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ORNL-TM-212

THERMALLY INDUCED CYCLIC STRAINS IN THE ORR LARGE-FACILITY DISHED HEADS

J. M. Corum
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CONTENTS

	Page
Abstract	1
Introduction	1
Results of Strain Measurements on Large-Facility Housings	2
Experimental Determination of Strains in the Large-Facility Dished-Head Model	11
Interpretation of Results	13
Appendix. Mechanical Properties of Aluminum Alloy 5154-0	20
References	27

THERMALLY INDUCED CYCLIC STRAINS IN THE ORR LARGE-FACILITY DISHED HEADS

J. M. Corum B. L. Greenstreet

Abstract

Measurements were made to determine the magnitudes of the temperature-induced strains in one of the large-facility housings of the ORR. The results from these measurements, along with data obtained from tests on a model of the large-facility housings, were used to estimate the peak strains. The structural behavior in terms of resistance to cyclic strains, or stresses, was then predicted from these peak values.

The effects were found to be less serious than anticipated. However, cracking of the dished heads may occur after 20 000 cycles for the present cooling-water exit-temperature range (70 to 135°F). Increasing the maximum cooling-water exit temperature to 150°F may reduce the number of cycles before cracking to 7600.

Introduction

A previous report[1] described the structural investigations which were made to determine the feasibility of increasing the power level of the Oak Ridge Research Reactor. Consideration was given to increasing the reactor cooling-water outlet temperature and to raising the coolant flow rate. An increase in the cooling-water outlet temperature would result in greater thermal-expansion stresses throughout the system, and a higher flow rate would be accompanied by higher hydrostatic pressures and consequently by larger stresses in portions of the core and reactor tank.

It was predicted that increasing the reactor cooling-water flow rate to 22 000 gpm would cause localized plastic deformation in certain regions of the core box. It was concluded, however, that the deformation could be tolerated and that the structural integrity of the core box would be maintained. It was also pointed out that vertical thermal expansion of the reactor tank might induce severe cyclic strains in those portions of the large-facility dished heads above and immediately adjacent to the obrounds, and, consequently, it was recommended that two specific steps be

taken to obtain information necessary to more accurately assess the structural integrity of the large facilities. These were (1) to obtain additional strain measurements on the large-facility housings and (2) to obtain mechanical properties data, including stress-strain correlations and strain-cycling data, for the housing material. These steps were taken and the effects of cyclic strains in the dished heads were re-examined.

The results of this extended investigation and the final structural evaluation are reported here. The strain measurements made on the north-facility housing, the strain-gage analysis of a 1/4-scale aluminum model of the large-facility housings, and an interpretation of the results are presented. The applicable mechanical properties of the dished-head material are discussed in the Appendix.

The authors wish to acknowledge the participation and contributions of several individuals in this work. Professors R. L. Maxwell and R. W. Holland of the University of Tennessee Mechanical Engineering Department were responsible for constructing and calibrating the special strain-measuring devices which were used. The measurements were made with the help of R. L. Maxwell, R. W. Holland, and J. E. Smith. J. E. Smith was responsible for conducting the model strain-gage analysis. Credit is also extended to the Reactor Operations group at the ORR for their assistance and patience during the several strain-measurement tests.

Results of Strain Measurements on Large-Facility Housings

Vertical thermal expansion of the ORR reactor tank produces large reaction forces between the large-facility obrounds and the dished heads, which are rigidly attached to the concrete pool wall. Since the obround-dished head region is less deformation-resistant than other parts of the reactor tank structure, these reaction forces produce large strains in the regions of the dished heads which are directly above and adjacent to the obround-dished head junctions. As the reactor undergoes its normal cycles of startup and shutdown, these strains become cyclic and could possibly cause damage that would lead to fatigue cracks.

Several series of measurements were made on the north-facility housing in order to determine the nature and magnitudes of these large strains. The first series was made using Huggenberger tensometers, which are mechanical strain gages. The gages were positioned on the large-facility housing by long poles, and the elongation readings were made from pool-side, using binoculars. The Huggenberger tensometers had three important limitations:

1. Lack of space between the dished head and the reactor vessel made it impossible to install a gage directly in the region where the large strains occurred.

2. The gages were difficult to position using long poles.

3. Precise readings of the gages could not be made.

All subsequent strain measurements were made using specially designed instruments which utilized waterproofed electrical-resistance strain gages. A photograph of one of the instruments is shown in Fig. 1. The instruments were located on the dished head by using long aluminum tubes (see Fig. 2), which were removed after the device was properly positioned. Strain in the dished head between the upper and lower contact points of the strain-measuring instrument produced displacements at the end of the cantilever beam, and these displacements, in turn, produced strains in the electrical strain gages attached to the beam. These strains were read using portable indicators and were converted into quantities applicable to the dished head by the use of predetermined calibration curves.

Successful measurements relating strain to cooling-water exit temperature were made at eight locations on the north-facility housing, as shown in Fig. 3. Measurements at locations 1, 2, 3, and 4 were made using Huggenberger tensometers, and the remaining measurements were made using the special instruments.

The Huggenberger tensometer measurements were made for the following conditions. The reactor cooling-water exit temperature was raised to approximately 105°F using reactor power. The reactor was then shut down, the water level was lowered to the reactor tank top, and the gages were positioned. The cooling-water exit temperature was then lowered approximately 30°F in steps of roughly 10°F each, and readings were made at the end of each incremental temperature drop. For the remaining measurements,

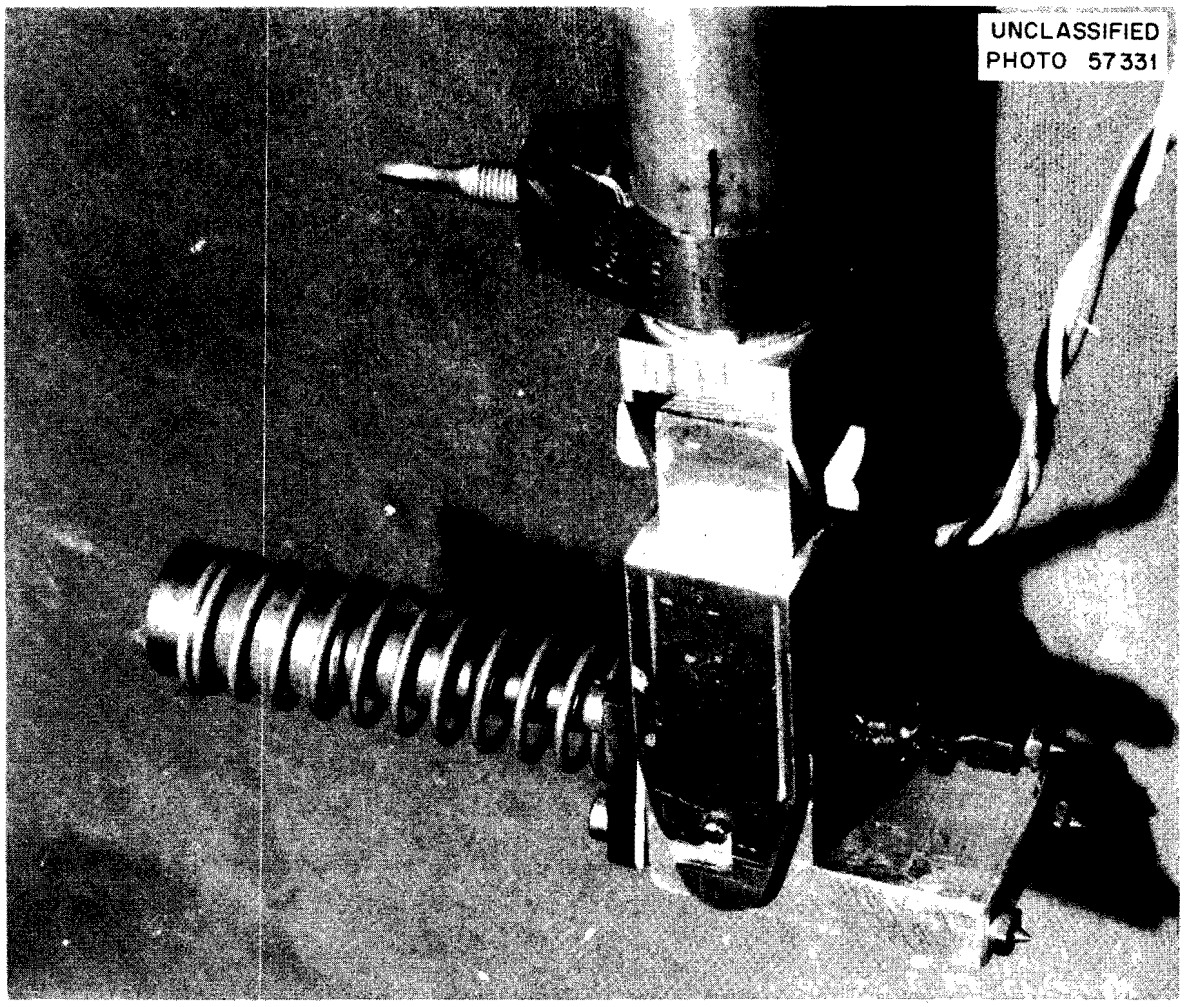

Fig. 1. Instrument Used for Measuring Strains in the Large-Facility Dished Heads.

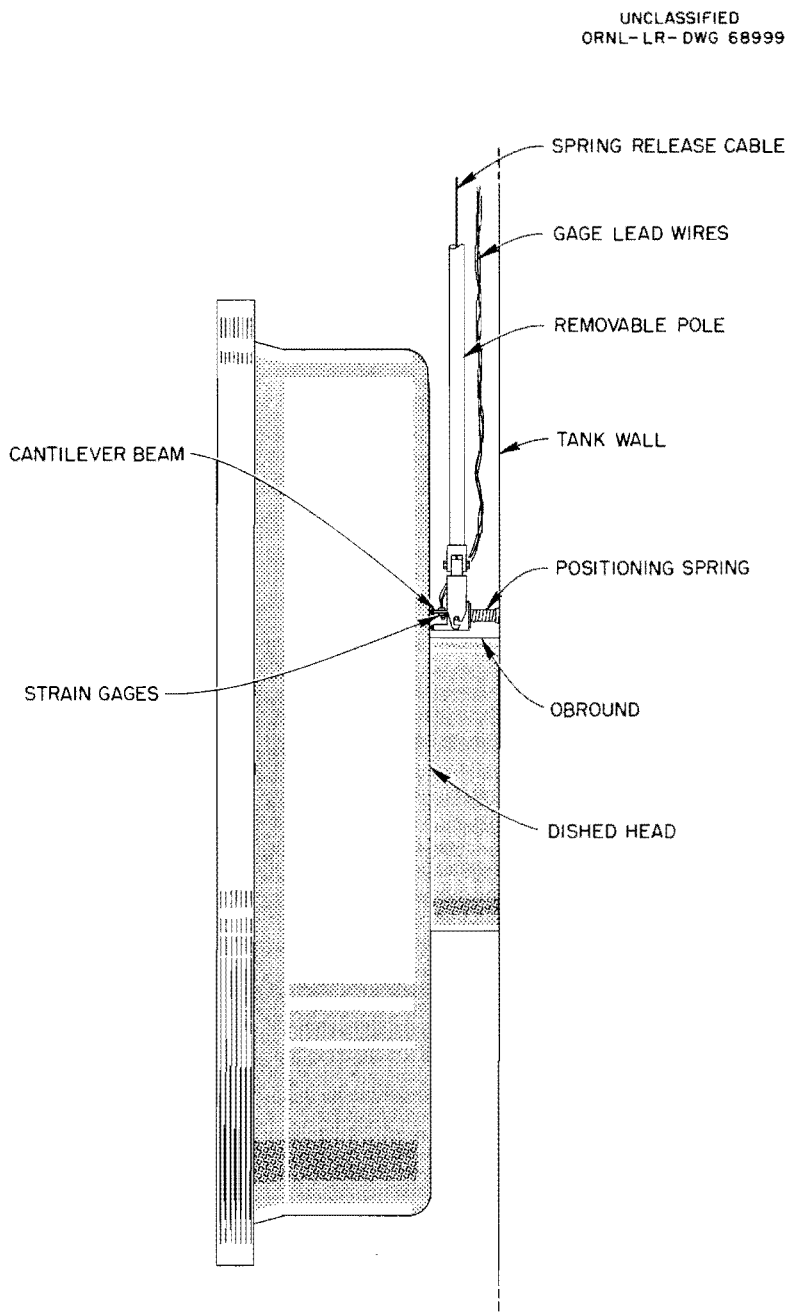

Fig. 2. ORR Large-Facility Housing with Strain-Measuring Instrument in Position.

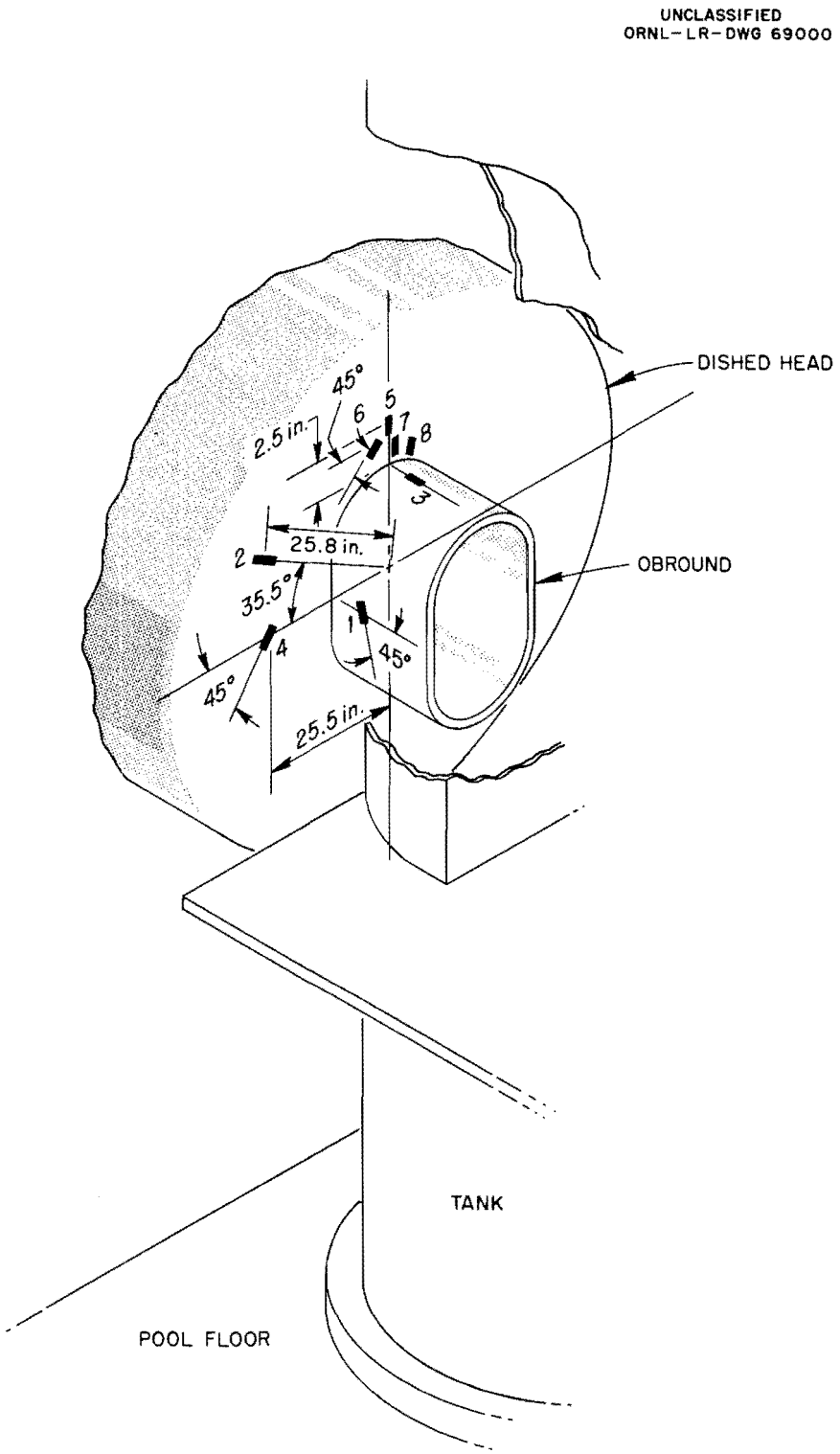

Fig. 3. Locations of Strain Measurements on Large-Facility Housings.

using the special instruments, the instruments were attached to the dished head with the reactor shut down and the cooling-water exit temperature near 70°F. The reactor was then brought to power and the cooling-water exit temperature raised to approximately 135°F. The temperature was held at this value until a quasi steady-state thermal condition was reached; the reactor was then shut down and the cooling-water exit temperature lowered to 70°F again. Strain measurements were made at 5-min intervals during the entire cycle. Strip charts which record the reactor cooling-water exit temperature as a function of time were used to correlate the strain measurements with temperature.

The strain data obtained with the Huggenberger tensometers are shown in Figs. 4 and 5 as functions of the cooling-water exit temperature. Straight lines were arbitrarily drawn between the points. The dashed straight lines drawn through each set of data represent the approximate slope of the strain versus temperature data. The measurements which were made using the special instruments are shown as functions of the cooling-water exit temperature in Figs. 6 through 9. Again, the points were connected by straight lines, and dashed straight lines were drawn through each set of data to represent the approximate slope in each case. The arrows distinguish the data taken during heating and those taken during cooling. The peculiar behavior exhibited at low temperatures in Fig. 6 was caused by the pool water level being raised during the initial part of the heating period and lowered during the latter portion of the cooling period. The change in pressure head produced strain changes in the dished head which are superimposed on those produced by temperature.

The strain-measurement results depicted in Figs. 4 through 9 were used, in combination with the results of the model strain-gage analysis and mechanical properties of the dished-head material, to assess the effects of the present cooling-water exit temperature range, as well as the effects which may be expected when the maximum cooling-water exit temperature is raised.

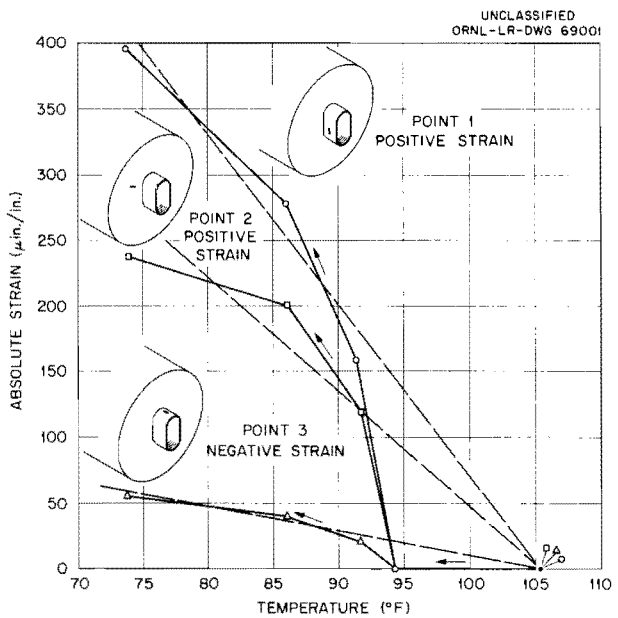

Fig. 4. Measured Strain Versus Cooling-Water Exit Temperature at Locations 1, 2, and 3 on the Large-Facility Housings.

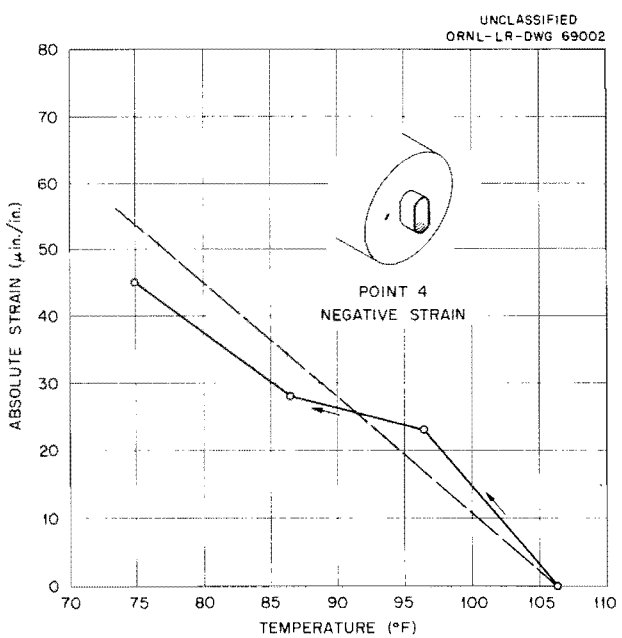

Fig. 5. Measured Strain Versus Cooling-Water Exit Temperature at Location 4 on the Large-Facility Housings.

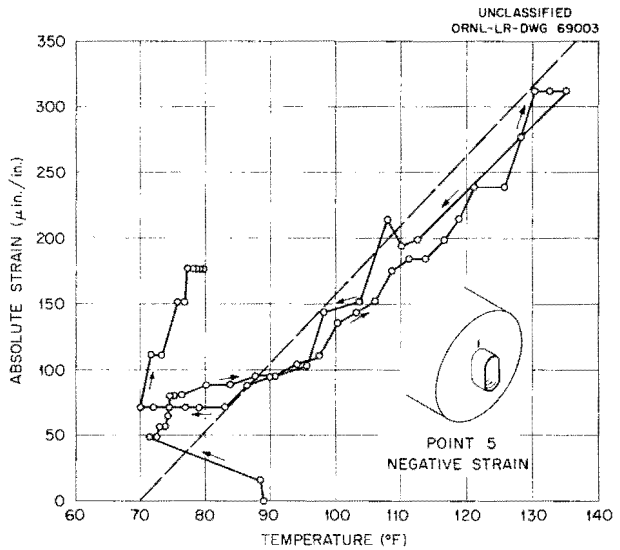

Fig. 6. Measured Strain Versus Cooling-Water Exit Temperature at Location 5 on the Large-Facility Housings.

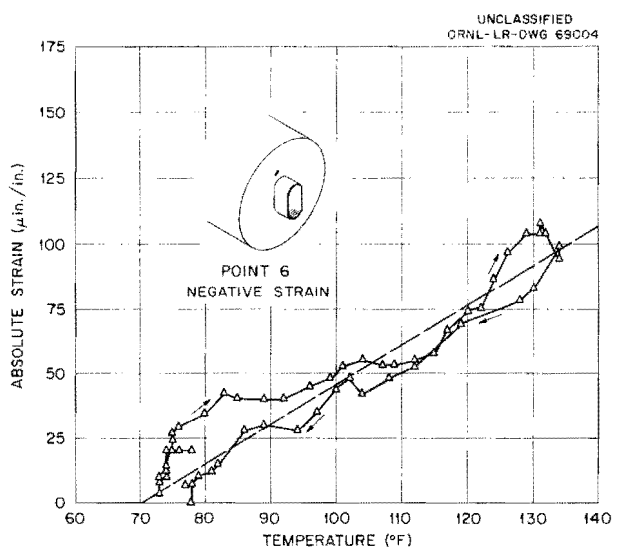

Fig. 7. Measured Strain Versus Cooling-Water Exit Temperature at Location 6 on the Large-Facility Housings.

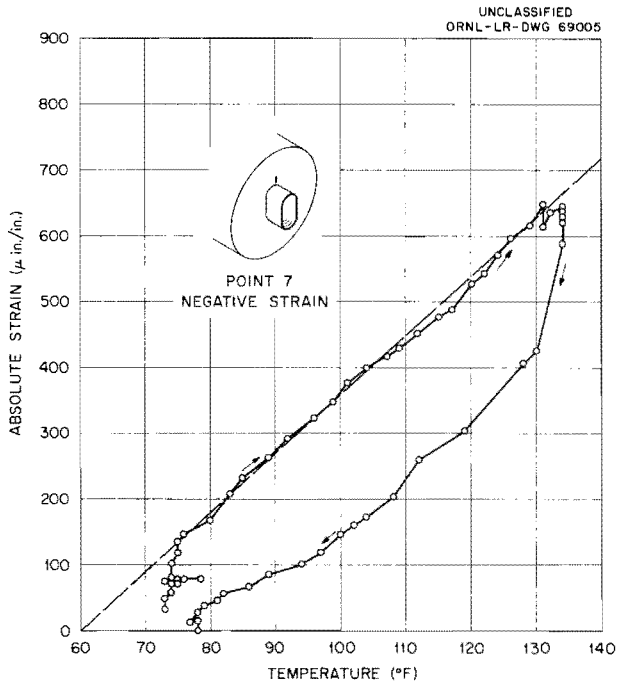

Fig. 8. Measured Strain Versus Cooling-Water Exit Temperature at Location 7 on the Large-Facility Housings.

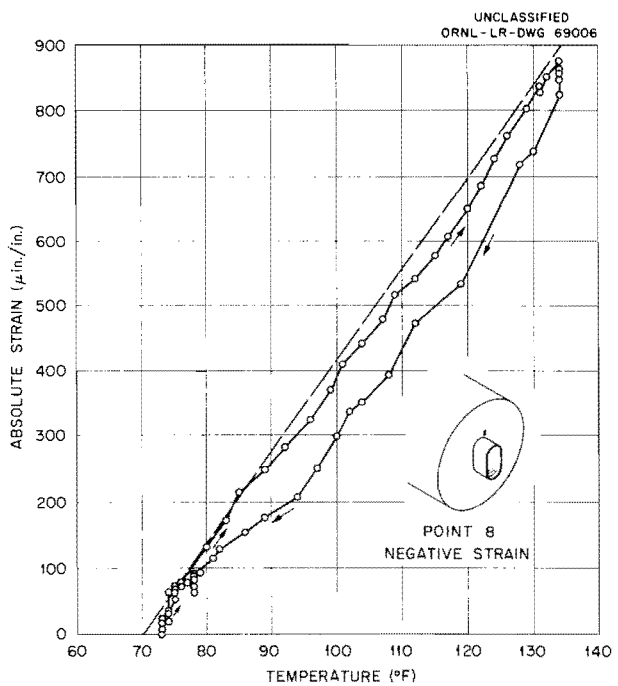

Fig. 9. Measured Strain Versus Cooling-Water Exit Temperature at Location 8 on the Large-Facility Housings.

Experimental Determination of Strains in the Large-Facility Dished-Head Model

As discussed in the previous report,[1] a 1/4-scale aluminum model of the large facilities was constructed at the University of Tennessee for the purpose of performing electrical-resistance strain-gage analyses on the model under various loadings. The previous report contained the results of tests performed on the model at the University. These tests were restricted to small strains, however, and random loadings were used that did not accurately simulate those actually imposed on the large-facility housings.

In order to study the behavior of the housings when large strains are imposed on them, the model was instrumented with new gages and subjected to additional tests. These tests had four specific objectives:

1. to determine the magnitudes of the peak strains when strains corresponding to those selected points on the actual housing were duplicated;
2. to determine the effects of local yielding in the dished heads on the strain magnitudes and distributions;
3. to verify that the maximum strains occur on the pool side of the dished head and in the region directly above the obround;
4. to determine the biaxiality of strains at critical locations in the dished heads.

The first and second objectives were specified in order to predict the peak strains which would occur in the dished heads if the cooling-water exit temperature were increased beyond the maximum value for which measurements were made (135°F). The third objective was specified to ensure that strain measurements on the large-facility dished heads were actually made at the location where the maximum strains occur, and the fourth objective was important because biaxiality affects fatigue life.*

The model and the method of loading are shown in Fig. 10. The lower flat plate, which is attached to the loading-frame bed, represents the

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*The effects of biaxiality on fatigue life are discussed in the Appendix.

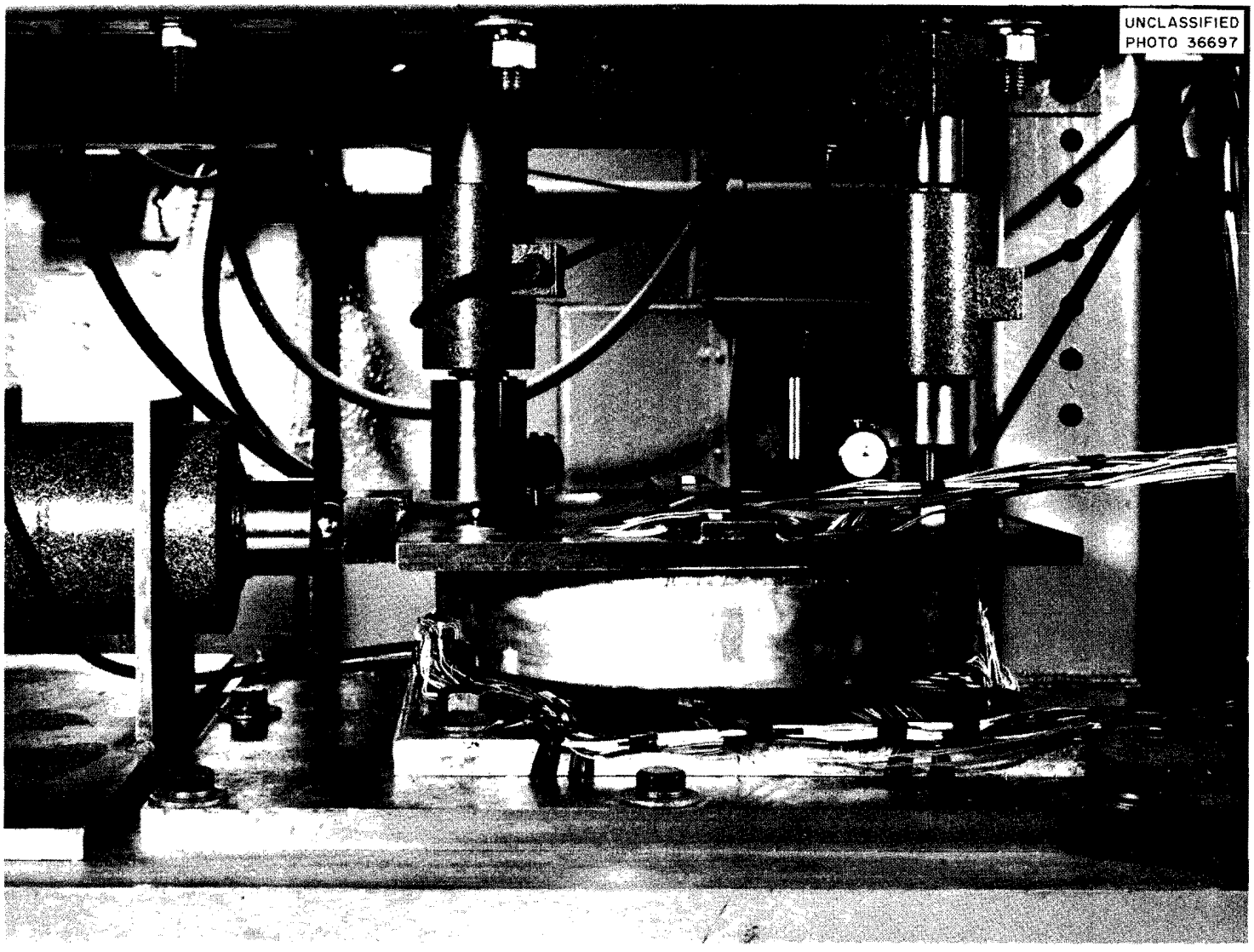

Fig. 10. Large-Facility Housing Model During Testing. Original reduced 24%.

reactor tank wall, and the upper plate represents the pool wall. The model was loaded horizontally through the large load cell at the left. This horizontal loading represents the vertical force exerted on the dished head by the obround as the reactor cooling-water exit temperature increases. The two vertical loadings on the model were used to keep the upper flat plate parallel to the lower plate as the horizontal load was applied. These vertical loadings correspond to the couple applied to the dished head by the pool wall to which it is bolted. A total of 56 gages were applied to the model. Gages with a 1/4-in. gage length were used, except in the immediate vicinity of the dished head-obround junction, where 1/16-in. gages were used in order to measure accurately the strain concentrations at these points.

The model was loaded in varying increments of horizontal load up to a total load of 24 636 lb. Strain readings were recorded after each increment of load was applied. It was found that the maximum strains always occurred on the pool side of the dished head immediately adjacent to and above the obround. In addition, the gages which were tangent to the top of the obround showed approximately zero strain for all loads. Thus, the strain biaxiality in the region of maximum strain was zero, and the last two objectives of the test were fulfilled. Except for the above observations, only the results for several key gage positions will be given. The chosen gage locations are shown in Fig. 11 and correspond to the locations for which measurements were made on the actual large-facility housing or to positions of maximum strains. Gages numbered 1 through 5 are in locations corresponding to similarly numbered locations at which measurements were made on the actual large-facility housing. The strains at each location in Fig. 11 are plotted in Fig. 12 as a function of horizontal load.

Interpretation of Results

The preceding sections described the actual strain measurements made on one of the large-facility dished heads and the strain measurements made on a scale-model of the large facilities. A discussion of the mechanical properties of the dished-head material (aluminum alloy 5154-0)

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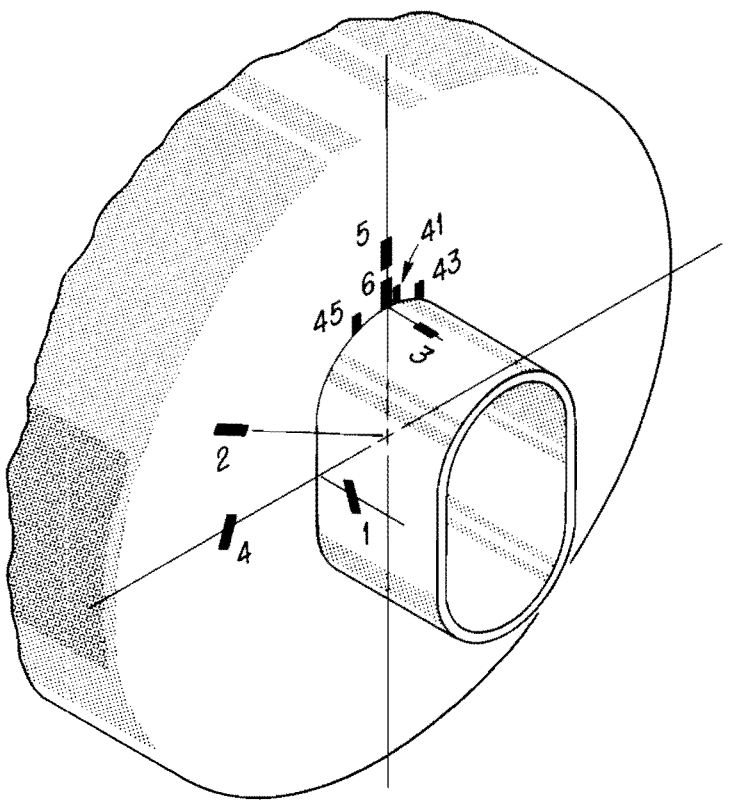

Fig. 11. Key Strain Gage Locations on Model of Large-Facility Housings.

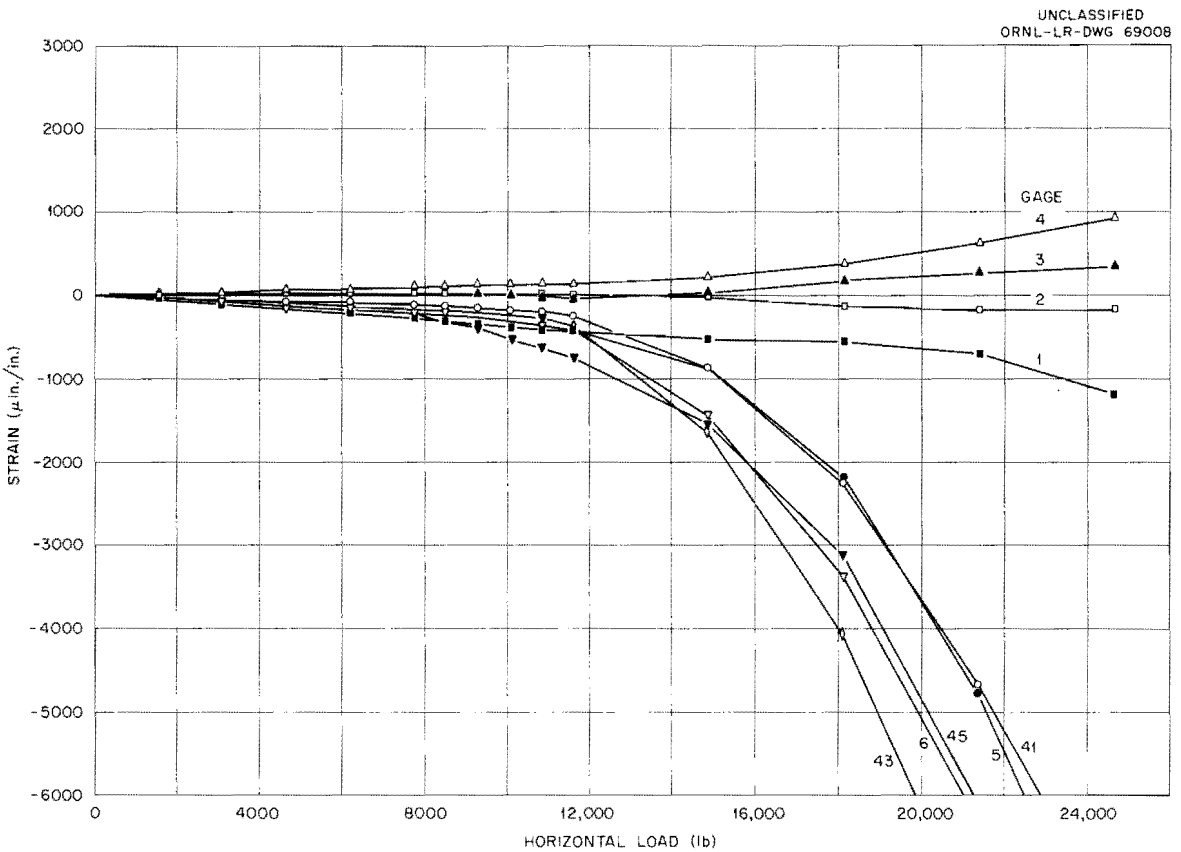

Fig. 12. Strains at Key Gage Locations Versus Horizontal Load on Large-Facility Housing Model.

is given in the Appendix. The results will now be considered in conjunction with the mechanical properties to evaluate the effects of cyclic strains in the large-facility dished heads.

The results of the strain measurements (Figs. 4–9) made on the north-facility housing at the locations shown in Fig. 3 are given in Fig. 13, where the strain-temperature correlation for each gage point is represented by a single straight line, the slope of which was determined from the dashed straight lines in Figs. 4 through 9. All strains in Fig. 13 were referenced to zero at a temperature of 70°F, since this is the minimum reactor temperature. The solid portions of each curve span only the cooling-water exit-temperature range over which measurements were actually made, and the dashed portions are extrapolations based on the assumption that the strains remain linear with temperature up to 150°F. A careful comparison of the strains in Fig. 13 with those of Fig. 12, which shows the model test results, indicates that the strain magnitudes, for each location, at a temperature of 135°F are in the general range of strain magnitudes for corresponding locations on the model when a horizontal load of approximately 12 000 lb is applied. This is within the load range for which the strains cease to be linear with horizontal load. Figure 12 indicates that, as the load is increased beyond the 12 000 lb range, the larger strains increase at increasing rates. However, the temperature change corresponding to a given increment of horizontal load, when the total horizontal load is above 12 000 lb, would be greater than the temperature change corresponding to the same increment of horizontal load when the total load is less than 12 000 lb. Thus, if a plot of the actual strains which would occur in the large-facility housing at cooling-water exit temperatures above 135 deg were available, it would show that the maximum strains would not deviate greatly from linearity, at least for temperatures below approximately 150°F.

The model results presented in Fig. 12 were obtained from a single loading into the plastic range. If subsequent cyclic loading were applied to the model, a shakedown period would occur during which the plastic strains would diminish in magnitude because of strain hardening of the material. An examination of Fig. A.1 of the Appendix, which shows two

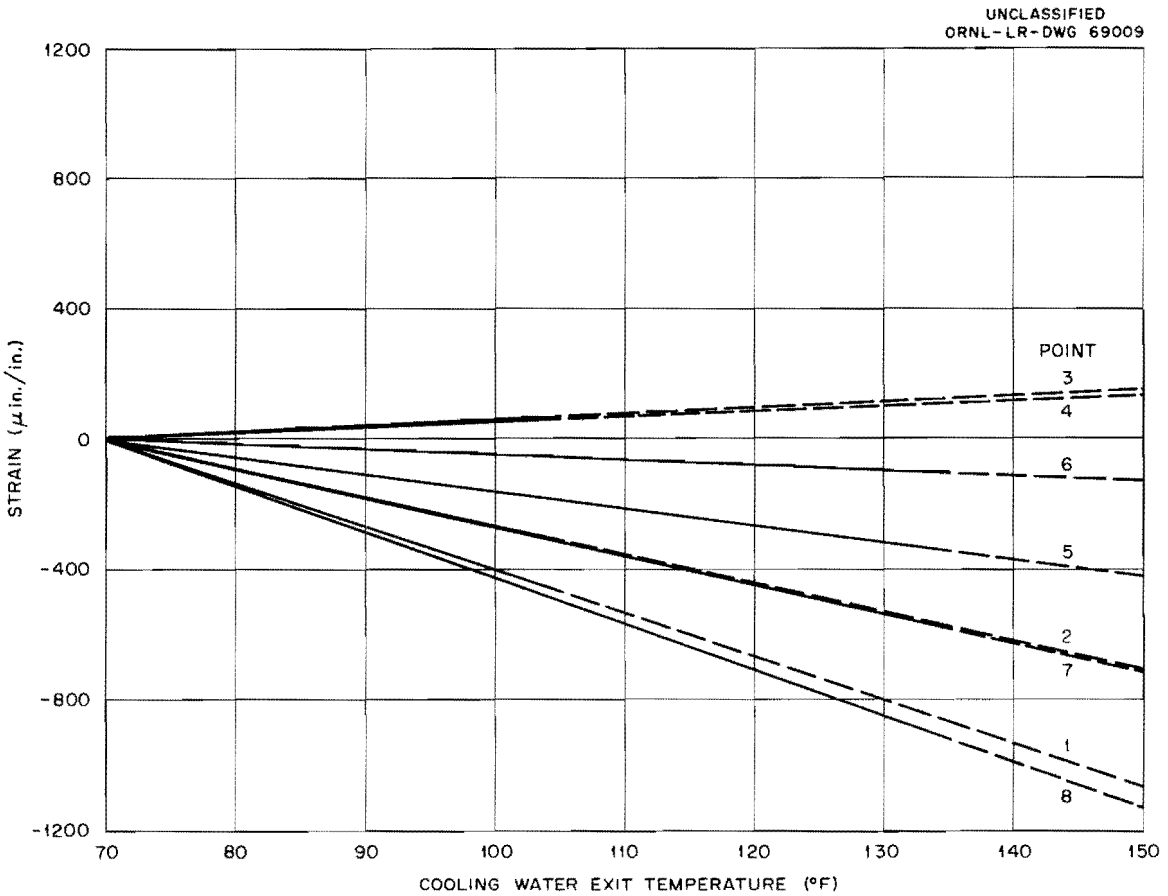

Fig. 13. Extrapolation of Measured Strains Versus Cooling-Water Exit Temperature at Each Location on the Large-Facility Dished Heads.

short-time stress-strain curves for the dished-head material, indicates that the typical alloy 5154-0 specimen exhibits elastic behavior up to a strain of approximately 900 μin./in. However, the alloy 5154-0 rod material exhibits elastic behavior up to a strain of approximately 1750 μin./in. The effects of strain hardening are further illustrated by stress-strain data for a typical aluminum alloy repeatedly strained by moderate amounts into the plastic region. The data indicate that if the material is unloaded and then reloaded, it remains elastic up to the previous maximum stress. From these observations, it is concluded that even if short-time plastic strains should occur, or have occurred, in the dished head, the material would strain harden so that during subsequent cycles the strains would remain essentially elastic. In addition, it is shown in the Appendix that stress relaxation of the dished-head material will not contribute any significant time-dependent plastic strain during a reactor cycle. Thus, the linear extrapolations in Fig. 13 represent reasonable approximations of the strains which would occur at cooling-water exit temperatures as high as 150°F.

The maximum strains occur at point 8; the magnitudes of these strains are −920 μin./in. and −1130 μin./in. at cooling-water exit temperatures of 135 and 150°F, respectively. Referring to Fig. A.2 in the Appendix, which gives the total strain range versus cycles for the dished-head material, it may be concluded that the parent dished-head material can withstand an indefinite number of cycles between cooling-water exit temperatures of 70 and 150°F. However, the strain at point 8 in Fig. 13 is at the obround-dished head weld junction, and the weld material is less resistant to fatigue than the parent alloy. Since the model test data indicated that the strain perpendicular to the maximum measured strain at point 8 was zero, the stress range at that point is given by

$$\Delta\sigma = \frac{E}{1 - \mu^2} \Delta\epsilon_t \quad ,$$

where E is the modulus of elasticity, μ is Poisson's ratio, and $\Delta\epsilon_t$ is the total strain range. Using 920 and 1130 μin./in. as the strain ranges for cooling-water exit temperatures of 135 and 150°F, respectively, the

corresponding stress ranges become 10 300 and 12 650 psi. The fatigue-strength of aluminum welded joints is discussed in the Appendix. Figure A.3 represents the fatigue strengths of welded joints, which may be assumed to be representative of the obround-dished head junctions. The fatigue curve is based on complete specimen failure. As mentioned in the Appendix, fatigue cracking of nonwelded aluminum material first occurs at approximately 80% of the number of cycles to complete failure, and it will be assumed that this is also the case for welded joints. Using Fig. A.3 and the above assumptions, it may be concluded that cracking of the dished head-obround weld joints will occur after 20 000 cycles of 70 to 135°F operation of the reactor or after 7600 cycles of 70 to 150°F operation. Previous 70 to 135°F cycles should be counted in the latter case.

The applicable curves in Figs. A.2 and A.3, which were used to obtain the cycles-to-failure estimates, were obtained from the original fatigue data by applying a reduction factor of at least 10 on cycles and 2 on strain range or stress range. As discussed in the Appendix, the latter factor was applied to compensate for the detrimental effect of water on the fatigue strength of aluminum alloys. Although reduction factors were applied, the cycles-to-failure estimates should be considered as conservative estimates of the number of cycles in which failure will actually occur and not as design values wherein factors of safety have been included.

APPENDIX. Mechanical Properties of Aluminum Alloy 5154-0

The damaging effects of cyclic strains are believed to be due mainly to the plastic component of the total strain occurring during each cycle. The magnitude of the plastic strain depends not only on the short-time stress-strain characteristics of the material but also on the relaxation characteristics at the temperature and stresses involved. Any relaxation that occurs during a cycle results in a portion of the elastic strain becoming plastic and thus increasing the plastic strain per cycle. In addition, strain-cycling fatigue data are affected by the strain ratio (ratio of minimum-to-maximum strain in a cycle), temperature of the test, and stress biaxiality in the test specimen. The fatigue characteristics of aluminum alloys are also extremely sensitive to the presence of water. Thus, in order to accurately assess the strain-cycling effects in the large-facility dished heads, the following mechanical properties data were needed:

1. ordinary short-time stress-strain curves for determining the minimum strain at which short-time plastic deformations will occur,
2. relaxation data for determining the time-dependent plastic strains which occur during the duration of a reactor cycle, and
3. strain-cycling fatigue test data, including information on the effects of strain ratio, temperature, biaxiality, and environmental effects, for determining the fatigue life of the material.

In addition, data indicating the effect of a welded joint on fatigue strength were needed because the highly strained region is at a weld joint, and the results of fatigue-crack propagation studies were required to indicate how rapidly a fatigue crack might propagate if it developed.

The large-facility dished heads are made of aluminum alloy 5154-0, which contains magnesium. The 5000-series alloys are weldable materials used in structures such as pressure vessels. In contrast to the copper-type aluminum alloys (2000 series), which are widely used in aircraft applications, the mechanical properties of the magnesium-type alloys have received comparatively little attention. The need for mechanical properties data for alloy 5154-0 was discussed with Dr. Marshall Holt of the

Alcoa Research Laboratories, and, as a result, Alcoa subsequently provided considerable information applicable to the dished-head material. In addition, the Syracuse University Research Institute (SURI) under contract with the Atomic Energy Commission is investigating the strain cycling characteristics of aluminum alloy 5454-0, which is used as a nuclear pressure vessel material. This alloy is similar in chemical composition and mechanical properties to the dished-head material, 5154-0. Comparisons of the nominal composition and the mechanical properties of the two alloys are presented in Tables 1 and 2. The data were taken from Refs. 2 and 3. Based on the close similarity between the two alloys and on the opinion of the Alcoa Research Laboratories,[3] the strain-cycling data generated by SURI for aluminum alloy 5454-0 were assumed to be representative of alloy 5154-0. The published creep data for alloy 5454-0 were also assumed to be representative of alloy 5154-0,* and relaxation data were derived from these creep data.

*Limited creep data subsequently obtained for alloy 5154-0 substantiate this assumption.

Table 1. Comparison of Nominal Compositions of Aluminum Alloys 5154-0 and 5454-0

Alloy	Alloying Elements (%)		
	Manganese	Magnesium	Chromium
5154-0		3.5	0.25
5454-0	0.8	2.75	0.10

Table 2. Comparison of Typical Mechanical Properties of Aluminum Alloys 5154-0 and 5454-0

Alloy	Strength (psi)			Elongation in 2 in. (%)	Endurance Limit[a] (psi)
	Ultimate	Yield	Shear		
5154-0	35 000	17 000	22 000	27	17 000
5454-0	36 000	17 000	23 000	22	20 500

[a]Based on 5×10^8 cycles of completely reversed stress.

Two stress-strain diagrams for alloy 5154-0 are shown in Fig. A.1. One curve is typical for wrought material, and the other is for rod material. Both curves were furnished by Alcoa and indicate the wide variation in the proportional limit which can be expected.

The strain measurements made on the model of the large-facility housings indicated that the strain biaxiality in the region of highest strain was zero. This same condition was obtained[4] at SURI in strain-controlled reverse-bend cycling tests on flat plates when the width-to-thickness ratio, w/h, of the plates was greater than 8. Thus, the data obtained from wide plates are applicable to this case. The large-facility dished heads were welded to the tank assembly while the tank was at a temperature of 105°F. Thus, as the reactor is cycled from room temperature to its operating temperature and back, the maximum strains are expected to undergo complete reversals about a mean strain of zero at 105°F. The strain ratio, R (ratio of minimum-to-maximum strain), is thus approximately −1. The temperature of the dished heads was taken to be 100°F. A reversed-bend, strain-controlled, fatigue curve is reported in Ref. 5 that fits the above conditions. The upper left curve in Fig. A.2 presents this SURI curve for the alloy 5454-0. Reference 4 indicates that the effect of biaxiality on fatigue is almost nil at 10 000 cycles. Thus the strain cycling curve should join an ordinary reversed-bending fatigue curve with the stress converted to strain range. Fatigue data for the alloy 5154-0 obtained from Alcoa[6] are presented by the upper right curve in Fig. A.2. The continuous lower curve, which was used in the analysis, was obtained by using a reduction factor of at least 2 on strain range and of at least 10 on cycles. The presence of fresh water drastically reduces the fatigue strength of aluminum alloys.[7,8] This is especially true if fatigue and corrosion operate simultaneously, as is the case for the large-facility dished heads. The results of tests in which corrosion was brought about by wetting the test pieces in the presence of air indicated that the rotating-beam fatigue strength of aluminum alloys was reduced by as much as a factor of 2. It would appear, however, that the influence of oxygen is by no means negligible, because, when the corrosive solution is employed in the absence of air, higher endurance limits

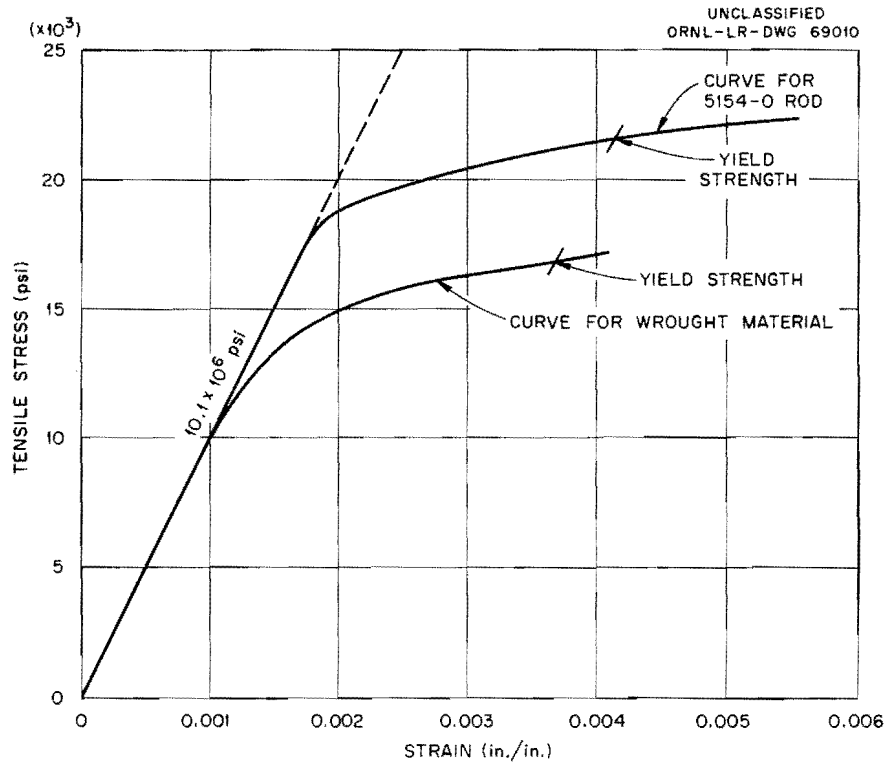

Fig. A.1. Short-Time Stress-Strain Curves for Aluminum Alloy 5154-O.

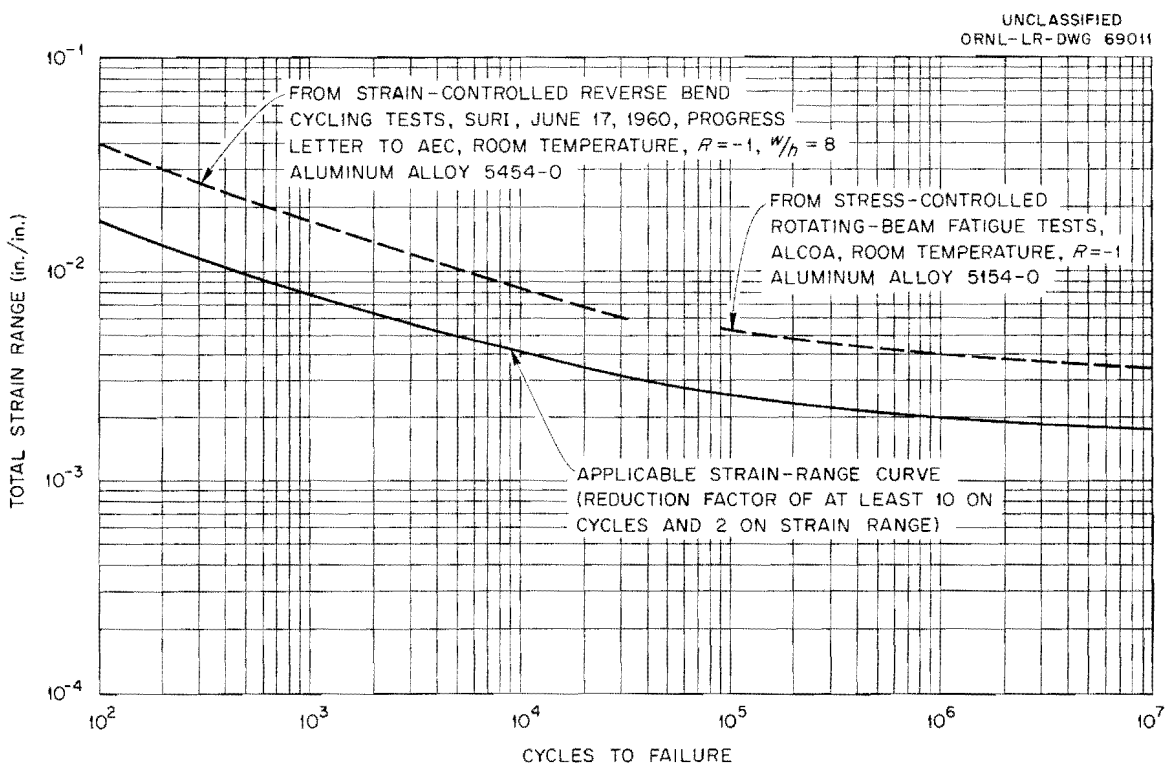

Fig. A.2. Total Strain Range Versus Number of Cycles for Aluminum Alloy 5454-O.

are found. As a conservative estimate, the reduction factor of 2 on strain range in Fig. A.2 is due largely to the effects of water on the fatigue behavior. The remaining reductions were applied to account for scatter of test data, size effects, and surface finish.

The regions of the dished heads that are subjected to the maximum strains are adjacent to the welded dished head-obround junctions. Data were obtained from Alcoa which indicate that the fatigue strength of welded aluminum joints is considerably less than the fatigue strength of the parent alloy or alloys.[9,10] The results also show that the fatigue strength is almost independent of alloy composition and, when an attachment is made to a solid plate by fillet welds, the fatigue strengths are practically the same as those of plain butt-welded joints. No tests were performed on alloy 5154 with a -O temper; however, tests were performed on the same alloy with a -H34 temper; the results are shown in Fig. A.3. The upper curve was drawn through the minimum of the test points. The lower curve was taken from the upper one by using a reduction factor of at least 10 on cycles and 2 on stress range, as was done in Fig. A.2. The lower curve was then considered to be indicative of the number of cycles which the dished head-obround weld junction will withstand before failure.

Relaxation data for aluminum alloy 5154-O could not be found in the literature. However, creep data for alloy 5454-O were found[11] for the temperature range between 200 and 500°F. These data were extrapolated to 100°F, and relaxation curves were obtained by the methods described in Ref. 12. The relaxation curves (stress versus time) for initial stress levels of 10 000 and 20 000 psi were converted to accumulated plastic strain versus time correlations as shown in Fig. A.4. It is seen that for either initial level the interchange of elastic strain to plastic strain is very small for probable reactor operating cycle times.

The Alcoa Research Laboratories are investigating fatigue-crack propagation in aluminum alloys.[13] The tests are performed on flat plate fatigue specimens with a single hole in the center. The specimens are stress cycled until a visible crack appears; the cycles are then continued until the crack reaches an edge of the specimen. In all the tests the

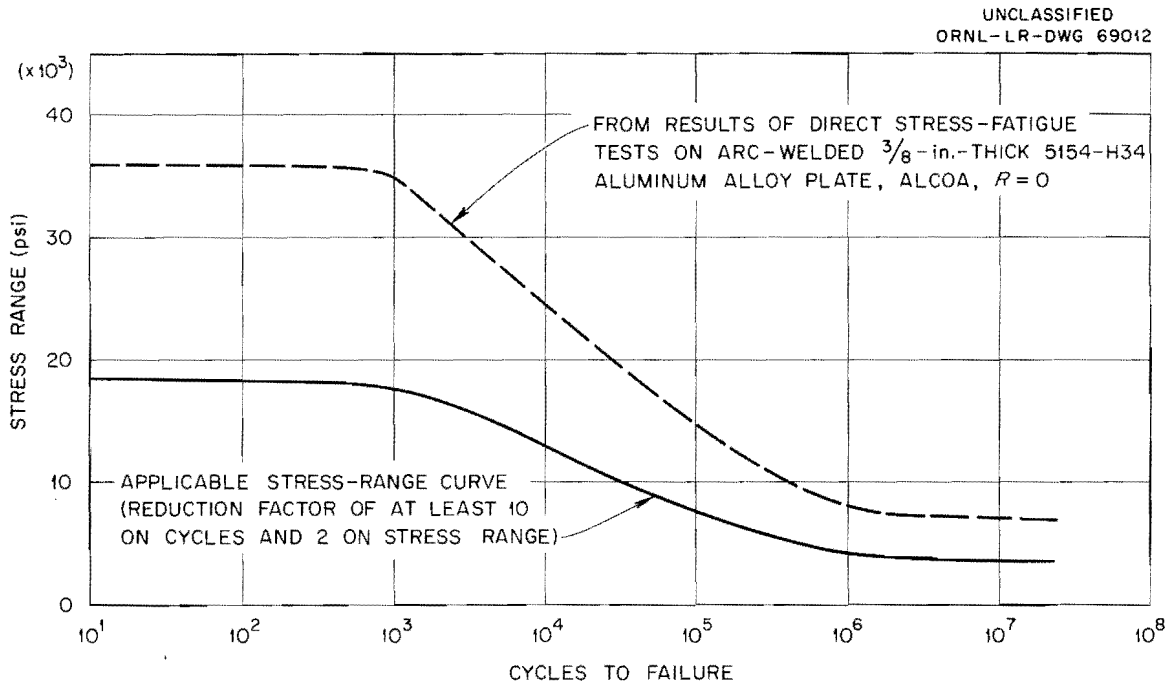

Fig. A.3. Stress Range from Direct Stress-Fatigue Tests on Arc-Welded 3/8-in.-Thick 5154-H34 Aluminum Alloy Plate.

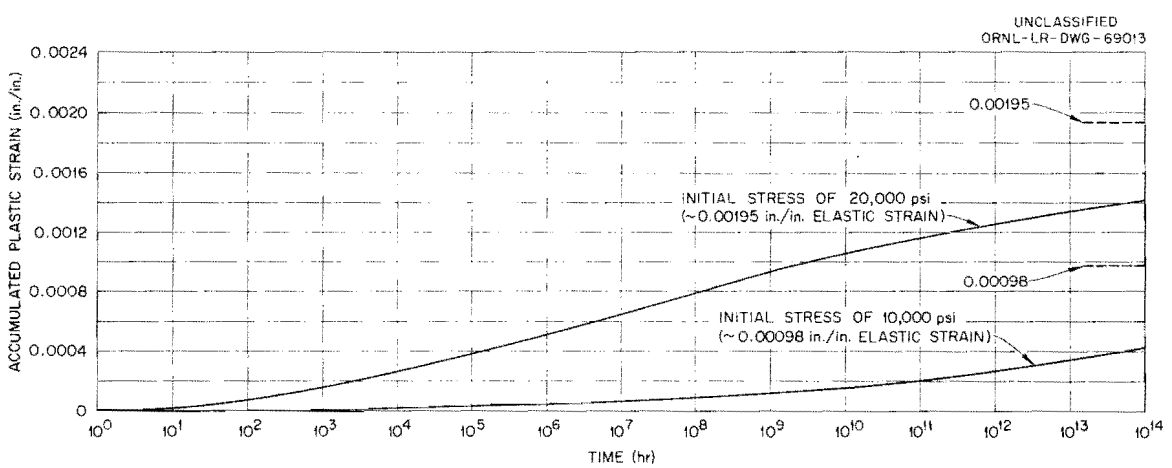

Fig. A.4. Accumulated Plastic Strain Due to Relaxation Versus Time for Two Initial Elastic Strain Levels in Aluminum Alloy 5454-O at 100°F.

results indicated that several thousand cycles are required for a crack to propagate 3 3/4 in. to the edge of the specimen after it is first detected. The reversed-bend strain-controlled fatigue tests performed by Syracuse University Research Institute[4] indicated that the first appearance of cracks in aluminum alloy 5454-O usually occurred at about 80% of the number of cycles to complete failure.

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