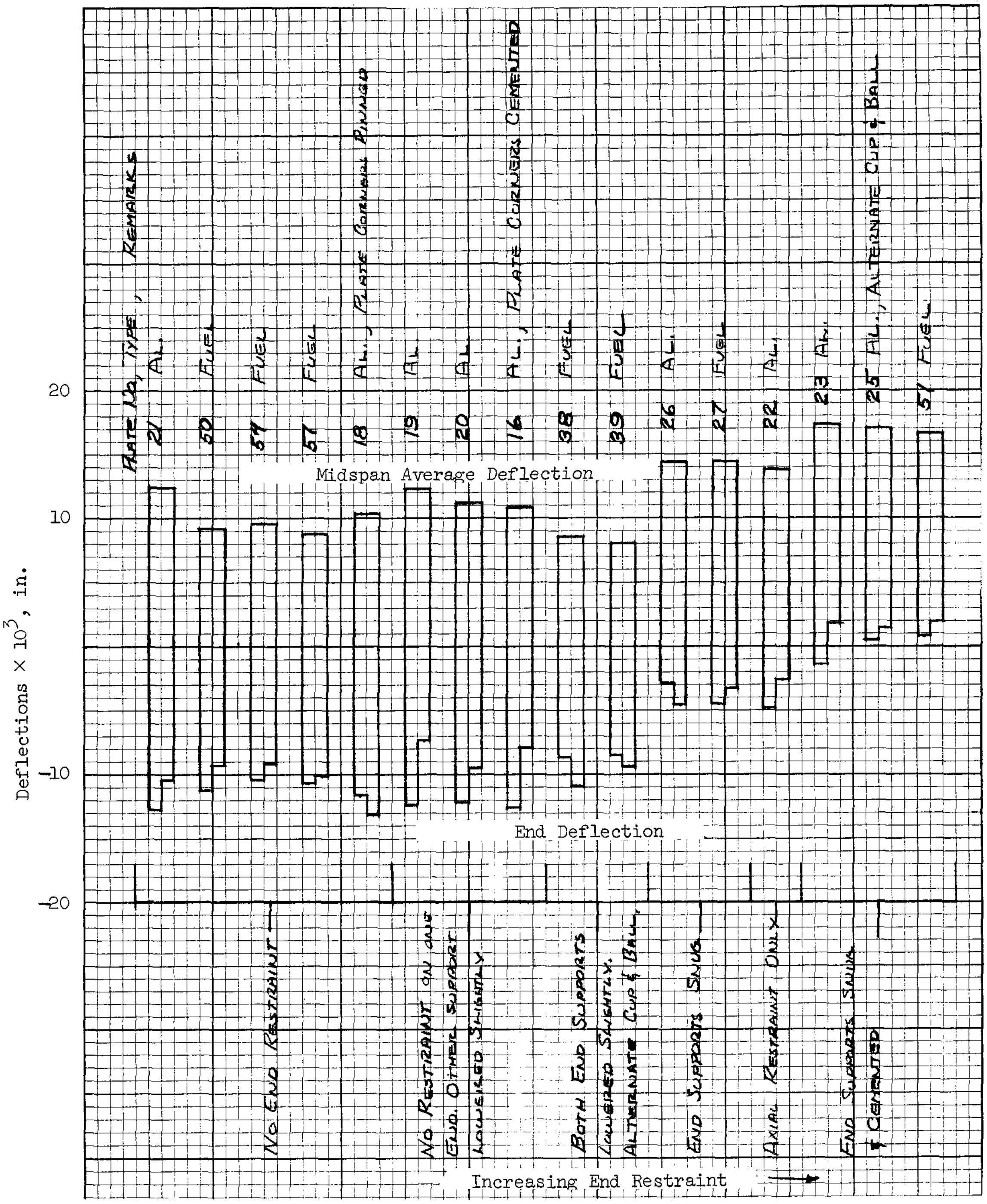

Fig. 16. Deflection Versus End Restraint for 1/4-in. Tabs (All Secured), Split Steel Base.

2 in. of carbon steel plate to each end of a 20-in.-long aluminum plate, the attachment being made by means of a 1/4-in. overlap, epoxy-cemented joint. The results of these tests are shown in Fig. 17, and indicate that the mid-span deflection for a "cold end" plate is significantly greater than for a regular free ended plate and somewhat more than that for a regular plate with fixed ends. Furthermore, the end deflection was about the same as for the free ended plate, thus resulting in a summation of end and mid-span deflections greater than for any other combination. Since the steel is stronger than the aluminum (some plastic flow appears to take place in the aluminum),and since the modulus of elasticity of the steel is greater,it is expected that for an actual aluminum plate with an axial temperature discontinuity the mid-span deflection would be somewhat less.

Different Edge Restraint

The actual degree of edge restraint is another unknown insofar as the actual HFIR core is concerned. Therefore several degrees of edge restraint were investigated. The greatest degree of edge restraint was achieved by pulling the clamp bars down tight against the edge of the plate. However, this condition was used only for pressurization tests and thus cannot be compared with the other data. The next highest degree was achieved with all 1/4-in. tabs being secured with the cupped set-screw without the bar bearing against the plate. The least degree of edge restraint was achieved with 1/8-in. tabs, in which case only every other tab was secured, and in one area two tabs were skipped to simulate a missed weld.

Results from these tests are shown in Fig. 18. As indicated there is very little difference in deflection, but there is a trend for decreasing deflection with decreasing edge restraint. This would be expected because the smaller and/or fewer the number of tabs the higher the stress and thus strain in the fixed tabs, a primary consideration in determining what size and how many attachment welds must be used in an actual element.

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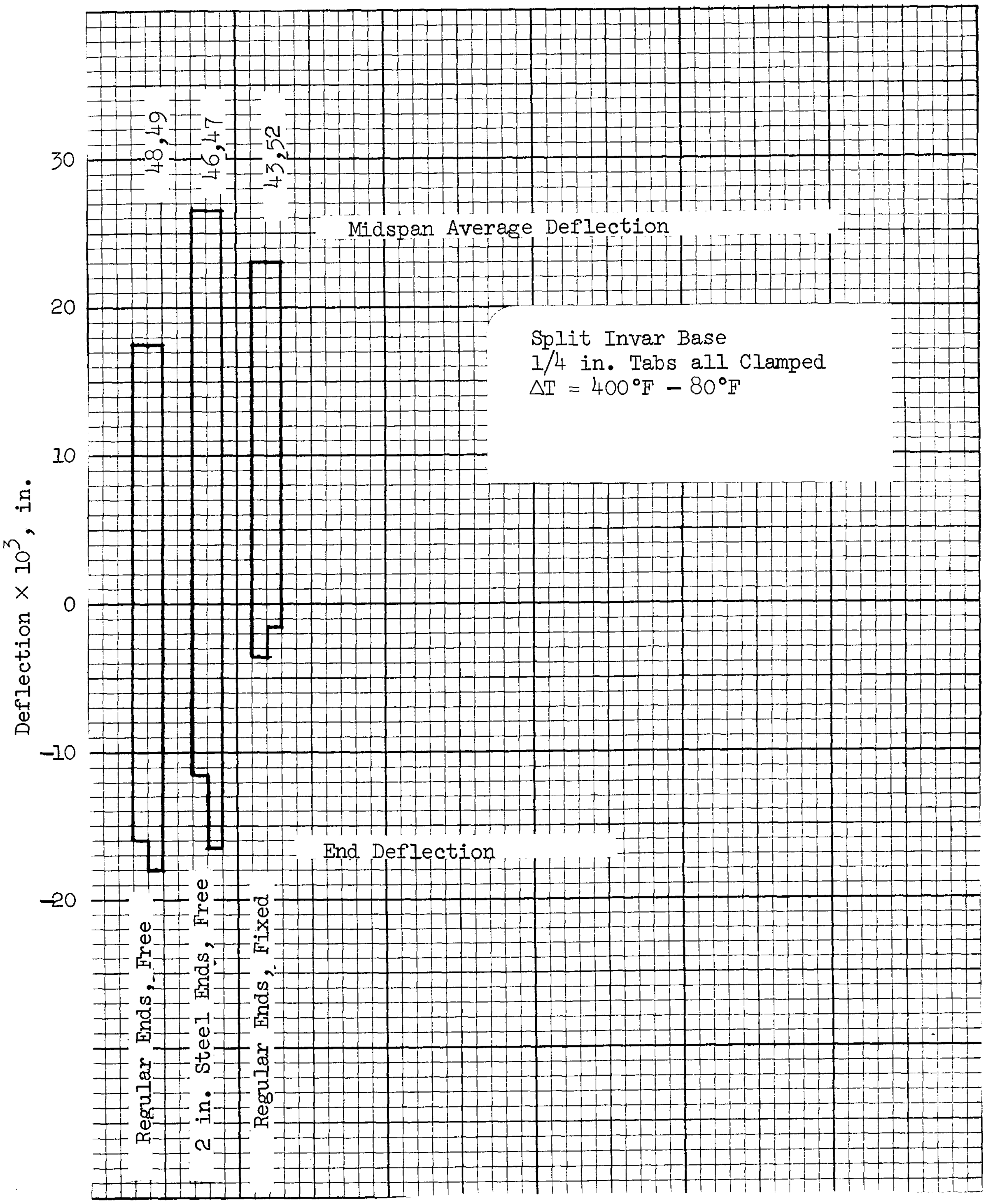

Fig. 17. Comparison of Regular Plates and Plates with 2-in. Steel Ends.

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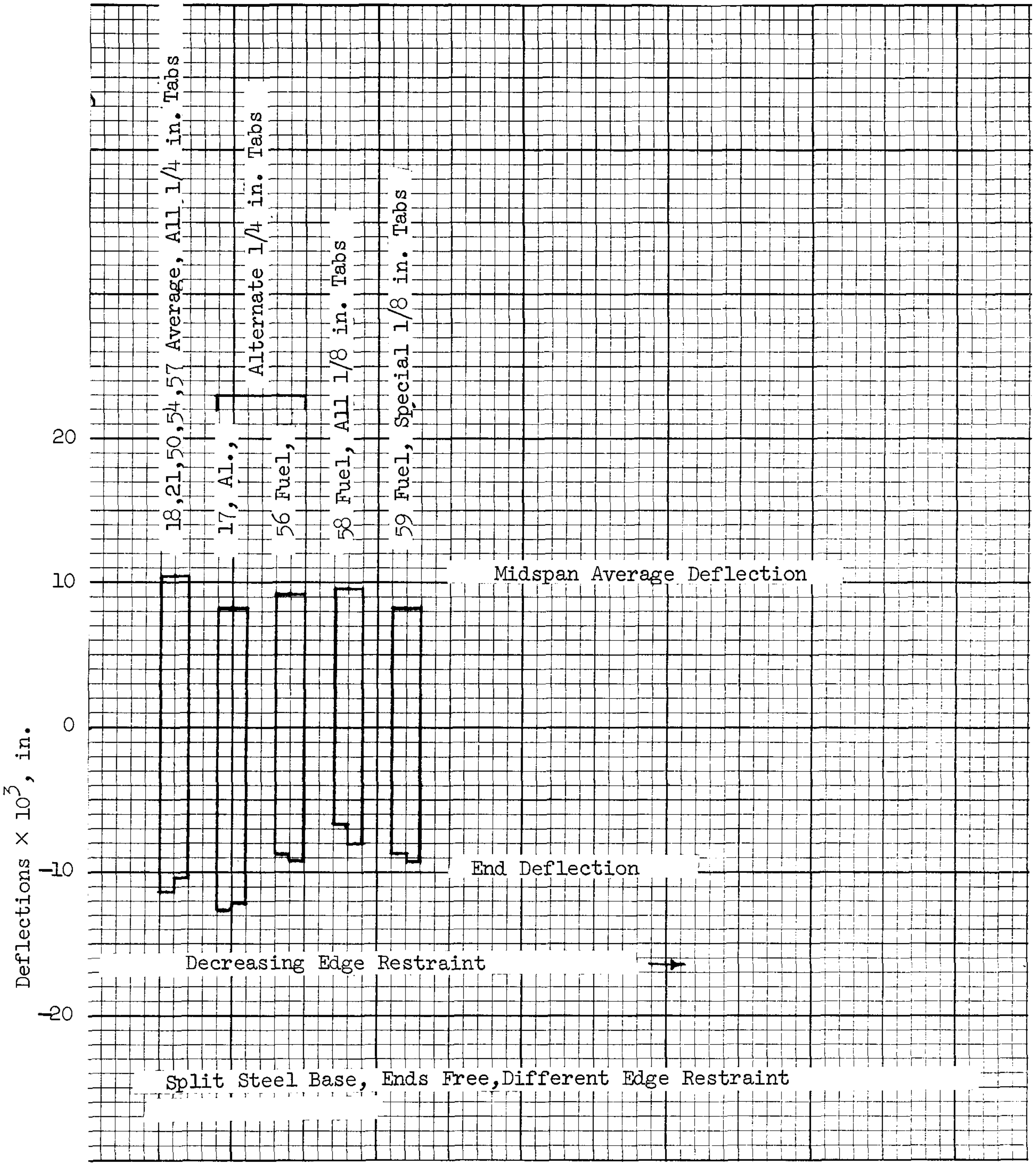

Fig. 18. Effect of Various Edge Restraints.

Split and Non-Split Base Comparison

Another edge attachment variation involves the freedom or lack thereof of an edge of the plate to move "radially" relative to the other edge. As discussed previously, freedom for this type of relative movement is incorporated in the design of the HFIR element and was simulated in the experiments by splitting the base longitudinally and then attaching the two pieces with aluminum blocks. Before splitting the base, experiments were conducted so as to superimpose the radial differential effect on the longitudinal. A comparison of deflections obtained with the split and nonsplit Invar base is shown in Fig. 19. As indicated the general shape of the deflection curve is the same for the two cases, but the radial restraint nearly doubles the mid-span deflection. One important aspect of this increased deflection is that since the stresses in the plate are higher there tends to be more creep and less resistance to differential pressure loads. These effects are discussed in the following sections.

Maximum Differential Expansion Test

The differential transformers used for measuring deflections were limited to a sustained temperature of about 400°F, but were able to function satisfactorily for a brief period of time at a temperature of at least 600°F. The 400°F limit in conjunction with the carbon steel base was high enough for HFIR operating conditions, but we were curious to find what temperature and differential expansion would be required to result in plate buckling (attainment of critical load conditions). In an attempt to satisfy this curiosity a plate (No. 66) having 1/4-in. tabs was installed on the split Invar base with all tabs secured and the ends unsupported and was subjected to a slowly increasing temperature up to 600°F. The differential strain for this case was 2.8 times what it was for a steel base assembly at 400°F, the latter combination being typical of HFIR conditions, and still the plate did not buckle.

The deflection curve for the above extreme case is shown in Fig. 20. It is noticed that after reaching a temperature of about 300°F the shape and deflection of the plate remained nearly constant, indicating that

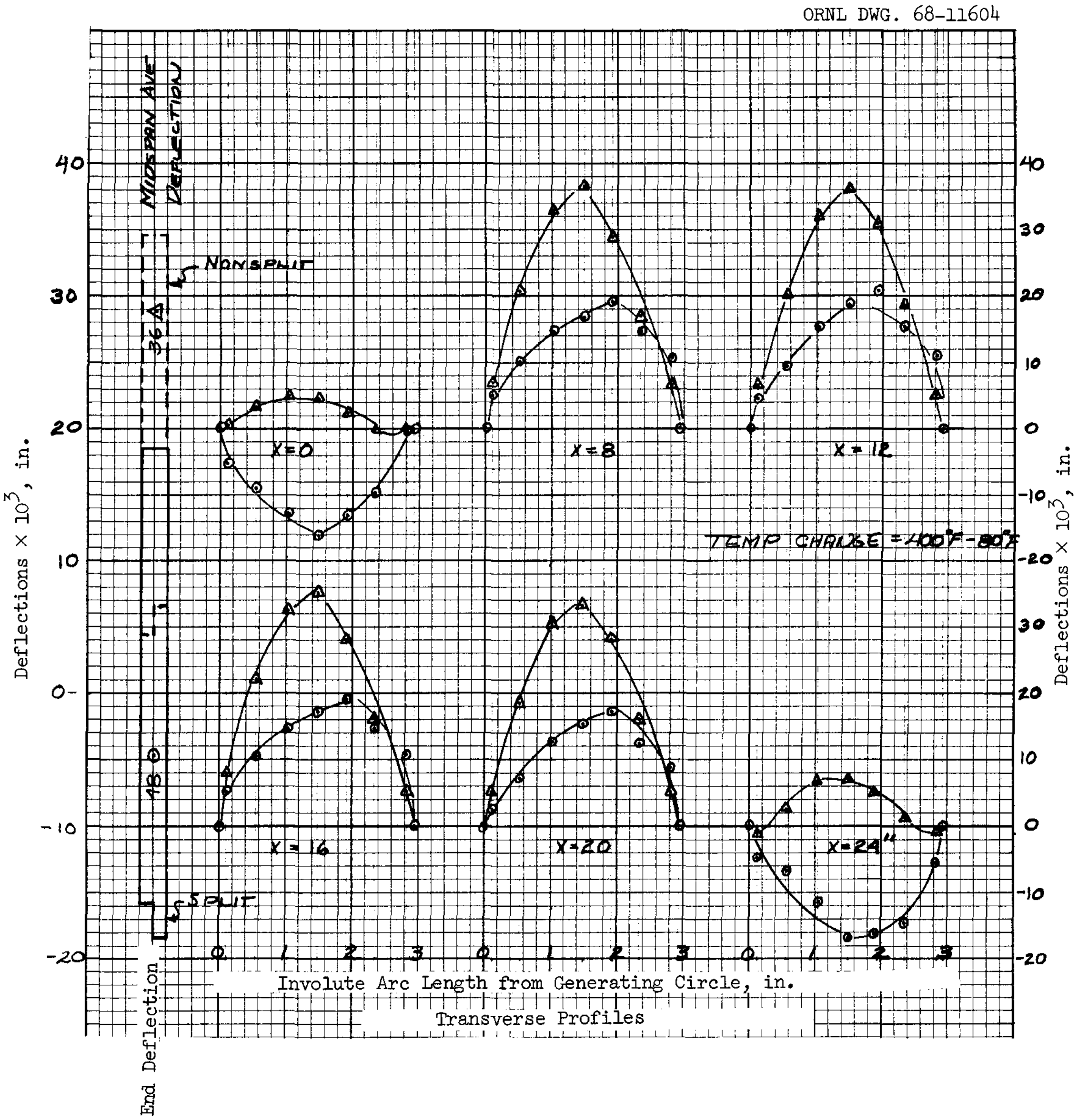

Fig. 19. Comparison of Deflections with Split and Nonsplit Base (Invar Base).

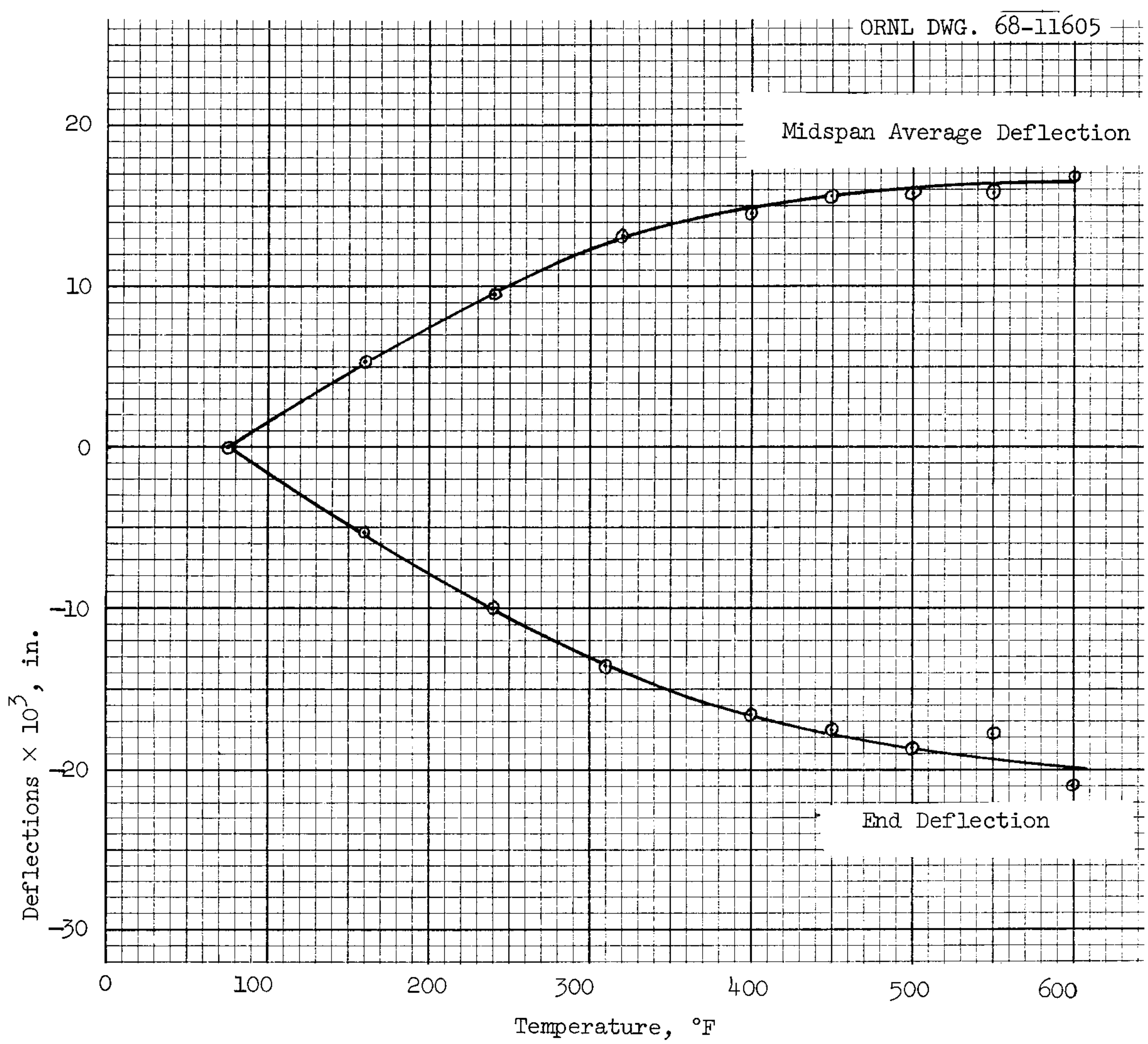

Fig. 20. Plate Deflection Versus Temperature for Fuel Plate on Invar Split Base, Free Ends,

relief (plastic flow) at the tabs prevented further deflection of the plate and thus perhaps prevented the plate from buckling. A plate having greater edge restraint might actually have buckled during such a test. On the other hand, reducing the degree of edge restraint to reduce plate deflections and the buckling tendency would eventually lead to failure of the attachment.

Plate Temperature as a Variable

In order to include plate temperature as a variable it was necessary to use at least two bases having significantly different coefficients of thermal expansion. For this purpose carbon steel, Monel, and Invar were used. (The particular Monel obtained for the experiments had a coefficient very nearly the same as that for carbon steel and thus was not of much value for the purpose at hand.) Differential expansion curves for the steel and Invar bases are shown in Fig. 7. These curves were obtained by actually measuring the difference in unrestrained axial expansion between a plate and a base as the oven temperature was raised in increments.

As indicated in the above figure an all-aluminum plate was used with the steel base, while a fueled plate was used with the Invar base. Since the fueled plate is basically an aluminum plate, its coefficient, as determined by experiment, is for our purpose the same as that for the all-aluminum plate.

Figure 7 shows that above about 300°F the difference in temperature required between the two assemblies to achieve the same differential strain is 100°F or more. It appeared that in terms of plate deflection such a temperature difference would be important because of sensitivity of aluminum strength properties to temperature. A comparison of plate deflections versus differential strain for the two assemblies is shown in Fig. 21. It is observed that the colder assembly produces slightly greater deflection, presumably because the tabs retain greater strength at the lower temperature. However, considering the accuracy with which data was obtained and the accuracy generally required in applying the data to design, it is concluded that over the range of temperatures

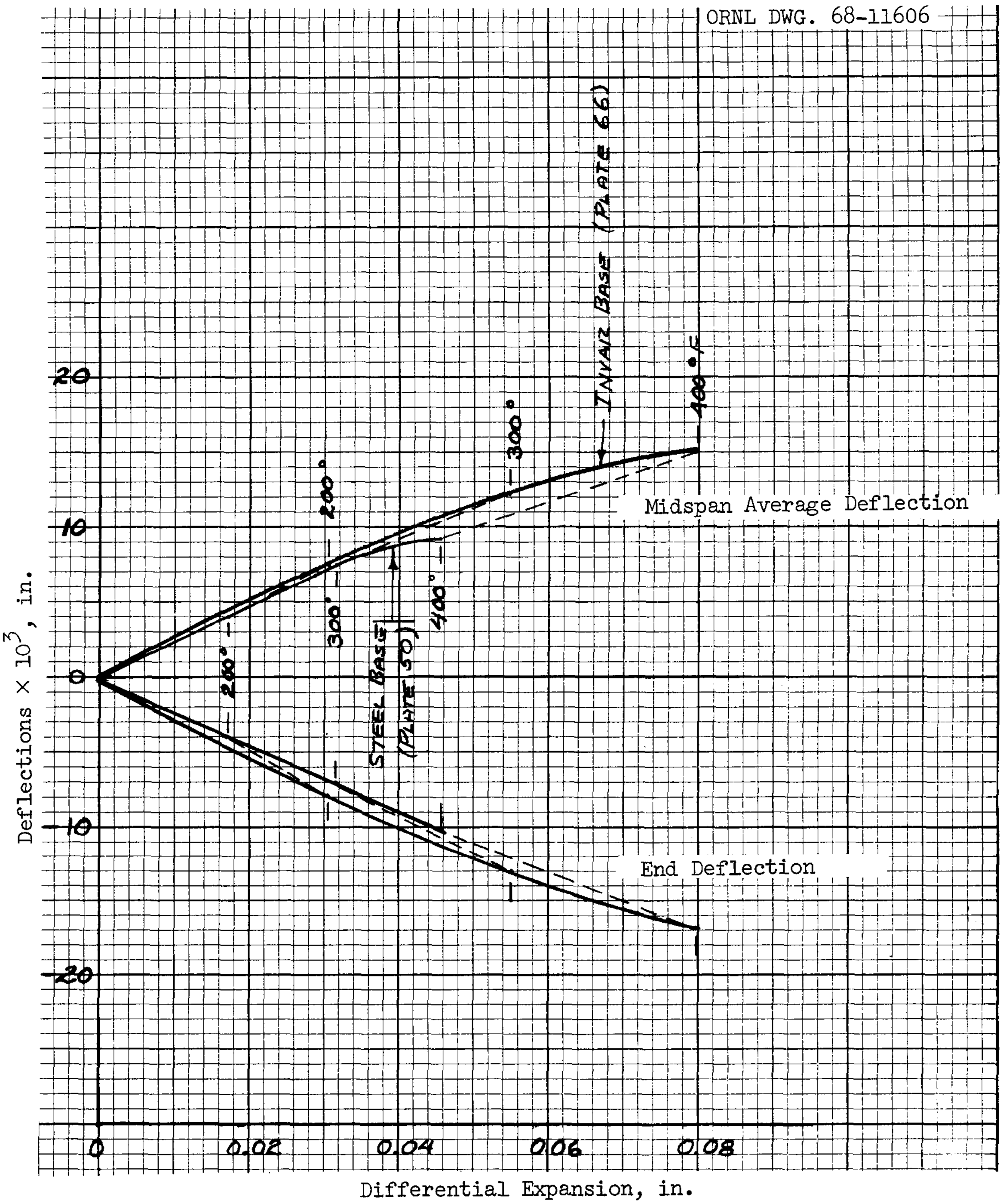

Fig. 21. Plate Deflection (Position No. 4) Versus Differential Strain Between Plate and Base for Invar and Steel Bases.

involved in the experiments there is essentially no effect of plate temperature on deflections for a given differential strain.

Initial Shape of Plate

Deflection and the tendency toward buckling are presumably influenced by the initial shape of the plate. This factor was investigated to some extent in two ways: "accepting" tolerances in shape associated with fabrication and with installation, and purposely inducing perturbations in plate shape by various techniques.

One way of inducing a shape perturbation was to use alternate cup and ball force applicators on the tabs, in which case the greater deformation of tab metal under the ball created an inward membrane displacement of the plate relative to the adjacent tabs secured with cup-shaped applicators. The effect on initial plate shape is shown in Fig. 22, which is an axial trace of transformers 4 and 7 for the room temperature and 400°F conditions. As indicated, the alternate cup and ball initial attachment produced an axial sine wave near the plate edge with a wave length of about 2 in. Upon heating the assembly to 400°F the net deflection was essentially the same as for a plate installed in the usual manner.

The shape of a plate after installation was determined by comparing the shape, by means of the transofmers, with the involute standards at one end. Typical comparisons are shown in Fig. 23, which shows the plus and minus deviations from the standards. As indicated, the center portion of the plate tended to be flatter than the standard (larger radii of curvature) while the ends in some cases tended to hump up. From the standpoint of HFIR design the tendency toward larger radii of curvature introduces conservatism with respect to buckling since a flatter plate is more likely to buckle.

Variations such as those in Fig. 23 are probably responsible for some of the spread in deflection data, but as mentioned earlier the spread is really not very large from the standpoint of application of data to core design. Thus it is concluded that initial plate shape had little effect on the results.

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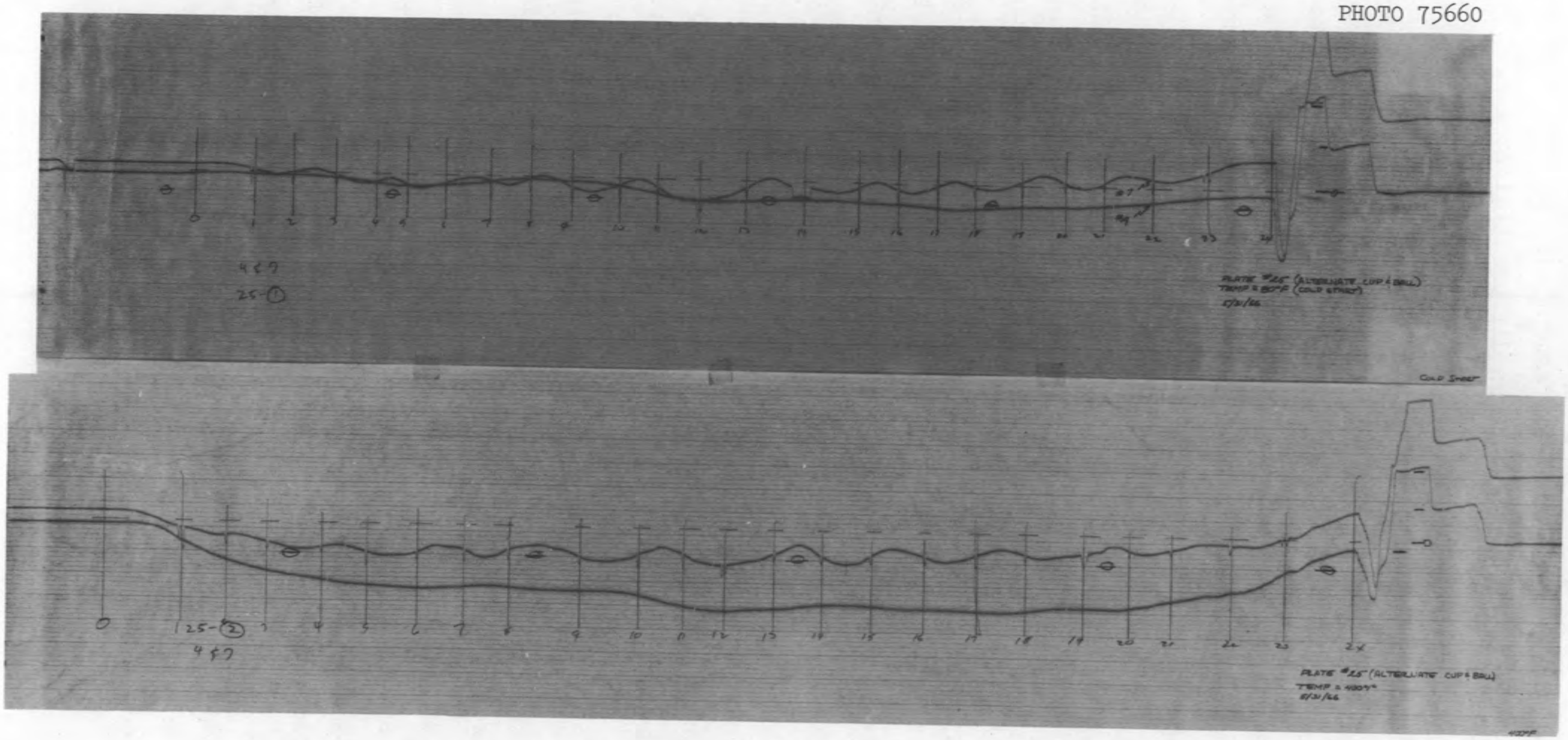

Fig. 22. Axial Traces for Positions 4 and 7 with Alternate Cup and Ball Edge Attachment.

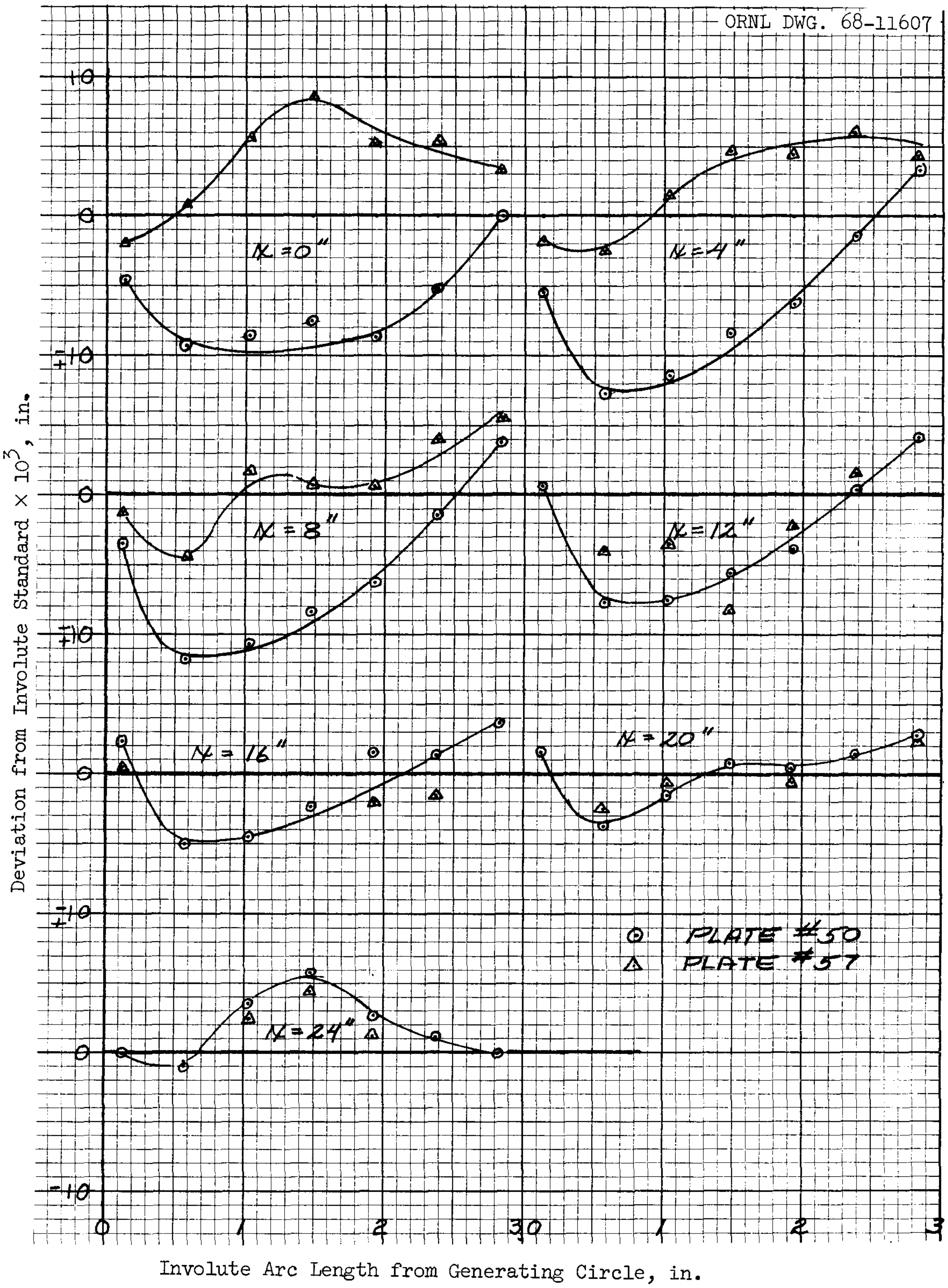

Fig. 23. Involute Arc Length from Generating Circle (in.) Shape of Installed Cold Plate Relative to Involute.

Creep and Thermal Cycling

Creep tendencies were looked for up to 400°F in several tests, in which case the maximum temperature was maintained for as much as 15 days. There were no signs of significant creep, and thus it was concluded that creep was not an important factor in the design and analysis of the HFIR plates.

Thermal cycling effects were also investigated, and it was determined that thermal cycling between room temperature and 400°F for up to four cycles had essentially no effect on plate deflection relative to the initial cold shape.

Pressure Deflections

Pressure deflections were investigated to some extent to determine what effect they might have on the thermal deflections and buckling tendencies. These experiments were necessarily restricted to the non-split bases, but it was possible to apply pressure to either side of the plate, a vacuum being used in the cavity to achieve "external" pressure. The vacuum tests were of course limited in pressures; however, the achievable differential was greater than that expected in an actual HFIR fuel assembly during reactor operation. Results from these "external" pressure experiments showed no tendency toward buckling, and the deflections were very small. It was assumed that the deflections per unit pressure were essentially the same as for the case with "internal" pressure (over a reasonable range of pressures), and thus most of the pressure experiments were conducted with "internal" pressure.

Internal pressure tests were conducted with five different plate edge attachments: completely clamped edge, 1/4-in. tabs all secured, every other 1/4-in. tab secured, every other 1/4-in. tab secured (special), and 1/8-in. tabs all secured. In order to maintain pressure in the assembly the plate ends had to be snug against the involute blocks and cemented.

Results of the tests are shown in Figs. 24 through 28. Figure 24 shows the results for two assemblies that were first brought to temperature with no pressure differential. Upon reaching a maximum temperature of 400°F the pressure was applied and increased in increments to 30 psi. As

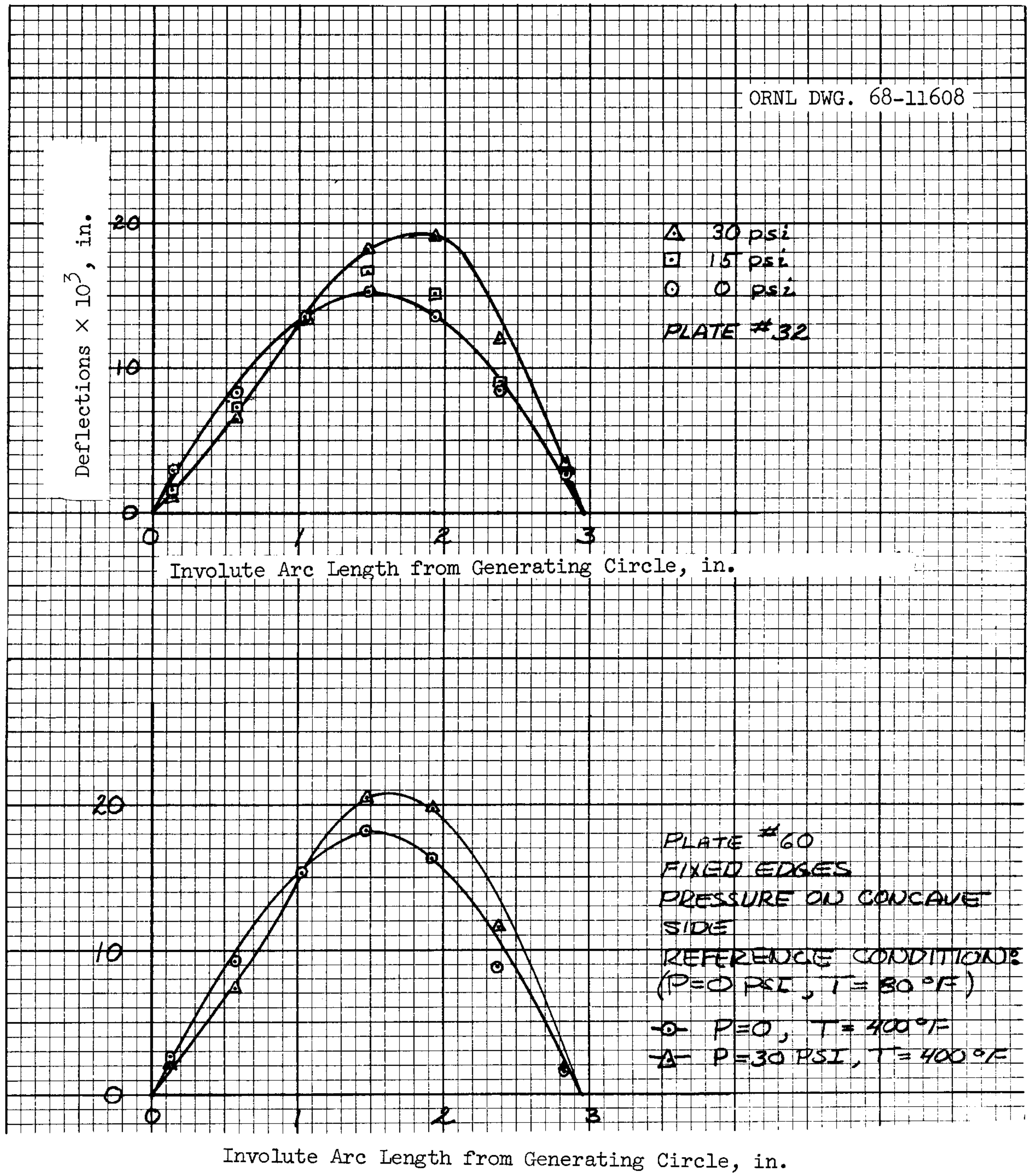

Fig. 24. Plate Deflections Caused by Temperature and Pressure.

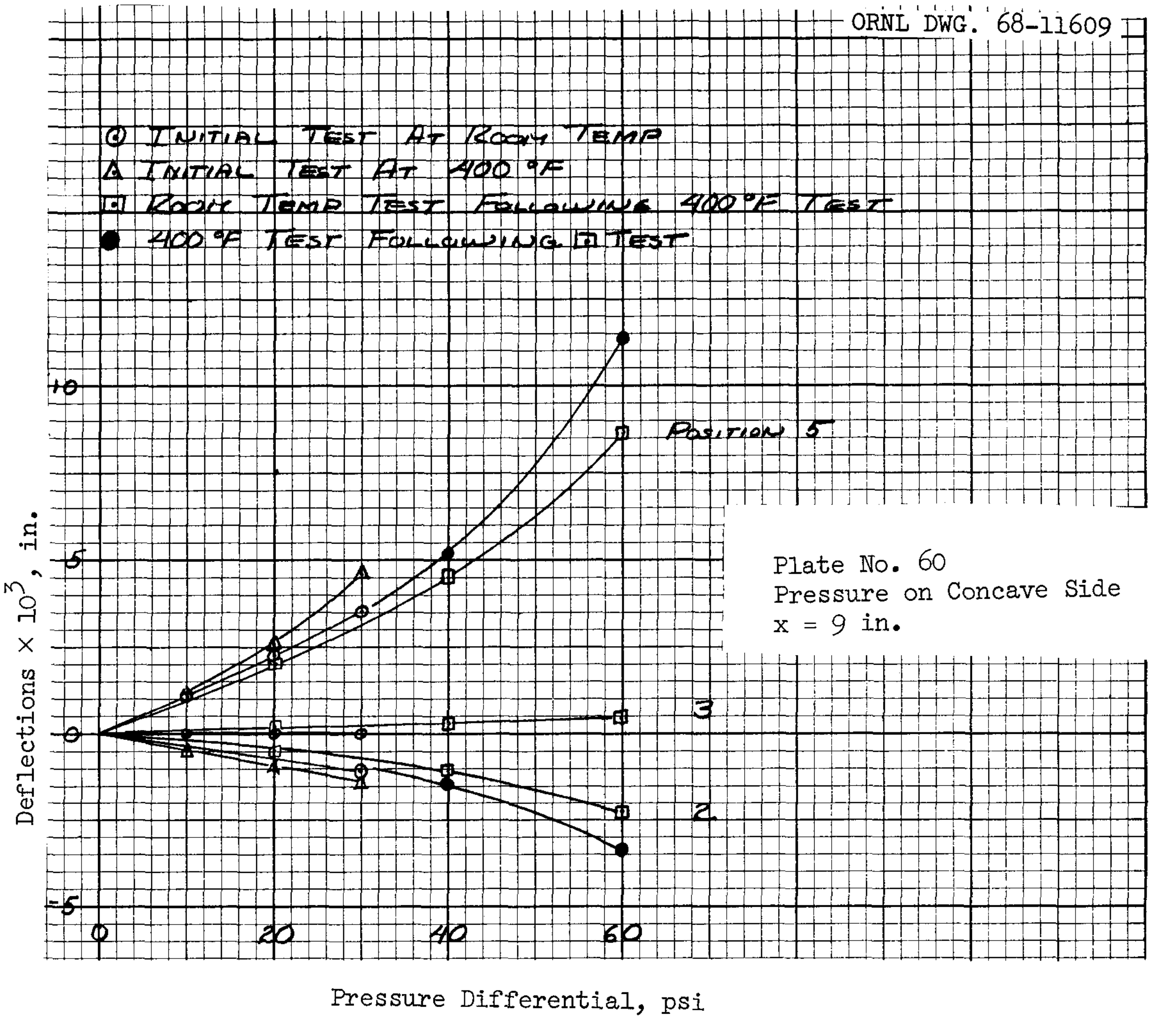

Fig. 25. Effect of Temperature and Pressure Cycling on Plate Deflection.

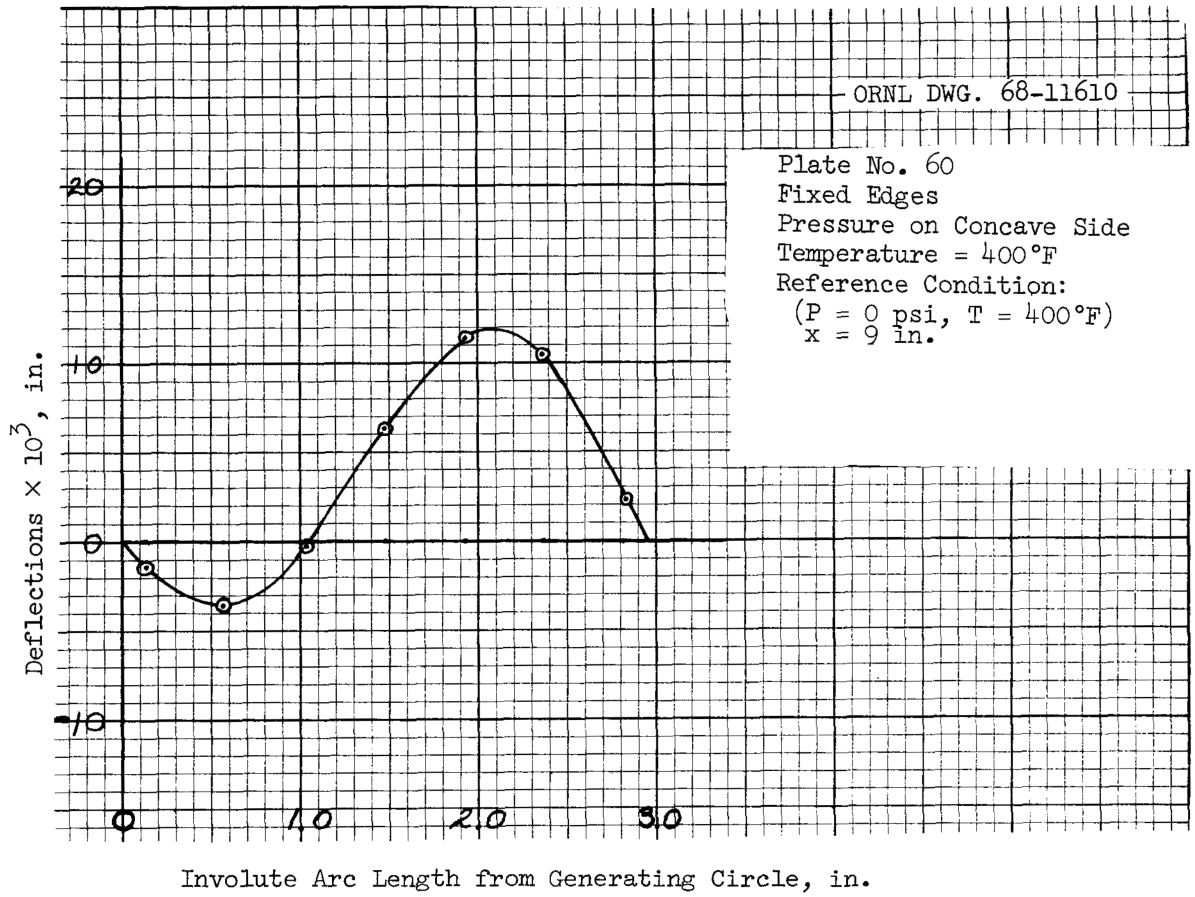

Fig. 26. Plate Deflections at 400°F with 60 psi Pressure on Concave Side Following Several Pressure and Thermal Cycles.

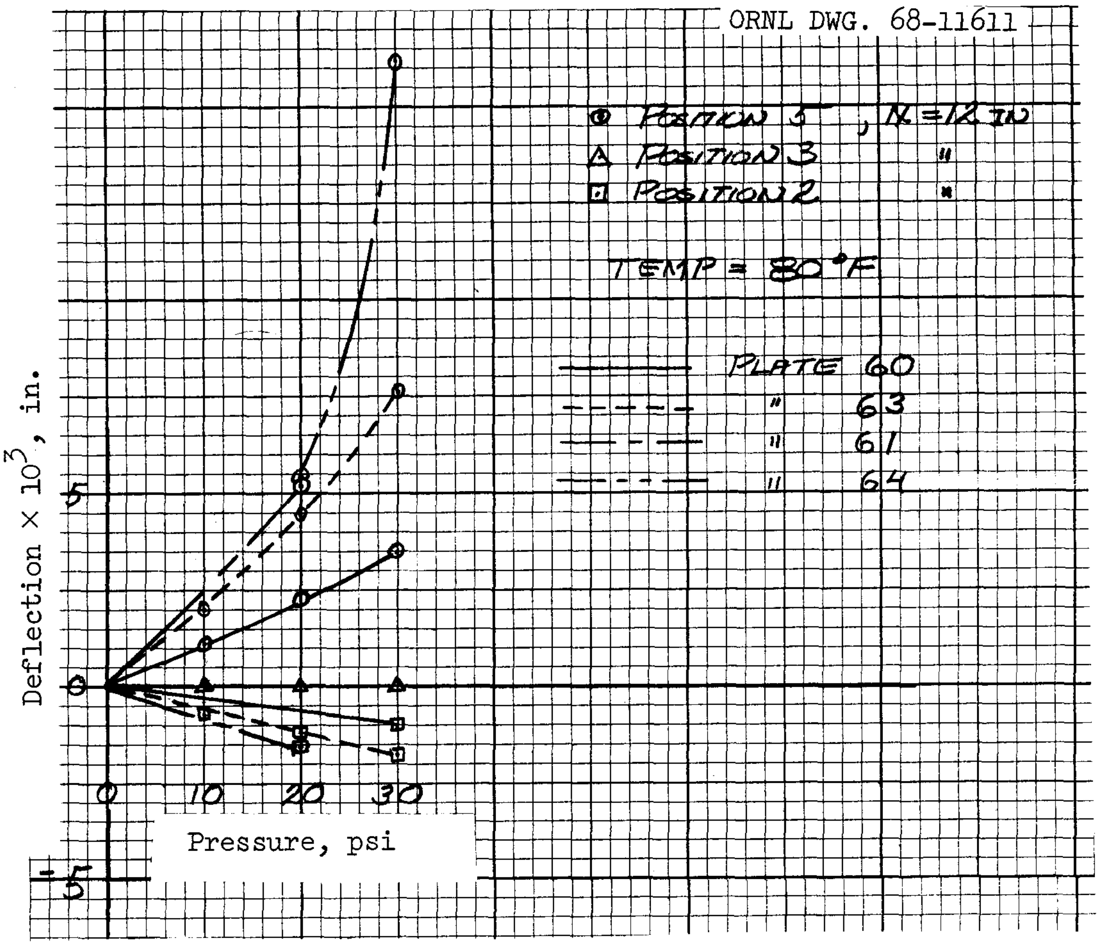

Fig. 27. Deflection for Initial Pressurization Versus Type Edge Attachment.

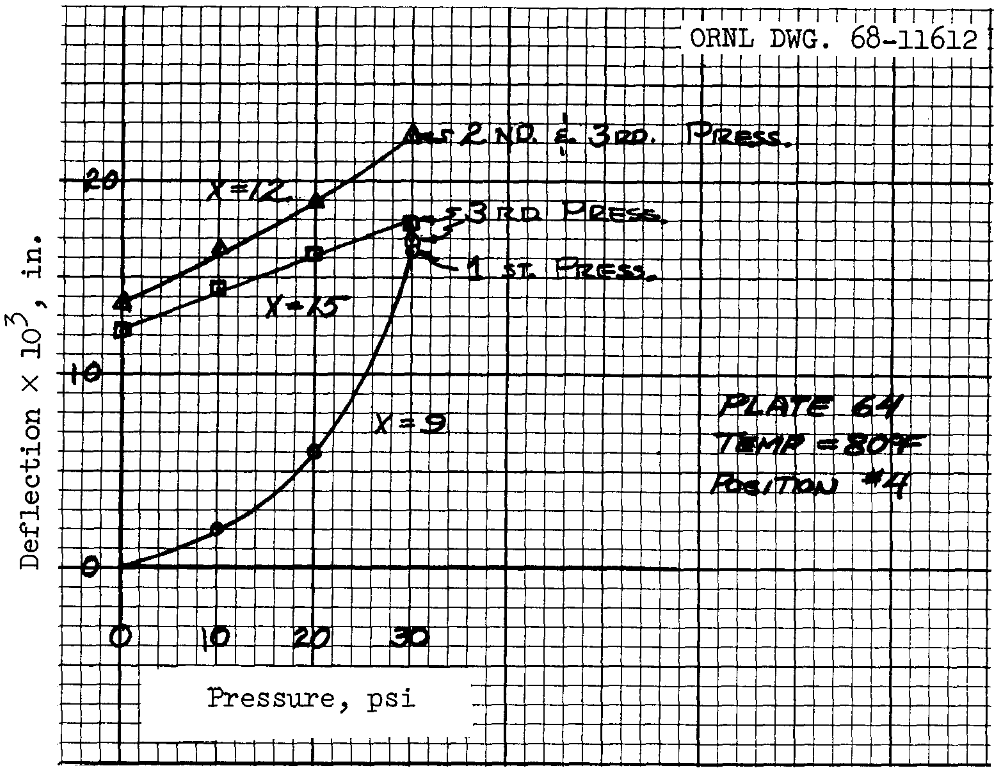

Fig. 28. Plate Deflections for Three Pressure Cycles.

would be expected the application of pressure tends to change the involute shape to that of a cylinder and thus produces negative deflections in the regions of relatively small radii of curvature. The results for two plates are shown so as to show the reasonably good agreement and thus establish some confidence in the results. In both cases the edges of the plate were clamped along the full length with the clamp bars (fixed edge condition).

Figure 25 shows the effect of thermal and pressure cycling on the shape of deflection-pressure curves. The zero deflection point in this figure is arbitrary since at the end of at least the first pressure cycle there is some permanent displacement. A plot of pressure deflection at 400°F and 60 psi versus position across the plate is presented in Fig. 26. This data corresponds to the fourth cycle in Fig. 25.

Figure 27 gives some indication of the effect of different degrees of edge restraint on pressure-induced deflections at room temperature. (In each case the pressure deflections at 400°F were about 25% greater.) For pressures below about 20 psi the pressure-deflections curves are essentially linear, indicating no plastic deformation. Above this pressure plastic flow definitely takes place at least in the case of 1/8 in. and every other 1/4-in. tabs.

Figure 28 shows the effect of pressure cycling on permanent set. Because of the way in which the test was run the permanent set of a specific point can only be inferred from data obtained from two very similar points. In Fig. 28 the comparison is made between mid-span points $x = 9$ in., 12 in., and 15 in. The $x = 12$ in. and $x = 15$ in. curves should, in a more general case, be the same. However, in this particular test excessive tightening of the tabs in the vicinity of $x = 12$ in. weakened these tabs relative to the others and permitted the plate to bulge in this area. Even so, the results indicate a rather large permanent set at 30 psi, typical work hardening of the material and probably some significant change in geometry. Table 3 lists approximate values for maximum deflection versus pressure curves for pressures less than 10 psi.

Table 3. Pressure Deflections for Different Edge Restraints

Plate No.	Edge Restraint	$\delta/\Delta p$ (mils/psi)
60	Continuous edge clamp	0.10
63	1/4-in. tabs	0.20
61	1/8-in. tabs	0.22
64	Every other 1/4-in. tab	0.22

The other edge condition examined consisted of every other 1/4-in. tab with one additional tab left out to represent one missed attachment weld. In this case the maximum deflection in the area of the missing tab was about 50% greater than in the unaffected areas, the affected area extending several inches in the longitudinal direction.

Comparison of Measured Pressure Deflections with Calculation

Earlier in the HFIR program, Chapman[6] calculated plate deflections resulting from uniformly applied pressure differentials for fixed edge and pinned edge conditions. His results have been compared with these experimental results, and agreement between fixed edge conditions is very good. There was not a true pinned edge case represented in the experiments, but it is of interest to note that the calculated pinned edge results agree well with the 1/4-in. tab results.

Chapman's calculations also show that the pressure deflections for the HFIR inner element fuel plates are about twice that for the outer.

APPLICATION OF DATA TO HFIR DESIGN

Thermal and pressure deflections of the fuel plates can have an effect on coolant flow and thus heat transfer if the deflections are not

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[6] T. G. Chapman, Thermal Expansion and Pressure Differential Induced Stress and Deflections of HFIR Involute Contoured Fuel Plates, USAEC Report ORNL (to be published).

the same for each channel. If the coolant channels were perfectly uniform in the cold condition, and if thermal deflections of all plates were identical, then there would be no differential pressure across the plates and the flow would be uniform throughout. Of course there are initial variations in coolant channels and heat generation rates and thus nonuniform flow and channel dimensions. In the actual case these variations are not uniform along the length of the channel, and it becomes necessary to use a numerical method of analysis to represent the actual case precisely. The data obtained in these experiments are not strictly applicable for a case with axial gradients. However, reasonably good results should be obtained by using the average temperature over the heated length for determining thermal deflections. Of course a similar assumption must be made regarding the side plate temperature so that an appropriate temperature difference will be obtained.

In recent HFIR core heat removal calculations[7] the plate thermal deflection curve was represented by a sine curve across the width of the plate, by a sine curve in the longitudinal direction near the ends of the plate and by a straight line between these ends. The origin of the longitudinal sine curve was at the end of the plate so that thermal deflections did not result in a change in channel inlet and outlet dimensions.

The assumption that the inlet and outlet dimensions of the HFIR channels do not change is a reasonably good assumption since the elements have combs at both ends. Furthermore, since the plates do not actually buckle in such a way as to produce a multinode curve, the effect of plate deflection is quite small, making an accurate selection of end conditions reasonably unimportant.

Preliminary calculations[3] associated with HFIR fuel plate and side plate temperatures indicated that the "hot plate" plate temperatures and the corresponding side plate temperatures were consistent with the use of the carbon steel base in the experiments up to a uniform temperature

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[7]H. A. McLain, HFIR Fuel Element Steady-State Heat Transfer Analysis, Revised Version, USAEC Report ORNL-TM-1904, Oak Ridge National Laboratory, December 1967.

of 400°F. In principal an iterative procedure should be used to arrive at the proper combination of plate temperature and differential expansion. However, as indicated in Fig. 21, if the plate temperature is not above about 400°F and if the differential strain falls somewhere between that achieved with the carbon steel and Invar bases, then the iterative process would appear to be unnecessary.

Another factor of interest is the degree of axial restraint provided by the side plates. In the experiments the base, which took the place of an actual side plate, was very rigid relative to the fuel plate and thus did not significantly reduce the axial interface forces as a result of being extended by these forces. On the other hand, in an actual element the fuel and side plate materials are the same and the cross sectional area of the fuel plate is about twice that of the side plate. If the fuel plate were attached continuously along its length and if it did not bend under load, the strain in the side plate would be appreciable and the strain in the fuel plate would be determined from

$$\epsilon_f = \left[\frac{T_f - T_s}{\left(\frac{A_f}{A_s} - 1\right)} + (T_{f_H} - T_f)\right]\alpha \,, \qquad (1)$$

where

ϵ_f = "hot plate" fuel plate longitudinal strain induced by differential expansion between fuel plate and side plate,

A_f = effective fuel plate cross sectional area,

A_s = effective side plate cross sectional area,

T_f = circumferentially averagedfuel plate temperature for fuel element,

T_s = circumferentially averaged side plate temperature for fuel element,

T_{f_H} = "hot plate" fuel plate temperature,

α = linear coefficient of thermal expansion.

If the side plate is "infinitely" rigid as was the case in the experiments, then $A_s = \infty$ and

$$\epsilon_f = (T_{f_H} - T_s)\,\alpha \ . \tag{2}$$

For the HFIR, $A_f/A_s \cong 2$, $T_f - T_s = 100°F$, and $T_{f_H} - T_f = 70°F$. For these conditions the fuel plate strain from Eq. (1) is about 61% of that from Eq. (2). If $T_{f_H} = T_f$, the percentage would be 33%.

The above analysis is not really valid for the HFIR because the plates do bend (deflect normal to their original surface), and the attachment is not continuous. Both of these conditions reduce the force that can be generated between the fuel plate and side plate, and this situation was well represented in the experiments. The net effect is a reduction in the side plate strain as calculated above. Thus, as a first approximation it was assumed that the experimental results, as applied to the HFIR, did not need to be corrected for side plate strain.

Pressure deflections for the HFIR fuel plates appear to be very small since the maximum pressure differentials are calculated to be only about 5 psi, indicating deflections of no more than 0.001 in. In the reactor the pressure differentials are not uniform over the plate; thus the actual deflections would be considerably less than those measured in the experiments for the same maximum differential pressure.

During the early stages of fuel element design it was believed that the pressure differentials across a fuel plate would be larger than now calculated, and furthermore there was some question regarding the accuracy of the plate deflection calculations. For these reasons it was decided to insert combs in each end of an element, where the largest differential potential exists. Since that time the inlet ends of the fuel plates have been beveled to reduce the potential differential, and there is now greater confidence in the deflection versus pressure curve as a result of these recent experiments and the good agreement between these results and Chapman's[6] calculations. Thus, in order to reduce fabrication costs and the potential for element damage during comb installation, a proposal[8] was made to build future cores without combs. It is of some interest to

[8]R. D. Cheverton, Oak Ridge National Laboratory, personal communication with ORNL HFIR Operations personnel, 1967.

note that two core loadings without combs have now been operated at full power for the normal life of the elements without any indications of difficulties attributable to the omission of combs.

ACKNOWLEDGEMENTS

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